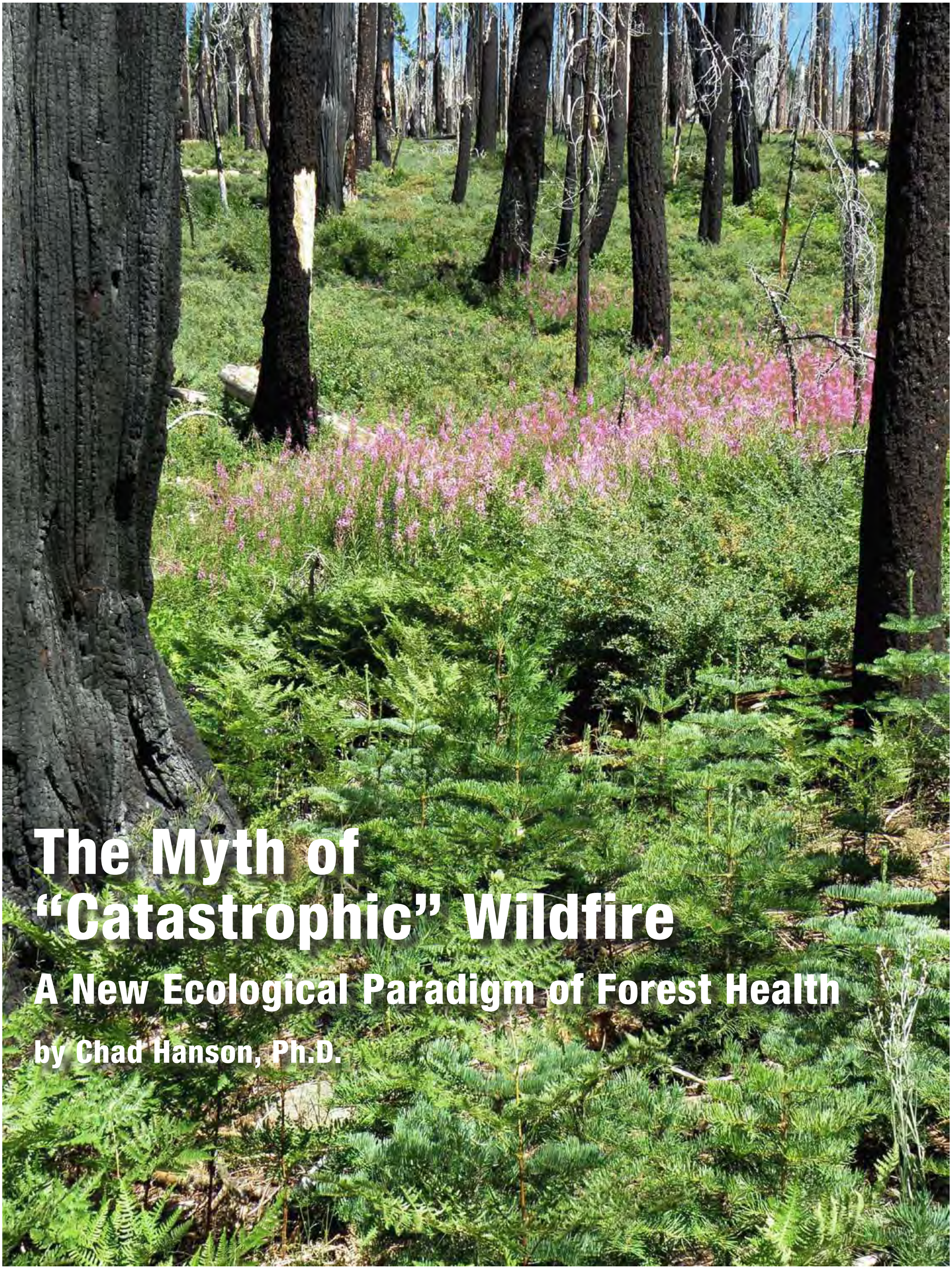
EXHIBITS 17-21

Exhibits to Center for Biological Diversity Comments
EPA Call for Information on Greenhouse Gas Emissions
Associated with Bioenergy and Other Biogenic Sources
Docket No. EPA-HQ-OAR-2010-0560
September 13, 2010

John Muir Project Technical Report 1 • Winter 2010 • www.johnmuirproject.org



The Myth of “Catastrophic” Wildfire

A New Ecological Paradigm of Forest Health

by Chad Hanson, Ph.D.

EXHIBIT 17

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The Myth of "Catastrophic" Wildfire: A New Ecological Paradigm of Forest Health

By Chad Hanson, Ph.D.

Preface

In the summer of 2002, I came across two loggers felling fire-killed trees in the Star fire area of the Eldorado National Forest in the Sierra Nevada. They had to briefly pause their activities in order to let my friends and I pass by on the narrow dirt road, and in the interim we began a conversation. One of the loggers pointed further down the road to a forest stand in which the fire burned less intensely. Most of the trees were alive and green. "I can see why people wouldn't want us to cut down a stand like that," he said, pointing to the green stand. "But what does it matter if we cut down an area like this?" he asked, referring to the heavily-burned area where high-intensity fire had occurred. "All of the trees have been killed. It's been destroyed. What sort of wildlife is going to live here?" he asked rhetorically.

I told the man that I didn't know the answer, and that his was a question that deserved some investigation. That conversation, and the curiosity it piqued in me, ultimately led me to graduate school to earn my Ph.D. in ecology, with a research focus on fire ecology in forest ecosystems. I found the answers to my questions to be as startling and counter-intuitive as they were undeniable, and increasingly I have wondered at the tremendous gap between the rapidly mounting scientific evidence and the widely held popular notions about wildland fire in our forests.

Every fire season in the western United States, we see on television the predictable images of 100-foot flames spreading through tree crowns, while grim-faced news anchors report how many acres of forest were "destroyed" by the latest "catastrophic" fire. The reaction is understandable. For decades, countless Smokey the Bear advertisements have told us that forest fires are bad and damaging. Until about 25 years ago, land management agencies, such as the U.S. Forest Service, genuinely believed that they could essentially eliminate fire from our forests if they had enough resources to suppress fires – and they sought to do just that.

By the late 20th century, however, forestry officials began to concede that, historically, frequent low-intensity fires were natural in our forests, slowly creeping along the forest floor after lightning ignitions, reducing fuel on the forest floor and naturally thinning-out brush and small trees. Though a begrudging acceptance of the benefits of low-intensity fire began to take hold, it was commonly assumed that areas of high-intensity fire, where tall flames killed most of the trees, were fundamentally the unnatural result of fuel accumulations from decades of fire suppression. Thus began the "catastrophic wildfire" paradigm, which divided fires into two categories: good fires and bad fires depending upon whether they burned at low-intensity or high-intensity, respectively.

A Forest Service public education brochure for the Sierra Nevada from 2004 captured the thinking underlying this paradigm. The brochure, entitled "Forests With A Future", portrayed high-intensity fires as an "eco-disaster" that "destroy wildlife habitat." No scientific studies were cited to support this characterization. Under the heading of "Good fires, bad fires", the brochure opined: "Fire is natural to the forest. But not the kind of fire that burns so hot, and shoots up so high, it destroys everything." The report blamed the perceived threat of high-intensity fire on a build-up of fuel from "fire suppression practices over the last century". It proposed a massive logging program on national forests, under the guise of "thinning", ostensibly to eliminate high-intensity fire from the landscape.

Ironically, in the “catastrophic wildfire” paradigm, land managers have requested, and received from Congress, increasingly more money for increasingly aggressive fire suppression tactics. The Forest Service justifies this by arguing that, except in rare cases, fires simply cannot be allowed to burn, since high-intensity fires will often occur. In these increasingly intensive fire suppression tactics, firefighters have frequently been placed in harm’s way to stop fires the land management agencies assumed to be destructive and unnatural – often in remote areas, and all too often with fatal consequences for firefighters.

Simultaneously, land managers have requested, and received, increasingly more money for forest “thinning” operations under the guise of “fuel reduction”. Land management agencies, such as the Forest Service, have used these funds to plan and implement thousands of commercial logging projects that remove mature trees, reasoning that they can thin more acres of forest if they sell many of the larger, fire-resistant trees – which are commercially valuable – to timber companies, using the sale of these trees to “offset” their costs. The Forest Service and other land agencies keep the revenues from these timber sales to enhance their budgets, creating a perverse incentive for more and more logging of larger and larger trees over increasingly vast expanses of the forested landscape. In this context, it did not take long for nearly everything to be described as “fuel” that must be removed. Live mature and old-growth trees have been, and are being, cut by the thousands, and dead trees are routinely sold to logging companies and removed, often leading to large areas being clearcut on public lands following wildland fires in the name of fuels reduction.

Commercial logging ostensibly to prevent “catastrophic fire” has been promoted heavily through a Bush-era policy known as the “Healthy Forests Initiative”, which essentially defines a healthy forest as one in which the trees are all green, there are few if any dead trees or downed logs, and fire is acceptable so long as it doesn’t kill any mature, commercially-valuable trees. This policy provides a compelling narrative to many, because it underscores and capitalizes upon deeply held cultural notions and perceptions about forests and fire. Once again, however, readily available ecological science was ignored.

And so, remarkably, under the “catastrophic wildfire” paradigm, the discredited policies of the past, including fire suppression and removal of mature, fire-resistant trees, has continued – even increased in many cases. Even as land managers and policy-makers lamented the mistakes of past management, essentially the same management has continued day after day, year after year.

Recently, however, a new paradigm has begun to emerge, informed by the latest ecological science. Over the past decade, a surge of scientific discovery has led researchers to fundamentally re-think previous assumptions about fire and forest health. In this new “forest ecology” paradigm, scientists have come to understand that high-intensity fires, or “stand-transforming fires”, occurred naturally in most western U.S. conifer forests historically, and we have far less fire now than we did prior to fire suppression policies. Scientists have also come to understand that dead trees, especially large dead trees, or “snags”, are not only the most ecologically valuable habitat features in the forest, but are also far too scarce, due to fire suppression and logging conducted under the guise of fuels reduction and forest health.

Most strikingly, recent scientific evidence has revealed that, contrary to previous assumptions, most current fires are predominantly low-intensity and moderate-intensity, and the relatively scarce high-intensity areas support the highest levels of native plant and wildlife biodiversity of any forest type in the western United States. Scientists now understand that, far from being “destroyed”, these high-intensity patches are actually natural ecological treasures. High-intensity, or stand-transforming, fire creates ecologically-vital “snag forest habitat”, which is rich with large snags, large downed logs, dense pockets of natural conifer regeneration, patches of native shrub habitat, or “montane chaparral”, and large live trees.

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Figure 1. Snag forest habitat in a mature mixed-conifer forest.

In snag forest habitat, countless species of flying insects are attracted to the wealth of flowering shrubs which propagate after stand-transforming fire – bees, dragonflies, butterflies, and flying beetles. Many colorful species of birds, such as the iridescent blue Mountain Bluebird, nest and forage in snag forest habitat to feed upon the flying insects. In order to feed upon the larvae of bark beetles and wood-boring beetles in fire-killed trees, woodpeckers colonize snag forest habitat shortly after the fire, excavating nest cavities in large snags. The woodpeckers make new nest holes each year, leaving the old ones to be used as nests by various species of songbirds. Many rare and imperiled bat species roost in old woodpecker cavities in large snags, and feed upon the flying insects at dusk. Small mammals, such as snowshoe hares and woodrats, create dens in the shrub patches and large downed logs, and raptors, such as the Spotted Owl, benefit from the increase in the abundance of their prey. Deer and elk browse upon the vigorous new plant growth that follows stand-transforming fire, and bears and wolves benefit from the increased abundance of their prey as well. A number of native wildlife species, such as the Black-backed Woodpecker, are essentially restricted to snag forest habitat for nesting and foraging. Without a continuous supply of this habitat, they won't survive.

Snag forest habitat is alive, and vibrant. It is colorful, and rich with varied sounds, given the sheer density of wildlife activity. It is the most rare, endangered, and ecologically important forest habitat in western U.S. forests, and the stand-transforming fires that create this habitat are not damaging the forest ecosystem. Rather, they are advancing ecological restoration. There is nothing "catastrophic" about wildland fire in these forests, especially where stand-transforming fire effects occur, creating snag forest habitat.

What is tragic, however, is the burning of homes in rural, forested areas. Our focus and our resources must be redirected to ensure protection of homes, rather than conducting pointless and destructive "fuels reduction" and "forest health" logging projects in remote forested areas based upon an outdated and unscientific management paradigm – a paradigm that financially benefits the timber industry and the budgets of land management agencies, but further deprives conifer forest ecosystems of the habitat features they need most to support imperiled species.

Fortunately, the means to protect homes from wildland fires are well understood, and fundamentally practical. The most recent science clearly shows that the only effective way to protect homes from fire is to reduce the combustibility of the home itself, by using fire-resistant roofing and siding and installing simple items like guards for rain gutters (which prevents dry needles and leaves from accumulating), as well as by creating "defensible space" through the thinning of brush and small trees within 100 feet of individual homes. If these simple measures are taken, the evidence clearly indicates that there is very little chance of homes burning, even in high-intensity fires (see, e.g., studies of Dr. Jack Cohen at www.firelab.org). Currently, however, only 3% of U.S. Forest Service fuels reduction projects are conducted adjacent to communities – and much of that 3% is well over 100 feet from homes.

We do not need to be afraid of the effects of fire in forest ecosystems of the western United States. Wildland fire is doing important and essential ecological work. It is keeping countless wildlife species alive. Our challenge, in the new and emerging paradigm, is to make certain that homes are protected so that we can allow wildland fire to do its vital and life-giving work in our forests. In short, we need to stop our futile battle against wildland fire and learn to live well with fire, reminding ourselves that western U.S. conifer ecosystems evolved with fire and are adapted to it. Excluding fire from these ecosystems is like trying to keep rain out of a rainforest.

Executive Summary

Popular myths and misconceptions about the ecology of fire and dead trees in western U.S. conifer forests are numerous, and are strongly at odds with the recent scientific evidence, which indicates the following about these forest ecosystems:

- ▷ The only effective way to protect homes from wildland fire is to reduce the combustibility of the homes themselves, and reduce brush and very small trees within 100 feet of the homes. Commercial thinning projects that remove mature trees hundreds of yards – and often several miles – from the nearest home do not protect homes, and often put homes at greater risk by diverting scarce resources away from true home protection, by creating a false sense of security, and by removing large, fire-resistant trees and generating combustible logging "slash debris", which increases potential fire severity. Currently, less than 3% of U.S. Forest Service "fuels reduction" projects are near homes.
- ▷ Patches of high-intensity fire (where most or all trees are killed) support the highest levels of native biodiversity of any forest type in western U.S. conifer forests, including many rare and imperiled species that live only in high-intensity patches. Even Spotted Owls depend upon significant patches of high-intensity fire in their territories in order to maintain habitat for their small mammal prey base. These areas are ecological treasures.
- ▷ Current fires are mostly low- and moderate-intensity, and high-intensity fire comprises a relatively small proportion of the total area burned. Areas that have not burned in a long time are not burning more intensely.
- ▷ Vigorous natural regeneration of conifer seedlings occurs after high-intensity fire. Numerous large trees also survive, and their growth tends to increase substantially after the fire, which converts woody material on the forest floor into highly usable nutrients for tree growth. By contrast, after very long absence of these fires, forests can lose so much of their productivity that, ultimately, sites lose the ability to support forest at all.
- ▷ There is far less fire now than there was historically. There is also less high-intensity fire now than there was prior to fire suppression policies.
- ▷ Fires are not becoming more intense.

- Predictions vary about the effect of global warming and climate change on forest fire activity, but the most recent projections indicate reduced fire activity in most forests due to changes in combustible vegetation, and increased precipitation in many areas. Even scenarios for increased fire activity would not rectify the current deep deficit of fire in forest ecosystems.

- Ton for ton, dead trees (“snags”) are far more important ecologically than live trees, and there are far too few large snags and logs to support native wildlife in most areas. Recent anecdotal reports of forest “destroyed” by beetles are wildly misleading and inaccurate.

- High-intensity fire burns cleaner than low-intensity, and produces fewer particulates.

- Current forests, including old-growth forests, are carbon sinks, meaning that they are absorbing more of the greenhouse gas CO2 than they are emitting. High-intensity wildland fire promotes high levels of carbon sequestration. Old-growth conifer forests cannot function as carbon sinks without fire. Without large, intense wildland fires to cycle nutrients and rejuvenate the productivity of the soil, forests can become carbon sources after about 600 years of age.

- Mechanical “thinning” decreases total carbon storage in conifer forests.

- Though timber interests have promoted increased logging by describing current forests as “overstocked”, the scientific data indicates that, due to past logging, as well as exclusion of wildland fire, forests of today have much less total biomass than historic forests. However, “biomass” thinning is a growing threat to forests, and is now associated with post-fire logging, and logging of unburned old-growth trees.

- Ecologically “healthy forests” are those that have an abundance of low-, moderate-, and high-intensity fire effects, and an abundance of large snags. We need more, not less, fire and large dead trees and downed logs to keep our forest ecosystems healthy. “Thinning” projects designed to prevent high-intensity fire and reduce future large snag densities are not promoting “forest health”, and post-fire “salvage” logging is profoundly destructive ecologically. Moreover, if fire suppression policies achieve their stated goal, many wildlife species that depend upon habitat created by high-intensity fire will be put at risk of extinction.

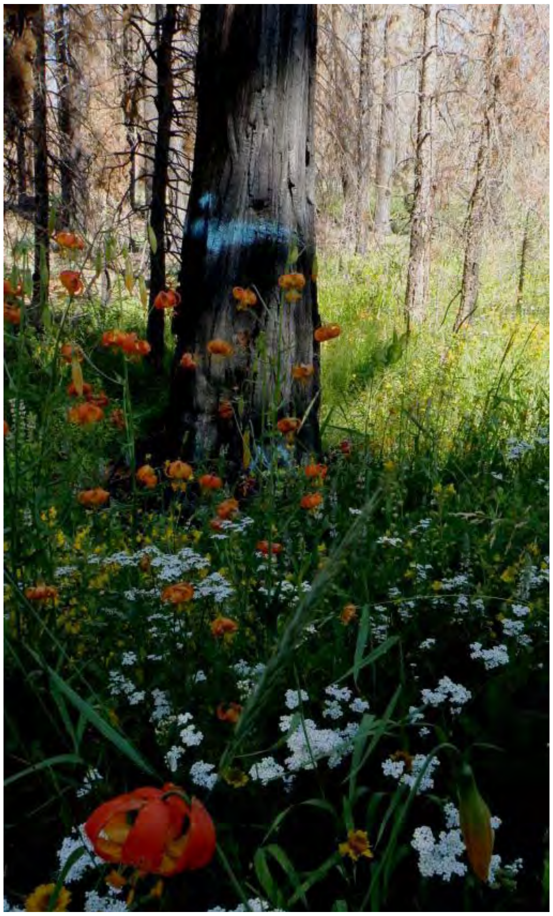

Fig. 2. Post-fire snag tree marked for logging.

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Note: Fire studies often use the term “fire severity” to describe the proportion of trees killed, while “fire intensity” is used to describe the energy released by the fire. In this report, I use the term “fire intensity” in reference to the extent of tree mortality. I do this for two reasons. First, high-severity areas and high-intensity areas are generally the same in conifer forests. Second, the term “severity”, like “catastrophic”, is pejorative in nature, and objective scientific discourse should seek to use value-neutral terms.

Myths and Facts

MYTH 1

Forest “thinning” projects in the Wildland/Urban Interface (WUI) protect homes from wildland fire in forested communities.

FACT 1

Commercial “thinning” logging projects do not protect homes.

The term “Wildland/Urban Interface”, or “WUI”, has been misleadingly used to justify commercial thinning logging projects – under the guise of home protection – miles from the nearest home. The scientific evidence is clear that the only effective way to protect structures from fire is to reduce the ignitability of the structure itself (e.g., fireproof roofing, leaf gutter guards) and the immediate surroundings within about 100 feet from each home, e.g., through thinning of brush and small trees adjacent to the homes (www.firelab.org–see studies by U.S. Forest Service fire scientist Dr. Jack Cohen). This area would be more properly described as the “Defensible Space Zone”. Regardless, only 3% of Forest Service “fuels reduction” projects are conducted within the WUI, adjacent to communities – and much of that 3% is well over 100 feet from homes (Schoennagel et al. 2009).

Moreover, most “thinning” projects allow removal of many of the larger trees in order to make the projects economically attractive to logging companies, and to generate revenue for the public land management agencies, such as the U.S. Forest Service. Where this is done near homes, it can increase the danger of structures burning. The removal of larger, mature trees in thinning operations tends to increase, not decrease, fire intensity by: a) removing large, fire-resistant trees; b) creating many tons of logging “slash” debris – highly combustible branches and twigs from felled trees; c) reducing the cooling shade of the forest canopy, creating hotter, drier conditions on the forest floor; d) accelerating the growth of combustible brush by reducing the mature trees that create the forest canopy, thereby increasing sun exposure; and e) increasing mid-flame windspeeds (winds created by fire) by removing some of the mature trees and reducing the buffering effect they have on the winds associated with fires (Hanson and Odion 2006, Platt et al. 2006). The scientific evidence clearly indicates that, where it is important to reduce potential fire intensity (e.g., immediately adjacent to homes) this can be very effectively accomplished by thinning some brush and very small trees up to 8 to 10 inches in diameter (Omi and Martinson 2002, Martinson and Omi 2003, Strom and Fule 2007). Removal of mature trees is completely unnecessary.

A July 20, 2008 article by Heath Druzin and Rocky Barker in the Idaho Statesman documents an excellent example of effective home protection. The article describes the Idaho town of Secesh Meadows, which decided to get serious about creating defensible space by reducing brush immediately adjacent to the homes. A high-intensity wildland fire approached the town, but dropped down to a slow-moving low severity fire once it reached the populated area. The fire burned right through the town, right past front porches, and kept moving, but did not burn down a single home. As resources are being spent on counter-productive commercial thinning projects that are hundreds of yards, and sometimes several miles, from the nearest town, homes remain unprotected in rural forested areas. This is entirely preventable.

MYTH 2

Low-intensity fire is natural and acceptable, but patches of high-intensity fire are ecologically destructive.

FACT 2

High-intensity fire patches create habitat that supports some of the highest levels of native biodiversity of any forest type in western U.S. forests.

Snag Forest Habitat

"Snag forest habitat", resulting from high-intensity fire patches (generally, stands with 75-80% or greater tree mortality from fire, exclusive of seedlings and saplings) that have not been salvage logged, is one of the most ecologically-important and biodiverse forest habitat types in western U.S. conifer forests (Lindenmayer and Franklin 2002, Noss et al. 2006, Hutto 2008). Noss et al. (2006) observed the following in reference to high severity fire patches: "Overall species diversity, measured as the number of species – at least of higher plants and vertebrates – is often highest following a natural stand-replacement disturbance…" Snag forest habitat is comprised of abundant standing fire-killed trees ("snags") of all sizes, especially larger trees, as well as patches of montane chaparral (dominated by flowering shrubs whose germination is facilitated by fire), dense pockets of natural conifer regeneration, large downed logs, numerous "fire-following" wildflowers, and widely-spaced large surviving trees. At the landscape level, high-intensity fire habitat (when it is left unlogged) is among the most underrepresented, and rarest, of forest habitat types. Noss et al. (2006) observed that "early-successional forests (naturally disturbed areas with a full array of legacies, ie not subject to post-fire logging) and forests experiencing natural regeneration (ie not seeded or replanted), are among the most scarce habitat conditions in many regions." The scarcity of this important natural habitat type is the result of fire suppression and post-fire logging.

Figure 3. Recent snag forest habitat in the Sierra Nevada.

Dr. Richard Hutto, one of the nation's top ornithologists, recently concluded the following, based upon the emerging scientific evidence: "Besides the growing body of evidence that large, infrequent events are ecologically significant and not out of the range of natural variation (Foster et al. 1998, Turner & Dale 1998), an evolutionary perspective also yields some insight into the 'naturalness' of severely burned forests… The dramatic positive response of so many plant and animal species to severe fire and the absence of such responses to low-severity fire in conifer forests throughout the U.S. West argue strongly against the idea that severe fire is unnatural. The biological uniqueness associated with severe fires could emerge only from a long evolutionary history between a severe-fire environment and the organisms that have become relatively restricted in distribution to such fires. The retention of those unique qualities associated with severely burned forest should, therefore, be of highest importance in management circles" (Hutto 2006).

There is strong consensus among ecologists that high-intensity fire, and resulting snag forest habitat, is something that must be preserved and facilitated, not prevented or destroyed. Lindenmayer et al. (2004) noted the following with regard to wildland fire: "…natural disturbances are key ecosystem processes rather than ecological disasters that require human repair. Recent ecological paradigms emphasize the dynamic, nonequilibrial nature of ecological systems in which disturbance is a normal feature… and how natural disturbance regimes and the maintenance of biodiversity and productivity are interrelated…" Smucker et al. (2005) concluded: "Because different bird species responded positively to different fire severities, our results suggest a need to manage public lands for the maintenance of all kinds of fires, not just the low-severity, understory burns…" Kotliar et al. (2007) observed that the results of their study "demonstrated that many species tolerate or capitalize on the ecological changes resulting from severe fires…", and concluded that: "Fire management that includes a broad range of natural variability (Allen et al. 2002), including areas of severe fire, is more likely to preserve a broad range of ecological functions than restoration objectives based on narrowly defined historic fire regimes (Schoennagel et al. 2004)."

Fig. 4. Some of the many species living in snag forest habitat.

Older, mature forests that burn at high-intensity are particularly important, since cavity-nesting species tend to select larger snags for nesting and denning. Hutto (1995) concluded that, because "the most suitable nest trees for cavity excavation are snags that are themselves old-growth elements, one might even suggest that many of the fire-dependent, cavity-nesting birds depend not only on forests that burn, but on older forests that burn." In burned forests, woodpeckers preferentially select larger snags for foraging (Hutto 1995, Hanson 2007, Hanson and North 2008). Scientists have recently recommended that forest managers should ensure the maintenance of moderate-and high-intensity fire patches to maintain populations of numerous native bird species associated with fire (Hutto 1995, Hutto 2006, Kotliar et al. 2002, Noss et al. 2006, Smucker et al. 2005, Hanson and North 2008, Hutto 2008).

Fire-induced heterogeneity, including a mix of low-, moderate-, and high-intensity patches, leads to higher post-fire understory plant species richness compared to homogeneous low-severity fire effects (Chang 1996, Rocca 2004). Mixed-intensity fire, meaning a heterogeneous mix of high-, moderate-, and low-intensity effects, facilitates reproduction of numerous native herbaceous and shrub species (Chang 1996, Rocca 2004), the germination of many of which is triggered by fire-induced heat, charcoal, or smoke (Biswell 1974, Chang 1996). These flowering plants, in turn, increase biodiversity of flying insects, such as bees and butterflies. In addition, fire-caused conifer mortality attracts bark beetles and wood-boring beetles, some species of which have evolved infrared receptors capable of detecting burned forests from over 161 km away (Altman and Sallabanks 2000, Hutto 1995). Other insect species are attracted by the smoke from fires (Smith 2000).

As a result, bird species richness and diversity increases in heavily burned patches, which generally occur within a mix of low- and moderate-intensity effects. Woodpeckers feed upon bark beetle and wood-boring beetle larvae in snags and excavate nest cavities in snags; Mountain Bluebirds and other secondary cavity-nesting species use nest holes created the previous year by woodpeckers; granivores such as the Red Crossbill feed upon seed release from cones following fire; shrub-dwelling species like the Blue Grouse nest and forage within shrub growth scattered throughout high-intensity patches; while aerial insectivores (animals that feed upon flying insects) such as the imperiled Olive-sided Flycatcher prey upon the native bark beetles that are abundant in snag patches (Altman and Sallabanks 2000, Hutto 1995). Likewise, mammalian species, such as the Sierra Nevada Snowshoe Hare, which is listed as a Forest Service Sensitive Species (USFS 2001), depend upon post-fire shrub habitat following intense fire (Smith 2000, USDA 2001). Populations of small mammals experience overall increases shortly after high-intensity fire, and amphibians are positively associated with the large woody material that gradually accumulates in the decades following such fire effects (Smith 2000). As well, ungulates, such as deer and elk, forage upon post-fire flora, and large predators frequently seek their prey in burned patches (Smith 2000). Studies have detected higher overall bird species richness in intensely burned versus unburned forest in the western United States (Bock and Lynch 1970, Hutto 1995, Raphael and White 1984, Siegel and Wilkerson 2005). In one snag forest area resulting from the Manter Fire of 2000 in the southern Sierra Nevada, a total of 111 bird species were observed (Siegel and Wilkerson 2005).

Black-backed Woodpecker

There is perhaps no vertebrate species more strongly representative of the snag forest habitat type than the Black-backed Woodpecker (Picoides arcticus) (Hutto 1995, Hanson 2007, Hanson and North 2008, Hutto 2008). This species is a federally designated Management Indicator Species, acting as a bellwether for the viability of dozens of other species associated with snag forests (USDA 2004). One of only two woodpecker species globally with three toes instead of four, the Black-backed Woodpecker is able to deliver exceptionally hard blows due to added heel mobility resulting from the lack of a fourth toe and, as a consequence, it can reach beetle larvae that other woodpecker species cannot (Dixon and Saab 2000). One bird eats an astounding 13,500 beetle larvae per year (Hutto, unpublished data). From behind, the all-black coloring of this species confers excellent camouflage against the charred bark of a fire-killed tree, indicating a long evolutionary history with high-intensity fire (Hutto 1995). Though Black-backed Woodpeckers are occasionally, but rarely, seen outside of stand-replacement burns, forests outside of snag forest habitat are believed to be "sink" habitats which do not support them (Hutto 1995, Dixon and Saab 2000). In the northern Rocky Mountains, the Black-backed Woodpecker is largely restricted to recently severely burned conifer forest that is unlogged (Hutto 1995, Russell et al. 2007). The same has been found to be true in Sierra Nevada forests (Hanson 2007, Hanson and North 2008).

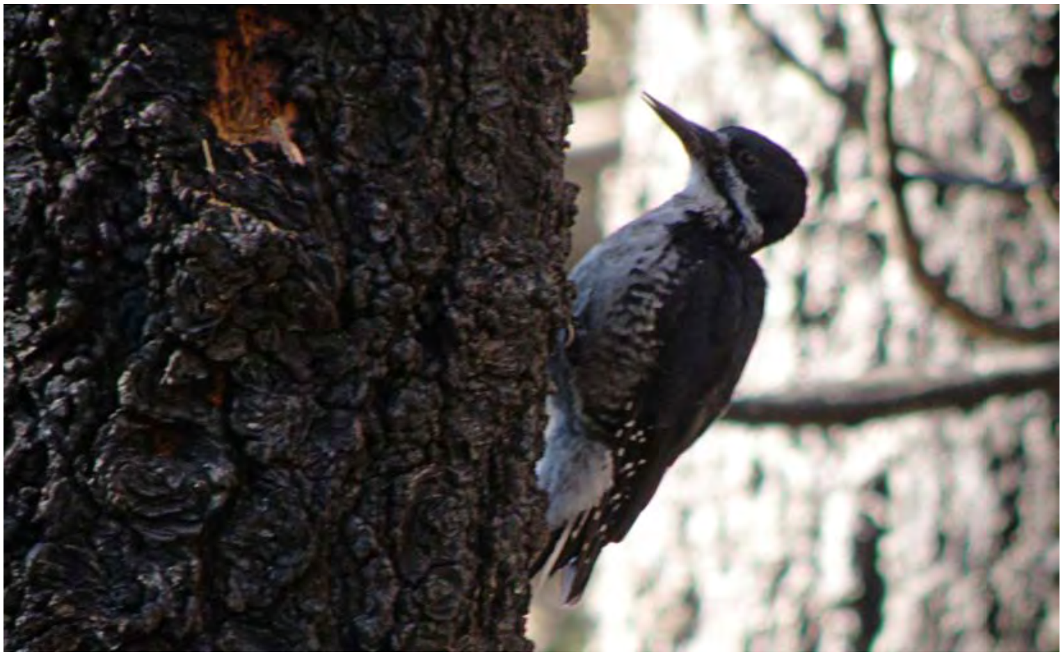

Fig. 5. Black-backed Woodpeckers are just one of the many wildlife species threatened by the loss of snag forest habitat due to fire suppression and "salvage" logging.

Black-backed Woodpeckers are strongly associated with large, unlogged high-intensity patches in areas that were mature/old-growth, closed-canopy forest prior to the fire (which ensures many large snags) (Hutto 1995, Saab et al. 2002, Saab et al. 2004, Russell et al. 2007, Hanson and North 2008, Hutto 2008, Vierling et al. 2008). Pre-fire thinning that reduces the density of mature trees can render habitat unsuitable for Black-backeds even if the area later experiences high-intensity fire, due to a reduction in the potential density of large snags caused by the earlier thinning (Hutto 2008). After approximately 5-6 years, when their bark beetle food source begins to decline and nest predators begin to recolonize the burn area, Black-backed Woodpeckers must find a new large, unlogged high-intensity patch in mature forest to maintain their populations (Hutto 1995, Saab et al. 2004). For these reasons, this species depends upon a continuously replenished supply of high-intensity burn areas (Hutto 1995).

Spotted Owls and Fire


Fig. 6. Snag forest habitat increases the Spotted Owl's small mammal prey and provides foraging habitat for Spotted Owls.

Recent scientific evidence regarding spotted owls in northwestern California and in Oregon found that stable or positive trends in survival and reproduction depended upon significant patches (generally between one-third and two-thirds of the core area) of habitat consistent with high-intensity post-fire effects (e.g., native shrub patches, snags, and large downed logs) in their territories because this habitat is suitable for a key owl prey species, the Dusky-footed Woodrat (Franklin et al. 2000, Olson et al. 2004). This habitat is not mimicked by logging, which removes snags and prevents recruitment of large downed logs, and which seeks to reduce or eliminate shrub cover. Logging can reduce owl survival and reproduction by preventing occurrence of natural post-fire habitat heterogeneity in the spotted owl territories.


Fig. 7. A California Spotted Owl roosting in a burned area within the McNally fire, Sequoia National Forest.

In a study conducted several years post-fire, Clark (2007) found that Northern spotted owls in southwestern Oregon were adversely affected by post-fire salvage logging, but his results show the opposite for unlogged moderately and intensely burned patches within the owls' territories. Specifically, he found that, in an area in which the spotted owl territories had been partially or predominantly salvage logged, occupancy decreased. For owls that had not been extirpated by salvage logging, the fire itself did not reduce productivity. Using radio-telemetry, Clark (2007) found that spotted owls used nesting, roosting, and foraging habitat (dense, old forest) that had burned at low-, moderate-, and high-intensity more frequently than would be expected based upon availability of these habitat strata on the landscape so long as these areas had not been salvage logged. The owls avoided salvage logged areas (and the few detections within salvage logged units were, on closer inspection by the author, generally found to be in unlogged retention areas within the logging units, such as stream buffers).

Interestingly, over four years of study in three fire areas, only one Barred owl was found within burned forests, while many were found just outside the fire perimeter (Clark 2007). Barred owls prey upon Spotted owls and are considered to be a significant threat (Clark 2007). In addition, recent radio-telemetry research in the Sierra Nevada has found that, in post-fire forest (nearly all of which was unmanaged), California spotted owls selected low-intensity areas for roosting and selected high-intensity areas for foraging (Bond et al. 2009). One might think of dense, old forest as the owl's bedroom, and high-intensity fire patches as its kitchen. Recent scientific evidence indicates that there is far less high-intensity fire in Northern Spotted Owl habitat than was previously assumed (Hanson et al. 2009, Hanson et al. 2010 in press in Conservation Biology). We do not yet fully know the potential adverse consequences of the ongoing fire deficit for Spotted Owls.

MYTH 3

Due to decades of fire suppression, and resulting fuel accumulation, most fires are currently dominated by high-intensity effects.

FACT 3

High-intensity fire is the exception, not the rule; and long-unburned areas are not burning more intensely.

Contrary to popular misconception, low- and moderate-intensity fire effects are heavily predominant in western conifer forests, and high-intensity effects comprise a minor portion of the overall area burned (Odion and Hanson 2008, Schwind 2008, Hanson et al. 2009). For example, in the Pacific Northwest since 1984, high-intensity effects occurred on only about 10-12% of the area burned, and on only about 12-15% of the total area burned in California (Schwind 2008).

Contrary to popular misconception, areas that have missed the greatest number of natural fire cycles, due to fire suppression, are burning mostly at low- and moderate-intensity and are not burning more intensely than areas that have missed fewer fire cycles (Odion et al. 2004, Odion and Hanson 2006, Odion and Hanson 2008). The notion that forested areas become increasingly likely to have high-intensity effects the longer they remain unburned is simply inaccurate. Instead, as the time period since the last fire increases, forests become more mature, and develop higher forest canopy cover. This reduces the amount of pyrogenic (combustible) shrubs, which need more sunlight, reducing overall high-intensity fire occurrence, based upon several decades of data from the Klamath mountains in California (Odion et al. 2009). It also reduces the amount of sunlight reaching the forest floor and understory. In such conditions, surface fuels stay moister during the fire season, due to the cooling shade of the forest canopy, and, due to reduced sunlight, forest stands begin to self-thin small trees and lower branches of large trees. This makes it more difficult for flames to spread into the forest canopy during wildland fire.

MYTH 4

Where high-intensity patches occur, the forest will not regenerate naturally due to soil damage or lack of seed sources from surviving conifers.

FACT 4

Forest growth and regeneration is vigorous after high-intensity fire, and fire-adapted forests need fire to maintain productivity. In the few places wherein post-fire conifer regeneration does not quickly occur, these areas provide important montane chaparral habitat, which has declined due to fire suppression.

The increase in available nutrients following fire, particularly higher-intensity fire, can lead to substantial growth pulses (Brown and Swetnam 1994 [Fig. 3], Mutch and Swetnam 1995 [Fig. 4]). This includes post-fire shrub growth, conifer regeneration, and growth release of surviving overstory trees. The conifer seedling/sapling regeneration is very vigorous in high-intensity patches (see, e.g., Donato et al. 2006, Hanson 2007b, Shatford et al. 2007). Ponderosa and sugar pines, which have declined in some western U.S. forests, appear to have a competitive advantage over fir and cedars in regrowth after high-intensity fire, as their post-fire proportions are higher than they were pre-fire, and pines tend to be tallest, fastest-growing conifer saplings in these areas (Hanson 2007b).

In the few places wherein post-fire conifer regeneration does not quickly occur, these areas provide important montane chaparral habitat, which has declined due to fire suppression (Nagel and Taylor 2005). As noted earlier, montane chaparral provides key habitat for a variety for shrub-dwelling species like the Snowshoe Hare and the Blue Grouse, which nests and forages within the shrub growth. The Dusky-footed Woodrat also inhabits these areas, which in turn provides food for the Spotted Owl. Likewise, ungulates, such as deer and elk, forage upon the shrubs, and their predators

Fig. 8. Natural conifer regeneration in a high-intensity patch of mixed-conifer forest.

Fig. 9. Natural conifer regeneration in an area of nearly 100% mortality from fire.

frequently seek prey in montane chaparral. Therefore, chaparral regeneration is another ecological benefit of high-intensity fire. On the whole, though, high-intensity fires are soon followed by vigorous forest regeneration.

By contrast, in the very long absence of large fires commonly thought of as “catastrophic”, forests can lose so much of their productivity that, ultimately, sites lose the ability to support forest at all. Wardle et al. (2004) concluded the following: “Our results have several implications. First, they suggest that the decline of natural forests, which is often observed in the long-term absence of catastrophic disturbance [including wildland fires], may arise through increasing limitation by [phosphorus] and reduced performance of the decomposer subsystem… Second, the results show that the maximal biomass phase (and associated rates of ecosystem processes) attained after primary or secondary succession cannot be maintained in the long-term absence of major disturbances.”

MYTH 5

Fire is now burning at unprecedented levels.

FACT 5

We are in a major fire deficit. There is now far less fire overall, and less high-intensity fire, than there was historically.

Fire extent in general remains heavily suppressed in western U.S. forests such that historic annual extent of burning was several times greater than the annual extent of burning under current conditions (Medler 2006, Stephens et al. 2007). Using more conservative estimates of historic fire extent (Baker and Ehle 2001), annual burning in forests prior to fire suppression was still several times higher than it is now. Western U.S. conifer forests remain in a serious “fire deficit” (Medler 2006). Even high-intensity effects are in deficit currently, relative to the extent of high-intensity fire prior to fire suppression and logging.

High-intensity fire was previously assumed to have been rare and of limited extent in most western U.S. conifer forests, largely because fire-scar studies documented frequent fire occurrence in most historic conifer forests, and it was assumed that frequent fire would have kept surface fuel levels low, preventing high-intensity fire. The problem, however, is that fire-scar records cannot detect occurrence of past high-intensity effects, wherein most trees were killed (Baker and Ehle 2001).

Historic data and recent reconstructions of historic fire regimes indicate that high-intensity fire was common in most conifer forests of western North America prior to fire suppression and logging, even in pine-dominated forests with frequent fire regimes “(Baker et al. 2007, Hessburg et al. 2007, Klenner et al. 2008, Whitlock et al. 2008, Baker et al. 2009). For example, a recent reconstruction of historic fire occurrence in a 1,587 ha (unmanaged) research natural area near Lassen Volcanic National Park found mid-elevation slopes to be dominated by moderate-intensity fire, mixed with some low- and high-intensity effects, while upper-elevation slopes were dominated by high-intensity fire (Beaty and Taylor 2001). Other research has found steep declines in montane chaparral within mixed conifer forest ecosystems in the Lake Tahoe Basin of the central and northern Sierra Nevada due to a decrease in high-intensity fire occurrence since the 19th century (Nagel and Taylor 2005).

In the late 19th century, John B. Leiberg and his team of United States Geological Survey researchers spent several years mapping forest conditions, including fire intensity in the central and northern Sierra Nevada. Leiberg recorded all high-intensity patches over 80 acres (32 ha) in size occurring in the previous 100 years

(Leiberg 1902). Using modern GIS vegetation and physiographic information, Hanson (2007a) compared fire locations to forest type and site conditions to examine patterns of high-intensity fire events, excluding areas that had been logged in the 19th century in order to eliminate the potentially confounding effect of logging slash debris (branches and twigs left behind by loggers). Hanson (2007a) used areas that Leiberg had mapped as having experienced 75-100% timber volume mortality.

Hanson (2007a) found that high-intensity fire was not rare in historic Sierra Nevada forests, as some have assumed. Over the course of the 19th century, within Leiberg's study area, encompassing the northern Sierra Nevada, approximately one-fourth to one-third of middle and upper elevation westside forests burned at high-intensity (75100% mortality) (Hanson 2007a). This equates to fire rotation intervals for high-intensity fire of roughly 400 to 300 years (i.e., for a fire rotation interval of 300 years, a given area would tend to burn at high severity once every 300 years on average). Available evidence indicates that current rates of high-intensity fire are considerably lower than this overall (Hanson 2007a). For example, the Final EIS for the 2004 Sierra Nevada Forest Plan Amendment indicates that, on average, there are about 15,000 acres of high-intensity fire occurring per year in Sierra Nevada forests (entire Sierra Nevada included) (USDA 2004). Given the size of the forested area in the Sierra Nevada, about 13 million acres (Franklin and Fites-Kaufman 1996), this equates to a high-intensity fire rotation interval of more than 800 years in current forests (longer rotation intervals correspond to less high-intensity fire).

Nor were pre-fire-suppression high-intensity patches all small, as has often been assumed. In fact, in unlogged areas mapped by Leiberg (1902), some aggregate patches of high-intensity effects were 20,000 to 30,000 acres in size, or larger (Leiberg 1902, Hanson 2007a (Fig. 3.1)), greater than any current high-intensity patches.

The findings of Hanson (2007a) are consistent with those of Beaty and Taylor (2001), whose reconstruction of historic fire regimes in unmanaged forests just north of Leiberg's study area found that, despite relatively frequent low-intensity fire occurrence, moderate- high-intensity fire were common and historically in these forests. Specifically, Beaty and Taylor (2001) found that approximately 15% of montane forests 1370-1770 m in elevation burned at high intensity over a 43-year period from 1883 to 1926 (Beaty and Taylor 2001). This equates to a high-intensity rotation interval of about 300 years. Bekker and Taylor (2001) found historic high-intensity fire rotations of 200 to 250 years in eastside mixed-conifer/fir forests types north of Leiberg's study area (California Cascades region). High-intensity rotation intervals of several hundred years in length, and much more frequent lower-intensity fire, indicates forests in which individual fires would, on average, tend to burn predominantly at low-and moderate-intensity, but would have the potential to burn at high-intensity under certain weather and fuel loading conditions. A high-intensity fire rotation of about 300 years was also found in the mixed-conifer and Jeffrey pine forests of the Sierra San Pedro de Martir in Baja California – forests that have never been subjected to fire suppression and have not been logged (Minnich et al. 2000).

Historic U.S. Geological Survey data gathered by Leiberg (1900b) provides further evidence of an active role for high-intensity fire prior to fire suppression. Leiberg (1900b) gathered comprehensive data on high-intensity fire occurrence for the period 1855-1900 in the Oregon Klamath region, presenting data on high-intensity (75-100% timber volume mortality) acres and acres logged for each township. Excluding the townships with any evidence of logging (in order to eliminate any confounding effects of logging), there were 12,700 acres of high-intensity fire in 72,580 acres of unmanaged forest over a 45-year period prior to fire suppression (Leiberg 1900b). This equates to a high-intensity rotation of 257 years. The high-intensity rotation within the Eastern Oregon Cascades physiographic province (Moeur et al. 2005) prior to fire suppression and logging was 165 years overall, and was 322 years for forests with more than 85% ponderosa pine (Leiberg 1900b), indicating far more high-intensity fire than is occurring currently (889-year high-intensity rotation in mature forests from 1984 to 2005) (Hanson et al. 2009, Hanson et al. 2010 in press in Conservation Biology).

Fig. 10. A recent snag forest patch in the Sierra Nevada.

Taylor and Skinner (1998), in a reconstruction of historic fire occurrence in a 3,878-acre study area in the Klamath Mountains of California, found that 14% of the area burned at high intensity 1850-1950, though they defined high-intensity very narrowly as areas in which fewer than 4 trees per acre survived the fire. Moderate-intensity effects occurred on 27% of the area, where moderate intensity was defined as only 4-8 surviving trees per acre (Taylor and Skinner 1998), which would be categorized as high-intensity in current fire intensity assessments. If all areas in which there were 8 or fewer surviving trees per acre are included in a calculation of a high-intensity rotation, the high-intensity rotation would be approximately 244 years. Their study area was just south of the Oregon/California border at elevations ranging from about 2,100 to 5,200 feet in elevation within Douglas-fir, Douglas-fir/pine, and mixed-conifer forests (Taylor and Skinner 1998). Wills and Stuart (1994) reconstructed fire history in three representative study sites in the Klamath National Forest of California, using fire-scar and tree age class data. They found that the historic, pre-fire suppression interval between high-intensity fire events was approximately 170 to 200 years in the first study site, about 100 years in the second study site, and was intermediate between these two in the third study site. Their study area was in forests dominated by Douglas-fir, sugar pine and tanoak at approximately 3,000 feet in elevation on slopes averaging 56% within the Salmon River Ranger District (Wills and Stuart 1994). In contrast, the estimate of the current high-intensity rotation in Klamath forests, using satellite imagery data for 1984-2005, is about 600 years (Hanson et al. 2009, Hanson et al. 2010 in press in Conservation Biology).

The high-intensity rotation prior to fire suppression (1800-1900) was found to be 385 years in mid-elevation conifer forests of the western Cascades of Oregon (Morrison and Swanson 1990), indicating several times more high-intensity fire than is occurring currently in mature forests of the western Oregon Cascades (Moeur et al. 2005).

Within forests dominated by fir, spruce, and lodgepole pine in Montana prior to fire suppression and the arrival of settlers, high-intensity rotations were 289 years in one area (Leiberg 1904a) and 190 years in another (Leiberg 1904b). In Montana's Bitterroot Forest Reserve (now called the Bitterroot National Forest) prior to fire suppression and the arrival of settlers, out of 2,462,464 acres of fir, spruce, and lodgepole pine forest, 2,270,000 acres burned at high intensity over the course of 140 years prior to fire suppression and the arrival of settlers, equating to a high-intensity fire rotation of 152 years (Leiberg 1900a). Of the 1,149,696 acres of ponderosa pine forest, roughly 25-30% burned at high-intensity over this same time period (Leiberg 1900a), equating to a high-intensity rotation of roughly 450-500 years. In the Bitterroot Reserve as a whole, the historic high-intensity fire rotation was 200-300 years. The current high-intensity rotation for the forests of the northern Rockies is 500 years, using interagency Burned Area Emergency Rehabilitation (BAER) fire intensity data (Rhodes and Baker 2008). This indicates considerably less high-intensity fire now than there was historically.

Even in dry ponderosa pine forests of the southwestern U.S., high-intensity fire naturally occurred prior to fire suppression and logging, with stand age plot data indicating historic high-intensity rotations of 300-400 years during the 1800s (Baker 2006). The current high-intensity rotation is about 625 years in southwestern U.S. forests (Rhodes and Baker 2008). Based on charcoal sediments, researchers have also determined that high-intensity fire was common in low-elevation ponderosa pine forests from about 1000 to 1400 A.D., contradicting the assumption that current high-intensity fire in such forests is uncharacteristic or unprecedented (Pierce et al. 2004, Whitlock et al. 2004).

Overall, the data indicate that there was about 2-4 times more high-intensity fire historically in western U.S. conifer forests than there is currently. This fire deficit translates to serious deficits in ecologically-vital snag forest habitat, and this is greatly exacerbated by the fact that much of the snag forest habitat that is created by fire is lost to post-fire "salvage" logging.

MYTH 6

Climate change and global warming will necessarily cause increased fire activity and intensity.

FACT 6

Current predictions vary, and may differ greatly from region to region. The most recent projections indicate that, in most forested regions of the North America, reduced fire activity is likely to occur, due to vegetation changes that will result in less combustible fuel, and due to increased precipitation in many areas.

Westerling et al. (2006) speculated that climate change may lead to more intense fires, but more recent studies refute this assumption. A comprehensive analysis of high-severity fire since 1984 by the U.S. Geological Survey in California, Oregon and Washington found no increasing fire intensity trend (Schwind 2008). Other research since then has supported that finding for an area in Yosemite National Park (Collins et al. 2009) and within the dry conifer forests of the Klamath and eastern Cascade Mountains in California, Oregon, and Washington (Hanson et al. 2010). Miller et al. (2008) reported an increasing fire intensity trend in Sierra Nevada forests since 1984. However, Miller et al. (2008) was based upon only 60% of the available fire data, and used recent vegetation data to exclude shrub habitat. The results of Hanson et al. 2009 (in review), which was based upon complete fire data, indicate that this method excludes relatively more high-intensity fire in conifer forest within the earlier years of the data set, creating the appearance of an increasing trend where none exists. This implies that recent high-intensity patches generally still visually appear to be conifer forest to those updating Cal-Veg mapping from remote sensing imagery, while older high-intensity patches frequently do not, likely due to greater post-fire snag attrition and maturation of montane chaparral. Another recent study inexplicably claimed that fires would become “more severe” and that there would be “increased proportions of high-severity fire” by 2020-2049 in Yosemite National Park, California, despite the fact that the study explicitly found that the high-intensity fire proportion would remain at 16% from the present through 2020-2049 (Lutz et al. 2009 [Table 1]).

Some previous climate modeling predicted increases in the annual area burned in most forested areas of the western U.S., but predicted decreases in some areas, such as California and Nevada (McKenzie et al. 2004). Increased temperatures are predicted to occur generally, but precipitation, including summer precipitation, is expected to increase as well in most areas (McKenzie et al. 2004). Moisture-related variables, e.g., humidity and precipitation, may be more important than temperature in predicting future fire occurrence (Parisien and Moritz 2009). Actual data from weather stations over the past several decades generally shows increases in precipitation, especially summer precipitation (which can significantly dampen wildland fire), in states comprising the western U.S. (Mote 2003, WRCC 2009), and in Canada’s boreal forests (Girardin et al. 2009). Some studies (e.g., Spracklen et al. 2009) still predict some increase in overall fire occurrence but do so by assuming that increases in spring/summer precipitation will be only 1/8 to ¼ of the increases that have actually been occurring over the past 100 years (Mote 2003). Even if some forested areas become hotter and drier, as opposed to warmer and wetter, they may experience decreased, not increased, fire activity due to a reduction in the most combustible vegetation (Parisien and Moritz 2009). This is supported by charcoal and pollen deposits, which allow scientists to correlate past climate to fire activity since the last Ice Age. The evidence indicates that hotter, drier conditions sometimes led to reduced fire effects, and cooler, wetter conditions did not necessarily lead to reduced fire effects (Gavin et al. 2007 [Fig. 6], Parisien and Mortiz 2009). Often, the periods with the largest temperature increases were associated with decreased, not increased, fire occurrence (Marlon et al. 2009 in press in Proceedings of the National Academy of Sciences). The most current research predicts decreased fire activity in most western U.S. conifer forest regions (Krawchuk et al. 2009 [see Fig. 3 of that study]). Westerling et al. (2006) found that, since the 1970s, the total area affected by fire (all intensities included) in western U.S. forests has increased marginally, though it is unclear how much of this is the result of more recent fire management policies allowing more fires to burn in remote areas. Given the massive fire deficit we are in, as discussed above, even if there is some increase in the average annual area affected by fire, we would still have far less fire than we did prior to fire suppression policies, and would remain in an unnatural fire deficit.

MYTH 7

Our forests are "unhealthy" because there are too many dead trees.

FACT 7

There are far too few large dead trees to maintain ecologically healthy forests.

Due in large part to the combined effects of fire suppression and post-fire logging, large snags (dead trees) are currently in severe deficit, contrary to popular belief. For example, recent U.S. Forest Service Forest Inventory and Analysis (FIA) data, using 3,542 fixed plots throughout California, shows that there are less than 2 large snags per acre in all forested areas (Christensen et al. 2008). The Sierra Nevada Forest Plan Amendment recommends having at least 3-6 large snags per acre to provide minimum habitat for the needs of the many wildlife species that depend upon large snags for nesting and foraging (USDA 2001, 2004). Some species need even higher densities of large snags, such as the California Spotted Owl, which prefers to have at least 20 square feet per acre of basal area in large snags (about 6-8 large snags per acre) to maintain habitat for its small mammal prey (Verner et al. 1992). Other species require much higher densities of large snags, such as the Hairy Woodpecker and Black-backed Woodpecker (Hanson 2007a, Hanson and North 2008).

Fig. 11. Black-backed Woodpeckers (center of image) foraging on a large snag.

A study published recently in Science (van Mantgem et al. 2009) found increasing tree mortality in old-growth forest plots, speculating that it is a result of climate change, as opposed to fire suppression. However, the study did not find higher mortality rates in the large, old trees within those plots. Moreover, the study was based on only 76 plots across the western United States (van Mantgem et al. 2009). Two recent U.S. Forest Service Forest Inventory and Analysis (FIA) reports (one for CA and one for OR), each of which used thousands of plots, found that current large snag densities are harmfully low (generally only 1-3 per acre, and less than 1 per acre in eastern Oregon), and management activities should be undertaken to increase large snag densities to prevent harm to wildlife populations (Christensen et al. 2008, Donnegan et al. 2008).

Some recent anecdotal accounts of forest “destroyed” by, or “lost” to, bark beetles across 1.5 million acres of lodgepole pine forests in Colorado are highly misleading and inaccurate. In fact, the beetles only kill a portion of the trees, creating vitally-important snags that benefit wildlife; the largest area found to have 100% tree mortality is only one acre in size (Rocca and Romme 2009). The surviving trees dramatically increase their growth rates following beetle mortality (Romme et al. 1986). Conifer mortality from bark beetles – which are native species in these forests – is a natural and necessary ecological phenomenon that generally occurs every few decades, and which occurred at large scales in western U.S. conifer forests historically as well (Romme et al. 1986, Shinneman and Baker 1997). Prior to the arrival of settlers and the onset of fire suppression, such events were well documented to have occurred across entire landscapes, and were found to play an important role in the natural ecological succession of conifer species as stands matured and aged (Leiberg 1900a, 1904a, 1904b). The recent areas of tree mortality in the Rockies are neither unprecedented nor unnatural (Romme et al. 2006).

Given the overall deficit of large snags, and the serious adverse consequences of this for myriad wildlife species, natural events that create additional snags should be welcomed, not viewed as a problem to be avoided.

MYTH 8

High-intensity fire creates far more particulate emissions.

FACT 8

High-intensity fire burns cleaner, and produces fewer particulate emissions.

Contrary to popular assumption, high-intensity forest fires produce relatively lower particulate emissions (due to high efficiency of flaming combustion) while low-intensity forest fires produce high particulate emissions, due to the inefficiency of smoldering combustion (Ward and Hardy 1991, Reid et al. 2005). For a given ton of fuel consumed, low-severity fires produce 3-4 times more particulate matter than high-intensity fires (Ward and Hardy 1991, Reid et al. 2005).

MYTH 9

Western U.S. conifer forests are becoming carbon sources due to increased fire.

FACT 9

Western U.S. conifer forests are major carbon sinks, where logging has been reduced.

Despite some speculation that western U.S. conifer forests could become carbon sources (Westerling et al. 2006, van Mantgem et al. 2009), the empirical data show the opposite to be true. Studies using very large data sets (several thousand plots), found that western U.S. forests, and old growth forests, are functioning as net carbon sinks (net sequestration of carbon, thus reducing greenhouse gases) and are expected to continue to do so long into the future (Donnegan et al. 2008, Luyssaert et al. 2008). Oregon’s forests, which were a substantial carbon source when logging levels on national forests were higher, are now a significant carbon sink (Turner et al. 2007). After accounting for emissions from wildland fire, net carbon sequestration in Oregon’s forests is now so great, due to dramatically decreased logging levels on public lands, that it offsets 41% of the state’s total

Fig. 12. Large surviving trees in a moderate/high-intensity patch wherein all small and medium-sized trees were killed.

emissions from fossil fuel burning (Turner et al. 2007). A recent study found that carbon sequestration would be maximized by ending all logging on U.S. public lands nationwide (Depro et al. 2008). In the continental United States, CO2 emissions from wildland fire are only about 5% of the amount resulting from human fossil fuel consumption, carbon sequestration from growth is about 25 times larger than carbon emissions from fire (Wiedinmyer and Neff 2007), and emissions from fire are offset by post-fire growth and carbon uptake. In a field-based study of four very large fires in two exceptionally large fire years (2002-2003) within the eastern Cascades of Oregon, researchers found that only 1-3% of the mass of living trees was consumed in the fires, and all four fires combined produced only about 2.5% of the statewide carbon emissions during the same two-year period (Meigs et al. 2009).

Moreover, the increase in available nutrients following fire (Schlesinger 1997), particularly higher-intensity fire, can lead to substantial growth pulses (Brown and Swetnam 1994 [Fig. 3 of that study], Mutch and Swetnam 1995 [Fig. 4 of that study]), which results in carbon sequestration. This includes post-fire shrub growth, conifer regeneration, and growth release of surviving overstory trees. The shrub growth and conifer seedling/sapling regeneration alone – which are very vigorous in high-intensity patches (see, e.g., Hanson 2007b, Shatford et al. 2007) – can add many tons of sequestered carbon within just several years post-fire. In a comprehensive analysis of all fires over 15 years (1980-1995) in boreal forests in Canada and Alaska, it was determined that it took an average of only 9 years after fire for forests to once again become net carbon sinks (Hicke et al. 2003). Unlike boreal forests, in most other western U.S. conifer forests, high-intensity effects do not typically equate to 100% conifer mortality, and the largest several conifers per acre, which can comprise the majority of the carbon stocks, tend to survive in a given stand, in most cases. Relatively moderate post-fire growth increases (from nutrient cycling) in these large surviving overstory trees can increase carbon stocks rapidly, and will tend to reduce the time it takes for a postfire area to once again become a net carbon sink, relative to fires in which there is zero tree survival. The magnitude of this effect in mixed-conifer forests warrants careful study. Generally, the existing data indicate abundant natural conifer regeneration after high-intensity fire in western U.S. conifer forests (see, e.g., Hanson 2007b, Shatford et al. 2007).

Researchers recently found that the highest carbon sequestration levels were in forests that had previously experienced considerable occurrence of high-intensity fire (Keith et al. 2009). They concluded the following: "Fire can kill but not combust all of the material in trees, leading to much of the biomass carbon changing from the living biomass pool to the standing dead and fallen dead biomass pools… The dead biomass then decays as the stand grows… Slow decomposition rates can therefore result in large total carbon stocks of dead biomass and regrowing living biomass." (Keith et al. 2009). The authors noted that the results of their study, which was conducted in Australia, are broadly applicable to other temperate forests globally, including U.S. conifer forests. Conversely, as forest stands become ancient, in the long absence of high-intensity fire effects, they can transition from carbon sinks (net carbon sequestration) to carbon sources (net carbon emission) after about 600 years of age (Luyssaert et al. 2008, S. Luyssaert 2009 pers. comm.).

MYTH 10

Forest "thinning" operations will increase carbon sequestration by reducing fire effects.

FACT 10

Commercial logging, including mechanical "thinning", reduces forest carbon storage.

One recent modeling study found that the areas with moderate/high-intensity wildland fire only (i.e., with no thinning), and areas with prescribed fire only, had greater overall carbon stocks over the course of a century than the forest thinning options (Hurteau and North 2009 [Fig. 1]). In addition, by the end of the century the moderate/high-intensity wildland fire scenario produces considerably fewer carbon emissions when compared to the thinning/prescribed-fire scenarios (about 38 tons C per ha [Fig. 1(a)] versus about 56 or 50 tons C per ha [Fig. 1(d) and (f)]; see also Fig. 2) (Hurteau and North 2009). It should also be noted that nearly half of the carbon from thinned trees becomes surface fuel and is burned, and another quarter is lost as mill residue, which is often burned as fuel (Ingerson 2007). Ultimately, only a minor portion of trees that are logged become wood products, and this carbon is not stored in this form for long, as softwood lumber has a half-life of less than 40 years (Smith et al. 2005), and is obviously not assimilated back into the forest ecosystem.

If Hurteau and North (2009) had used more realistic assumptions for their modeling, the difference between fire-only and thinning would have been even greater. For example, they assumed virtually no mortality from wildland fire in the mechanically thinned areas (Figs. 1(c) and 1(e)), while actual areas thinned similarly (i.e., removal of some mature trees as well as small trees) often tend to burn at moderate- and high-intensity, due to residual slash debris, increases in brush growth due to canopy cover reduction, and drying of surface fuels due to a reduction in the cooling shade created by the forest canopy (see, e.g., Hanson and Odion 2006, Platt et al. 2006). Conversely, Hurteau and North (2009) assumed unrealistically high mortality (moderate/high-intensity) in the fire-only area (Fig. 1(a)). Forests, even those that have not burned in several decades, are burning mostly at low and moderate intensity (Odion and Hanson 2008, Schwind 2008), not high intensity.

Another recent modeling study found that mechanical thinning, whether for wood products or biofuels, generally reduced overall carbon storage in forests relative to fire-only (Mitchell et al. 2009). The study concluded that thinning was not an effective way to maintain or increase carbon storage. Had this study taken into account post-fire growth increases due to nutrient cycling (as discussed above), the differences between fire-only and thinning would have been even greater. Further, this study assumed, unrealistically, that thinning consistently reduces fire intensity, which is inconsistent with the scientific data (Hanson and Odion 2006, Platt et al. 2006).

Further, even if we assume for the sake of argument that thinning will reduce potential fire intensity, Rhodes and Baker (2008) found that, due to post-thinning vegetation regrowth, as well as the extremely low rate of occurrence of high-intensity fire currently, an area would have to be mechanically thinned every 20 years for about 720 years to have a mere 50% chance of encountering high-intensity fire and reducing its intensity. Not only would the adverse impacts of such repeated thinning on soils, watersheds, and wildlife be profound, but such constant thinning would permanently suppress carbon storage levels.

MYTH 11

"Biomass" thinning is benign or beneficial in our forests; such thinning can reduce fire intensity and only removes some of the small trees.

FACT 11

Further reducing snag forest habitat created by high-intensity fire patches – habitat that is already in short supply – would be ecologically devastating to the many wildlife species dependent upon that habitat. Biomass logging also: a) reduces carbon sequestration; b) increasingly seeks to remove old-growth trees; c) is generally tied to larger timber sales; and d) tends to remove all or nearly all of the smaller trees, regardless of species.

Fig. 13. Understory vegetation in a recent snag forest patch.

The living and dead plant material in a forest is called biomass. This includes everything from the small diameter branches, trees, and shrubs up to the old-growth trees. Today we are seeing increasing aggressive calls – mostly from the timber industry and their political allies – to remove biomass from the forest ostensibly to reduce fire effects. This biomass logging removes trees from the forest to be burned in energy production facilities. However, as discussed above, we remain in a major fire deficit, and snag forest habitat, created by patches of high-intensity wildland fire, is one of the rarest and most endangered habitat types in western U.S. conifer forests; and it is also one of the most ecologically important and biodiverse forest habitat types. Forest management policies designed to further reduce this imperiled habitat would further exacerbate its current deficit, which is already critical. At present, many snag forest wildlife species have been federally listed in one or more regions as "Sensitive Species" or "Species at Risk" – meaning there is a significant concern about the viability of their populations – due to lack of habitat, greatly reduced populations, and/or declining populations. Such species include the Black-backed Woodpecker, the Olive-sided Flycatcher, and the Sierra Nevada Snowshoe Hare. Further degrading and reducing the habitat for such species would create a risk of extinction.

Biomass logging proponents also claim that this type of thinning should be used to maintain or increase carbon sequestration, supposedly by reducing fire effects. However, as discussed above, thinning does not maintain or increase carbon sequestration. The scientific evidence shows that thinning reduces overall carbon sequestration, and increases carbon emissions, relative to areas experiencing wildland fire and no thinning; and carbon sequestration is maximized by halting logging completely.

Though timber interests have promoted increased logging by describing current forests as “overstocked”, the scientific data indicates that, due to past logging, as well as exclusion of wildland fire, forests of today have much less biomass than historic forests (Bouldin 1999, Fellows and Goulden 2008). Carbon sequestration is maximized where logging is absent and wildland fire is present (Turner et al. 2007, Depro et al. 2008, Keith et al. 2009). Peak biomass levels have been found in areas that have experienced high-intensity wildland fire – the total biomass being comprised of the fire-killed trees and downed logs, as well as the regenerating post-fire stand of trees (Keith et al. 2009). Small diameter trees and downed woody material on the forest floor play a key role in maintaining forest productivity, and carbon stocks, because this woody material is most easily combusted in a wildland fire, creating a rich supply of available nutrients in the ash (Schlesinger 1997). For this reason, biomass thinning not only reduces carbon sequestration in the short-term, it also diminishes the forest’s productive capacity, and carbon sequestration potential, in the longer-term.

Moreover, typically biomass logging is just one portion of larger timber sales. First the larger trees are removed for lumber, then the smaller trees are removed as biomass for energy production; thus biomass logging and logging of mature trees are inextricably linked. Small trees are not merely “thinned”. Rather, nearly all of the small trees, including pines and oaks, are removed, eliminating an entire forest regeneration cohort. Moreover, the U.S. Forest Service and private timberland owners are increasingly proposing large post-fire salvage logging projects for biomass production, especially when the lumber market is weak. Entire snag forest ecosystems could be wiped out to produce kilowatts. Further, there have been a growing number of accounts of old-growth trees being proposed for biomass logging. For example, the 2008 Flea project on the west side of the Plumas National Forest proposed removal of old-growth hardwoods up to 30 inches in diameter (over 8 feet in girth) for biomass energy production; and hundreds of acres of old-growth juniper were clearcut in 2008 on U.S. Bureau of Land Management lands in northeastern California to supply a biomass plant near Susanville (Tom Knudson, Sacramento Bee, Sept. 21, 2008).

Further, due to clear carbon accounting errors that ignore emissions from biofuel logging, as well as due to perverse economic incentives favoring biofuel production in climate legislation/rules, recent evidence published in Science indicates that, unless the faulty system is changed, the majority of the world’s natural forests could be displaced for biofuel production, releasing as much greenhouse gas as is currently emitted from global fossil fuel consumption (Searchinger et al. 2009). Alarmingly, due to these carbon accounting errors and perverse incentives, this massive loss and degradation of natural forests, and the resulting doubling of current greenhouse gas emissions, would be mistakenly assessed as a 50% “cut” in greenhouse gas emissions – a dangerous fiction that threatens the world’s forest ecosystems (Searchinger et al. 2009).

Summary: For Ecologically “Healthy Forests”, We Need More Fire and Dead Trees, Not Less.

In light of the foregoing, the term “catastrophic wildfire” is not scientifically credible; rather, it is a term based upon misinformation, as well as cultural fears and misconceptions about fire. There is a major deficiency of wildland fire – including high-intensity fire – and large snags in conifer forests. Yet forest management is still bent upon suppressing fire, reducing snag densities, and eliminating post-fire habitat, which is greatly worsening the current deficits. If this management pattern continues, it could threaten populations of numerous native wildlife species, many of which are already rare and/or declining (Hutto 1995, Altman and Sallabanks 2000, Hutto 2006, Hutto 2008, Hanson and North 2008). Current forest management direction continues to be disconnected from the current scientific data, and remains heavily focused on mechanical thinning projects ostensibly to reduce future tree mortality from competition and wildland fire. This situation is made worse by management direction under the "Healthy Forests Initiative" on public lands, which makes the scientifically-outdated assumption that wildland fire and snag densities should be further reduced, and recommends logging operations to accomplish its stated goals. Current forest management also remains focused on post-fire "salvage" logging. Scientifically, however, there is probably no forest management activity more clearly and profoundly destructive to wildlife and biodiversity than post-fire "salvage" logging. Hutto (2006) concluded the following: "The ecological cost of salvage logging speaks for itself, and the message is powerful. I am hard pressed to find any other example in wildlife biology where the effect of a particular land-use activity is as close to 100% negative as the typical postfire salvage-logging operation tends to be." Lindenmayer et al. (2004), writing in the journal Science, observed that, "…[post-fire] salvage harvesting removes critical habitat for species, such as cavity-nesting mammals, woodpeckers, invertebrates like highly specialized beetle taxa that depend on burned wood, and bryoflora closely associated with recently charred logs…" Hutto and Gallo (2006) found a major adverse impact to the cavity-nesting bird community as a result of post-fire logging. In response to legislation proposed in Congress that would expedite post-fire logging on national forest lands, nearly 600 of the nation's top scientists signed a letter of objection, dated August 1, 2006. The scientists wrote the following: "When we, as scientists, see policies being developed that run counter to the lessons of science, we feel compelled to speak up. Proposed post-disturbance legislation… crafted as a response to recent fires and other disturbances, is misguided because it distorts or ignores recent scientific advances. Under the labels of 'recovery' and 'restoration', these bills would speed up logging and replanting after natural disturbances… such activity would actually slow the natural recovery of forests and of streams and the creatures within them… no substantive evidence supports the idea that fire-adapted forests might be improved by logging after a fire."

Based upon the scientific evidence summarized above, a new ecological paradigm has emerged – one that recognizes: a) historic conifer forests generally had a mix of low-, moderate-, and high-intensity effects; b) current forests have an unhealthy deficiency in wildland fire and large snags; and c) forest management activities should be undertaken to increase occurrence of mixed-intensity wildland fire and increase the density of large dead trees in order to maintain ecologically healthy forests.

Of course, as the new forest ecology paradigm is increasingly reflected in actual forest management policies in the coming years, it is important to ensure that homes are adequately protected. Resources must be focused on creating defensible space within 100 feet of homes in forested areas, and reducing the combustibility of the homes themselves. So-called "fuels reduction" projects far from homes are diverting important resources from home protection, and are creating a false sense of security in forested communities. By focusing our attention on ensuring public safety, we can also facilitate the restoration of the natural role of wildland fire in our forest ecosystems.

Those who benefit from the perpetuation of the "catastrophic wildfire" myth – chiefly the timber industry and their Congressional allies, as well as the federal land management agencies that pad their budgets through timber sale revenue – seek to convince the public that we need to fear the effects of fire in our forests. They would have us continue to spend billions of dollars not only subsidizing logging projects across millions of acres of mature and old-growth forest on public lands, but also funding increasingly aggressive fire suppression policies, while weakening federal environmental laws to expedite such programs. Fire-dependent wildlife species would be put at a growing risk of extinction.

The emerging forest ecology paradigm, in contrast, does not require these costly and destructive programs. It recognizes that wildland fire is doing important and beneficial ecological work in our forests. Moreover, within the forest ecology paradigm, policies are focused on ensuring that rural human communities adapt to wildland fire so that homes are protected. Both our forests and our communities will be healthier for the change.

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Fig. 8: Chad Hanson

Fig. 9: Doug Bevington

Fig. 10: Doug Bevington

Fig. 11: Chad Hanson

Fig. 12: Chad Hanson

Fig. 13: Doug Bevington

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Recommended Citation

Hanson, C.T. 2010. The myth of “catastrophic” wildfire: a new ecological paradigm of forest health. John Muir Project Technical Report 1. John Muir Project of Earth Island Institute, Cedar Ridge, California.

Contact

Chad Hanson, Ph.D., Director
John Muir Project
P.O. Box 697
Cedar Ridge, CA 95924

cthanson1@gmail.com
530-273-9290

www.johnmuirproject.org

The John Muir Project
of
Earth Island Institute

About the Author

Chad Hanson has a Ph.D. in Ecology from the University of California at Davis, with a research focus on forest and fire ecology in western U.S. conifer forests. Dr. Hanson is the Director of the John Muir Project (www.johnmuirproject.org), and is a researcher in the Plant and Environmental Sciences department at the University of California at Davis. He is the author of numerous scientific studies in peer-reviewed scientific journals on the subjects of fire history, current fire patterns, post-fire conifer response, and wildlife species dependent upon the habitat created by forest fire.

The upfront carbon debt of bioenergy

Prepared by: Giuliana Zanchi
JOANNEUM RESEARCH
Elisabethstrasse 5
A-8010, Graz, Austria
Email: giuliana.zanchi@joanneum.at

Naomi Pena
JOANNEUM RESEARCH
Email: naomi.pena@joanneum.at

Neil Bird
JOANNEUM RESEARCH
Email: neil.bird@joanneum.at

EXHIBIT 18

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Contents

Executive Summary

In the current climate change policy framework, the use of biomass for energy is considered a carbon neutral source. According to the principle of carbon neutrality, the GHG emissions produced by combustion of plant biomass are assumed to be re-captured instantaneously by new growing plants. This assumption is acceptable when the same amount of biomass that was burned will re-grow in a very short time as for annual crops. When the raw material is wood, the time needed to re-absorb the CO_2 emitted in the atmosphere can be long, depending very much on the source of wood. This delay can create an upfront "carbon debt" that would substantially reduce the capability of bioenergy to reduce the greenhouse gas emissions (GHG) in the atmosphere in the short to medium term.

The discussion on bioenergy carbon neutrality is fundamental, since the European Union (EU) adopted ambitious policy targets on the use of renewable energy sources and a substantial share of the total renewable energy will come from biomass. Biomass resources, which would not have been used without the new policies, and could have stored carbon in the biosphere, will be used to produce energy. According to estimates used by DG TREN, the projected renewable sources' deployment in 2020 will require the use of 195 Mtoe from biomass. The energy generation from solid biomass and biowaste is projected to be 58% of the total renewable energy generation in 2020 (140 Mtoe of 240 Mtoe) and it will cover 12% of the gross energy demand in the EU.

The extent to which the use of bioenergy reduces GHG emission can be quantified with a Carbon Neutrality (*CN*) factor. The *CN* factor is defined as the ratio between the net reduction/increase of carbon emissions in the bioenergy system and the carbon emissions from the substituted reference energy system, over a certain period of time. The *CN* is time dependent and it includes emissions from carbon stock changes. This study shows that different sources of biomass for bioenergy can have very different climate change mitigation potentials according to the time horizon that is considered, by assessing the development of their *CN* over time. There is forest biomass that can produce a GHG benefit in the atmosphere from the beginning of its use but it is not carbon neutral. Other sources of woody biomass will require a long time before producing a GHG benefit in the atmosphere, while some other sources can be carbon neutral from their initiation:

- When harvest residues, previously left on the forest floor are extracted for bioenergy, there is a carbon stock loss in the dead wood, litter and soil pools. It was estimated that the mitigation potential of such bioenergy material in a 20 year time horizon is reduced by 10-40% by this loss (*CN*=0.6-0.9).
- Additional fellings for bioenergy can produce a decrease of the overall carbon stock in the forest that significantly affects the GHG balance of the bioenergy material. In the short-medium term (20-50 years), additional fellings could produce more emissions in the atmosphere than a fossil fuel system (*CN*<0). In such a case, the use of additional fellings would produce only very long term benefits, in the order of magnitude of 2-3 centuries.
- The GHG balance of biomass from new plantations is affected by the carbon stock change due to the conversion from the previous land use (direct and indirect). The biomass source can be carbon neutral when the carbon stock change is zero or positive (e.g. conversion from abandoned croplands). If there is an initial carbon loss

> (e.g. conversion from a forest area), the biomass will produce an atmospheric benefit only after that the carbon stock change is fully compensated by the same amount of avoided emissions in replaced fossil fuels (150-200 years).

In the current accounting of GHG emissions in the climate change policy framework, there are two major gaps concerning the use of bioenergy. The first is a gap in spatial coverage. This gap resulted from adoption of an inventory methodology designed for a system in which all nations report into systems in which only a small number of countries have emission obligations, i.e., the Kyoto Protocol (KP) and the Emission Trading Scheme (EU-ETS). The second is a failure to differentiate between a system in which very long time horizons are relevant – efforts to mitigate climate change over the long term – and systems concerned with shorter-term horizons such as the EU 2020 and 2050 targets. Since the KP adopted the UNFCCC Inventory Guidelines without considering these differences, current accounting systems' difficulties in addressing the time-dependency of biomass' carbon neutrality can also be traced to this decision.

Policy approaches currently under discussion that could address the spatial or temporal gaps, at least to a limited extent, include the following:

1. More inclusive accounting of emissions from the land-use sector
2. Value Chain Approaches, including use of sustainability criteria
3. Point-of-use accounting

All of them are primarily intended to address problems that have emerged due to the difference in spatial boundaries, and point-of-use accounting can also address the time delay between use of biomass for energy and regrowth.

A more inclusive accounting of emissions from the land-use sector has been under consideration in the UNFCCC fora by widening the number of activities whose emissions must be counted in Annex-I countries and by adopting a mechanism to support REDD+ that should encourage emission reduction efforts in non-Annex-I countries. However, these approaches would only partially fill the existing spatial gap and they would be dependent on a continual series of policy agreements. A third option is a unified carbon stock accounting (UCSA) under which land-use sector emissions would be estimated across all managed lands without restriction to specific activities, but there is currently wide resistance to this approach. In addition, it would only partially resolve the accounting gap if only applied in Annex-I countries.

Under value-chain approaches GHG impacts along the entire series of steps – resource extraction or cultivation, transportation, and conversion to a final product – are taken into consideration. Under this approach bioenergy users are held responsible for the bioenergy embodied emissions and quantitative and/or qualitative criteria are set to limit the use of goods with high GHG-profiles. The EU Renewable Energy Directive's requirements for biofuel are an example of a value-chain approach. However, there is a disjunction between the Directive and the KP and EU-ETS. For the purpose of emission reduction targets, bioenergy will still enjoy zero emission status even if its GHG balance, assessed with the methodology in the Directive, is not zero. In addition carbon stock changes due to management changes are not accounted for.

Under point-of-use accounting, end-users are also held responsible for the emissions attendant on use of bioenergy and, in addition, emissions due to combustion would be assigned a non-zero multiplier (i.e., emission factor) to include the real GHG benefits due to bioenergy use. Under conditions where not all nations cap emissions in all sectors, point-of-use accounting is likely to provide better incentives and dis-incentives than other systems.

Two alternative ways to calculate emission factors at point-of-use are reviewed: calculating net value-chain emissions not covered by caps and use of Carbon Neutrality (*CN*) factors. DeCicco (2009) proposes a system in which assignment of emissions to biomass used for energy is combined with tracking the emissions occurring along its value chain that occur in non-capped sectors or nations. In such a system, the emission cap on fossil fuels serves as the incentive to lower the GHG emission profiles of biofuels.

CN factors can incorporate all emissions due to changes in carbon stocks. Moreover, they compare biomass emissions to the emissions of use of fossil-fuels in a time-relevant manner. Thus, use of *CN* factors by bioenergy users could, in principal, address both the areal gaps and timing issues. These issues have emerged as a result of the combination of the use of a ‘zero emissions’ factor at the point of biomass combustion under the KP and EU-ETS with the lack of accounting for land use change in Annex-I and non-Annex-I countries. The use of *CN*-factor labelled biomass would provide a straightforward way to calculate emission benefits relative to use of fossil fuels.

It is very likely that accounting systems will remain partial through the foreseeable future. Not all nations will cap emissions from their land use sector and many of those that do are unlikely to adopt a UCSA approach. During this period, a *CN* factor based only on emissions not falling under caps may be a useful approach.

1 Introduction

In the current climate change policy framework, the use of biomass for energy is considered a carbon neutral source. It is claimed that all the emissions produced by biomass burning are re-absorbed when it re-grows and therefore they are to be considered equal to zero.

A recent paper by Searchinger et al. (2009) highlighted that different bioenergy sources can have a different capability to contribute to GHG emission reduction and they are not all carbon neutral. The paper stresses that the carbon neutrality of biomass from existing forests is particularly controversial under the current accounting rules. Part of the problem is linked to the lack of a full-accounting system in the Land Use and Land-Use Change sector under the current climate policy binding agreements. Already in the past, Schlamadinger et al. (1997) came to similar conclusions and stated that the emission reduction effect of bioenergy from existing forests (logging residues, trees) has a time delay in the order of several decades. This delay can create an upfront carbon debt that would substantially reduce the capability of bioenergy to reduce the present greenhouse gas emissions (GHG) in the atmosphere in the short to medium term. The impact of this carbon debt is strongly dependent on the source of wood, the efficiency of conversion, the type of substituted fuel and the mix of final products (Schlamadinger and Marland 1996).

The discussion on bioenergy carbon neutrality is fundamental, since the European Union (EU) adopted ambitious policy targets on the use of renewable energy sources and a substantial share of the total renewable energy will come from biomass. In the current EU system, the negative GHG impact of bioenergy is partially addressed by the adoption of a sustainability criteria framework that should ensure sustainable provision and use of biofuels and bioliquids. The regulations require that biofuels and bioliquids comply with a minimum climate mitigation performance. Once the bioenergy product is accepted in the system, it is considered carbon neutral for the purpose of binding targets. Concerning the use of solid and gaseous biomass sources, the Commission produced only recommendations to Member States on the development of national sustainability schemes (COM 2010). Therefore no binding criteria are approved for biomass at this stage at the EU level. The recommended sustainability criteria for biomass are the same as those laid down for biofuels and bioliquids.

The real effectiveness of woody biomass in offsetting GHG emissions is to be discussed in order to ensure the development of policy instruments that will avoid perverse incentives to bioenergy and would increase GHG emissions instead of reducing them in the medium term.

This report summarizes the future scenarios of bioenergy demand by 2020 and the potential bioenergy production, taking into account different fuel mixes. It discusses and gives guidance to assess the real carbon neutrality of bioenergy when a medium term climate mitigation goal is considered. The main focus is on woody biomass used for bioenergy. Finally, policy options to include the bioenergy upfront carbon debt in the accounting systems are presented.

2 Bioenergy in the climate policy framework

Increased use of renewable energy is a key EU strategy for reducing emissions of CO_2 to the atmosphere. However, the Kyoto Protocol's adoption of the IPCC Inventory Guidelines results in a large fraction of emissions due to use of bioenergy not being accounted for under it or the EU-ETS. The EU Renewable Energy Directive attempts to address this gap for biofuels, but adoption of the same procedure for woody biomass would fail to address critical timing issues.

The current climate policy framework is led by the principle of differentiated responsibilities according to which industrialized countries, emitting the majority of greenhouse (GHG) emissions, are the main actors responsible for mitigating climate change.

Due to this principle, industrialized countries committed themselves to adopt policies and to take measures to limit anthropogenic emissions under the United Nations Framework Convention on Climate Change (UNFCCC). These countries, including the European Union (EU), are classified as Annex-I countries. With the ratification of the Kyoto Protocol, Annex-I countries adopted a binding target to reduce the GHG emissions of a certain percentage in comparison to a reference year (baseline).

The EU promoted a series of parallel policy actions to help comply with the Kyoto Protocol target. The emissions produced by industry are regulated by maximum emission caps in the EU-Emission Trading Scheme (EU-ETS). Most recently, the EU also approved a Directive for the promotion of the use of energy from renewable sources that establish national targets corresponding to “at least a 20 % share of energy from renewable sources in the Community's gross final consumption of energy in 2020“ (EC 2009).

The increased use of renewable energies is indeed one of the strategies to reduce future emissions of CO_2 and other GHGs in the atmosphere. Woody and herbaceous biomass are considered renewable energy sources and due to the fact that re-growing plants can recapture the carbon emitted with combustion. For this reason, bioenergy (from wood and crops) is regarded as having zero emissions in accounting systems of policies with a GHG emission reduction target.

2.1 Reporting and accounting systems

There is a fundamental difference between reporting under the UNFCCC and accounting under the Kyoto Protocol (KP) and the EU-ETS. As a consequence of its more limited spatial boundaries, accounting gaps occur under the KP that do not occur under UNFCCC reporting. These gaps are spatial in nature, but timing gaps are also a problem in the case of use of woody biomass.

UNFCCC reporting covers virtually all greenhouse gas emissions due to human activities world wide[1]. Under the KP and EU-ETS, however, only GHG emissions that occur in Annex-I or EU nations, respectively, enter the accounting system. GHG emissions that occur due to land use or biomass conversion and biomass production in non-Annex-I countries are not included in either the KP or EU-ETS. As well, in many Annex-I countries the decrease of forest carbon stocks, other than deforestation, are not

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[1] None of the systems covers emissions from unmanaged lands.

included unless the country has elected forest and soil management activities in its accounts. Due to the accounting convention, the emissions that occur when biomass is combusted for energy are also not counted. Recognition of the undesirable consequences of these accounting gaps led to adoption, in the EU Renewable Energy Directive, of provisions intended to account for all emissions due to biofuel use.

Reporting under the UNFCCC as well as accounting under the KP and EU-ETS is based on the IPCC Guidelines for National Greenhouse Gas Inventories. These Guidelines were developed for UNFCCC reporting. They stipulate that each nation prepare an Inventory of “greenhouse gas emissions and removals taking place within national territory and offshore areas over which the country has jurisdiction” (IPCC 1996). Since virtually all nations are signatories to the UNFCCC, this method results in essentially complete reporting of GHG emissions due to human activities. In particular, emissions due to land use changes as well as conversion of biomass to biofuels are reported for almost all nations.

The IPCC Guidelines were subsequently adopted for preparation of inventories under the KP. “The Conference of the Parties serving as the meeting of the Parties to the Kyoto Protocol Decides… that the IPCC good practice guidance … shall be used by Parties included in Annex-I to the Convention (Annex-I Parties) in their preparation of national greenhouse gas inventories under the Kyoto Protocol”. These inventories form the basis for determining compliance with targets, i.e. are used for accounting purposes. However, only a small sub-set of nations have KP targets. Thus, a reporting system designed for conditions in which virtually all nations participate is being utilized in an accounting system with different spatial boundaries: compliance with KP targets. This difference in spatial inclusiveness invalidates a key assumption underlying UNFCCC reporting: that emissions not reported in the energy sector will be reported in the LULUCF sector.

Biomass to be used for energy and biofuels are among many products that enjoy a preferential status due to this difference in the spatial boundaries of the UNFCCC and KP. Due to the “national territory” organization of inventories, the GHG emissions attributable to production of any goods imported from non-Annex-I countries are not included in KP compliance. The extent to which this eases EU compliance with targets is illustrated in Figure 1. The difference between imported and exported embodied carbon measures the extent to which the EU does not account for, and therefore does not take responsibility for, the CO_2 emissions caused by products it uses.

Biomass-used-for energy enjoys an additional advantage. This extra ‘advantage’ is due to the IPCC Guidelines specific to bioenergy. “Reporting is generally organized according to the sector actually generating emissions or removals…There are some exceptions to this practice, such as CO_2 emissions from biomass combustion which are reported in AFOLU (Agriculture, Forestry and Other Land Uses) Sector as part of net changes in carbon stocks” (IPCC 2006). Due to this provision, in addition to excluding emissions due to production and conversion in non-Annex-I nations, Annex-I nations also do not account for emissions that occur when they use bioenergy[2].

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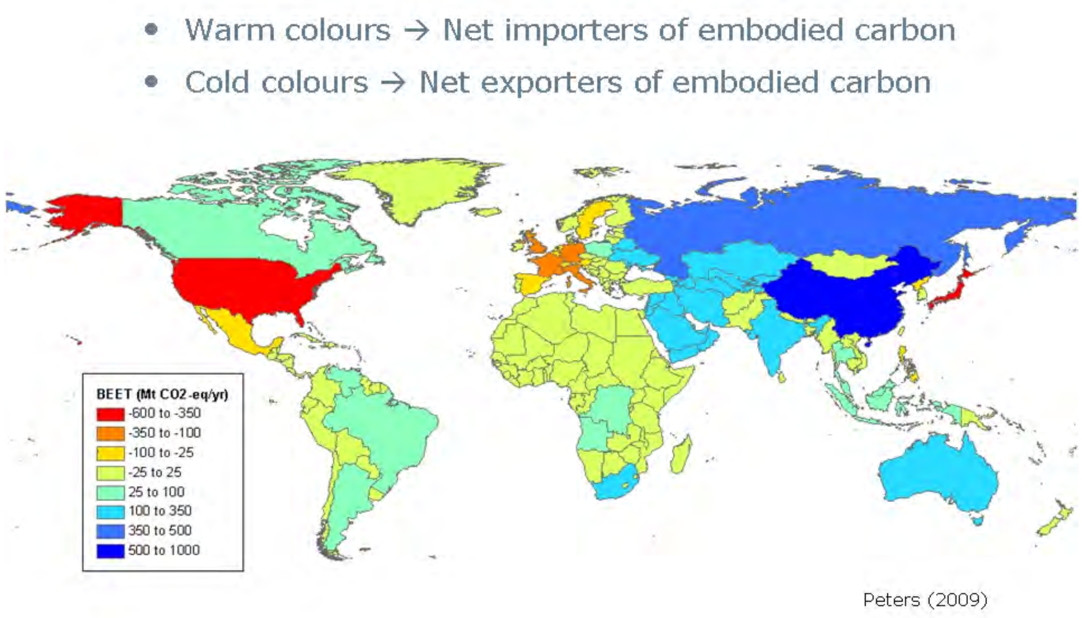
[2] In Table 1, Appendix III to Decision 20/CMP.1, which provides emission factors for the energy sector, CO_2 emissions from biomass are classified as N/A: Not Applicable, because Parties are either not required to report this source in the GHG inventories or not required to include it in their national total (UNFCCC 2006a).



- Warm colours → Net importers of embodied carbon
- Cold colours → Net exporters of embodied carbon

Peters (2009)

Figure 1 Trade balance of emissions calculated as the difference between imported and exported carbon

While the gap in accounting for emissions due to production of biomass-for-energy is most problematic where the biomass is imported from non-Annex-I nations, there is also an accounting gap where biomass is produced in Annex-I nations. In the case of Annex-I countries, the KP only requires accounting for emissions due to afforestation, reforestation and deforestation (ARD). Emissions from lands remaining in forests, grasslands, and agricultural lands are included only on a voluntary basis.

The consequence of all of these provisions is that bioenergy enjoys a status under the KP that is not warranted, in general, by its actual emission profile. Use of biomass for heat and power or biofuels produced outside of Annex-I nations is, with the exception of transport emissions, essentially “GHG-free energy” under KP accounting. Use of biomass from such sources results in an apparent 100 percent reduction of the GHG emissions of the fossil fuels it replaces in electric power plants and petroleum products. If deforestation is avoided, the only emissions that must be accounted for in Annex-I nation sourced biomass are those from energy used in biomass conversion and transport. Thus, the KP accounting system encourages Annex-I countries to use bioenergy even in cases where it causes considerable GHG emissions globally.

The EU-ETS was designed in large part to assist in meeting the target established for the EU under the KP. Therefore it is not surprising that the EU-ETS adopted the accounting rules of the KP, with all of their consequences. The EU also, partly to assist in GHG reduction goals but also for energy security and other reasons, adopted a Directive setting mandates for renewable energy, including renewable transportation fuels (EC 2009). However, by the time the Directive was developed, a range of stakeholders had become concerned about the consequences of encouraging use of biofuels when emissions, particularly emissions due to land use change outside of the EU, were not accounted for. Consequently, the Directive includes provisions that attempt to hold EU bioenergy users responsible for emissions along the biomass production and delivery value chain.

The Directive includes mechanisms intended to cover emissions from both direct and indirect land use change. To address direct land use change, raw materials used for biofuels cannot be obtained from primary or undisturbed native forests, land converted from forests or wetlands since 2008, or peatlands drained after 2008. Further, to qualify for compliance with the Directive, a biofuel's GHG emissions per MJ must be at least 35% lower than those of the fossil fuel they replace. In calculating whether a biofuel meets this requirement, emissions due to cultivation of the biomass and direct land use change must be included. Two provisions address indirect land use change. First, if the biomass is produced on degraded or contaminated land, a specified amount (29 gCO_2 MJ^{-1}) can be subtracted[3]. In addition, the Directive charges the EC to submit a report by 2010 accompanied, if appropriate, by a proposal "…containing a concrete methodology for emissions from carbon stock changes caused by indirect land use changes…" (EC 2009). Recently, the EU Commission decided to postpone the decision whether similar regulations should be adopted at the EU level for forest biomass used for heat and power. The Commission only made recommendations to Member States on the development of national sustainability schemes that are consistent with the regulations in the Directive (COM 2010).

The attempt of the Directive to account for emissions due to use of biofuels is only partially successful. First, although the Directive attempts to prevent EU biofuel demand for biomass-for-energy from causing emissions due to land use change, it will fail to do so unless its provisions encouraging use of degraded land are successful. Without sufficient increases in use of degraded land and productivity, increased demand for biomass will trigger land use change and accompanying emissions. If land use change is 'prohibited' for biomass for energy, instead of producing this biomass on converted land, biomass to meet other needs (e.g. food) will be produced through conversion.

A second problem results from the disjunction between Directive and KP and EU-ETS rules. Although the Directive ensures that only biofuels with an emission profile better than petroleum products can be used to meet renewable energy targets, this does not impact their contribution to EU-ETS and KP targets. Under both of these regimes, substitution of biomass for fossil fuels reduces emissions accounted by close to 100 percent (i.e. except for emissions due to conversion of biomass, transport, and deforestation in the EU). Consequently, under these regimes, combustion of biofuels whose GHG balance, assessed with the methodology in the Directive, is not zero, will still enjoy zero emission status and bioenergy use will still be attractive well beyond what justified by its GHG profile.

A final consideration, with regard to the Directive in the context of use of woody biomass, lies in its approach to timing issues. Just as the adoption of an inventory approach to systems with different spatial boundaries led to problems, adoption of the current approach to biofuels for all bioenergy applications would introduce anomalies. The time horizon over which woody biomass sources provide carbon neutrality compared to the use of fossil fuel varies significantly depending on the source of biomass and the fuel-substitution pathway. In particular, the degree to which increased use of woody biomass

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[3] This provision attempts to reduce indirect land-use change impacts of bioenergy demand by providing an incentive to produce the biomass on land not in use to satisfy, e.g. food, feed, or fibre demand. In this way, the food, feed, and fibre demand can continue to be met on land already in use, avoiding further land use change.

for energy lowers or increases GHG emissions compared to fossil fuels by a given date depends on the source of the biomass as well as the fossil fuel for which it is substituted. Within the time horizons of the 2012, 2020, 2030, and even 2050 GHG emission targets, increased use of woody biomass may increase GHG emissions or may make small, medium, or significant contributions to lowering them. Another way to view this is that the carbon neutrality concept of sustainably produced biomass, which underlies the acceptance of the UNFCCC inventory approach for the KP, is true only over time periods which, in some cases, exceed the time horizons of the targets for whose achievement biomass is being recommended. Particularly cases where management change rather than land use change is involved, adoption for other bioenergy pathways of the Directive approach to biofuels would not resolve near-to-medium term targets concerns. The following sections explore this timing issue for a range of biomass sources in further detail.

3 Bioenergy deployment in Europe

According to estimates used by DG TREN, the projected RES deployment in 2020 will require the use of 195 Mtoe from biomass. The 195 Mtoe will be produced mainly from domestic biomass, i.e. 173 Mtoe of domestic solid biomass will be used in 2020, which is equal to 78% of the domestic EU potential. The remaining 22 Mtoe will be imported, divided into 5 Mtoe of forest products and residues and 16.9 Mtoe of biofuels. The energy generation from solid biomass and biowaste is projected to be 58% of the total renewable energy generation in 2020 (140 Mtoe of 240 Mtoe) and it will cover 12% of the gross energy demand in the EU.

The promotion of climate mitigation policies and the establishment of a renewable energy target are strong drivers for the demand of bioenergy in Europe. Several studies have analysed the possible deployment of the renewable energy market in the next decades, taking into account different policy scenarios, energy prices and technology development.

In this study we considered the demand projections based on the *PRIMES* modelling and the renewable energy source (RES) deployment based on the *GREEN-X* model to be consistent with scenarios and assumptions considered by the European Commission. We analysed the most recent studies that take into account the current policy target in the Renewable Energy Directive (D on RES) (EC 2008, Resch et al. 2008, Ragwitz et al. 2009).

a) Energy demand

The PRIMES projections forecast the future energy demand in Europe under different policy scenarios and energy prices (EC 2008) (Table 1).

Among the PRIMES projections, there are:

- A *baseline* scenario that includes current trends, policies already implemented and moderate energy prices. The share of renewable energy on the final energy demand is projected be around 13% in 2020. Even with high oil prices, the percentage of renewables is estimated to be 15% of the final energy demand; and
- A *new energy policy* scenario that assumes the implementation of new energy efficiencies policies to reach energy and climate targets. Under this scenario and moderate energy prices, the final demand for renewables will be 20% of the final energy demand. Therefore, it is necessary to implement new policies to reach the 20% target set in the D on RES.

The total primary energy demand for renewables is today covered mainly by the domestic primary production in the EU. The net imports of RES in 2005 were only 1% of the primary energy demand. However, the imports need to increase to 9% of the primary energy demand in 2020 to comply with the 20% target (*new energy policy* scenario).

Table 1 Energy production and demand in 2005 and 2020 according to PRIMES

Year	2005	2020			
Scenario		Baseline		New Energy Policy	
Oil price		61\$ bbl^{-1}	100\$ bbl^{-1}	61\$ bbl^{-1}	100\$ bbl^{-1}
EU primary production (Mtoe)	**896**	**725**	**774**	**733**	**763**
Oil	133	53	53	53	52
Natural gas	188	115	113	107	100
Solids	196	142	146	108	129
Nuclear	257	221	249	218	233
Renewables	122	193	213	247	250
Net imports (Mtoe)	**975**	**1,301**	**1,184**	**1,033**	**962**
Oil	590	707	651	610	569
Natural gas	257	390	330	291	245
Solids	127	200	194	108	124
Renewables	1	3	8	23	24
Primary energy demand (Mtoe)	**1,811**	**1,968**	**1,903**	**1,712**	**1,672**
Oil	666	702	648	608	567
Natural gas	445	505	443	399	345
Solids	320	342	340	216	253
Renewables	123	197	221	270	274
Nuclear	257	221	249	218	233
Final energy demand (Mtoe)	1,167	1,348	1,293	1,185	1,140
% Renewables on final energy demand	*8.9%*	*13.1%*	*15%*	*20%*	*21%*

Source: EC 2008

b) RES deployment

The future deployment of renewable energy in EU-27 has been quantified by several projects with the *GREEN-X* model that forecasts the deployment of RES in a real policy context. The potential supply of energy from each technology is described at country level analysed by means of dynamic cost-resource curves (http://www.green-x.at).

In this study, we considered the final results of the "Employ-RES" project up to 2020 (Ragwitz et al. 2009). The RES deployment is projected under the PRIMES policy scenario and high energy prices (100\$ bbl^{-1} in 2020), because, under these conditions, the demand for renewable energy matches the 20% RES target. As a term of comparison, in a business as usual (BAU) scenario the RES share in the final gross energy demand would be 13.9% in 2020. In the *policy* scenario, improvements of the support conditions for RES are preconditioned for all EU countries, including a removal of non-financial deficiencies and the implementation of feasible energy efficiency measures.

In the *policy* scenario, the RES will reach a 20.4% of final (gross) energy demand in 2020[4] (239.5 Mtoe, Table 2). The D on RES includes an additional target for biofuels that will have to reach 10% on the demand for diesel and gasoline. In the projections the share of biofuels will reach 8% of transport fuel demand in 2020, corresponding to a 10% of diesel and gasoline demand.

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[4] The final energy demand used in the Employ-RES report is slightly different but fully comparable to the data presented in EC 2008.

Concerning biomass, the allocation of biomass resources to the various sectors and technologies is based on feasible revenue streams under a specific policy scenario. The projections to 2030 show a saturation of the bioenergy growth due to limitations of domestic resources and the presumed limitation of alternative imports from abroad (Ragwitz et al. 2009).

Table 2 RES deployment in EU-27

Generation category	Mtoe			% on generation category
	2006	2010	2020	2020
RES-E - Electricity generation				
Biogas	1.5	2.2	7.1	7%
Solid biomass	4.9	8.3	15.6	16%
Biowaste	1.2	2.0	2.9	3%
Geothermal electricity	0.6	0.6	0.7	1%
Hydro large-scale	26.0	27.2	28.0	29%
Hydro small-scale	4.0	4.5	5.3	5%
Photovoltaics	0.2	0.3	1.7	2%
Solar thermal electricity	0.0	0.1	1.2	1%
Tide & wave	0.0	0.2	0.5	1%
Wind onshore	8.4	14.0	24.9	25%
Wind offshore	0.3	0.8	10.1	10%
RES-E total	**47.0**	**60.2**	**98.2**	
RES-E CHP	*5.2*	*8.3*	*16.2*	*16%*
share on gross demand (%)	***16.4%***	***19.6%***	***32.4%***	
RES-H - Heat generation				
Biogas (grid)	1.5	1.6	1.9	2%
Solid biomass (grid)	5.3	9.2	20.8	19%
Biowaste (grid)	2.4	3.6	5.2	5%
Geothermal heat (grid)	0.8	0.9	1.5	1%
Solid biomass (non-grid)	49.7	53.8	65.7	59%
Solar therm. heat.	0.8	1.6	8.3	7%
Heat pumps	0.8	1.3	8.2	7%
RES-H total	**61.3**	**72**	**111.6**	
RES-H CHP	*7.1*	*10.7*	*18.2*	*16%*
RES-H distr. heat	*2.9*	*4.7*	*11.2*	*10%*
RES-H non-grid	*51.3*	*56.7*	*82.2*	*74%*
share on gross demand (%)	***10.4%***	***11.9%***	***21.7%***	
RES-T - Biofuel generation				
Traditional biofuels	3.7	6.8	11.4	39%
Advanced biofuels	0	0	1.3	4%
Biofuel import	0.4	2.5	16.9	57%
RES-T total	**4.1**	**9.3**	**29.7**	
share on gross demand (%)	***1.1%***	***2.4%***	***8.3%***	
share on diesel and gasoline demand (%)	***1.4%***	***2.9%***	***10.0%***	
RES TOTAL	**112.4**	**141.5**	**239.5**	

Source: Ragwitz et al. 2009

c) Biomass potential

The RES deployment in Employ-RES is based on a domestic availability of biomass of 221 Mtoe yr^{-1} in 2020[5]. The types of domestic fuels are: agricultural products and residues, forestry products and residues and biowaste. The share of domestic fuels is divided in: 30% of agricultural products, 32% forestry products, 14% of agricultural residues, 16% of forestry residues and 8% of biowaste. In addition, forestry imports equal to 5% of the domestic available biomass are included.

In 2006, the EEA estimated the environmental potential of bioenergy in Europe. The total potential was estimated to be 234.2 Mtoe in 2020 (Table 3). The potential in the different sectors is: 41% from agriculture, 17% from forestry and 43% from waste. The differences with the potential in the RES deployment studies are mainly due to a different classification of biomass. In the EEA study agricultural residues, demolition wood, waste wood and black liquor, manures and sewage sludge are included in the waste sector. In the RES deployment studies, only the biodegradable fraction of municipal waste is considered a biomass source from waste. When a similar classification is adopted in the EEA study, the biomass potential in Europe in 2020 is 39-47% from agriculture, 45-53% from forestry and 8% from waste, i.e. the share is comparable to the RES deployment studies.

Other studies report similar estimates. For instance, a study by Siemons et al. (2004) reports a total bioenergy potential of 210.3 Mtoe in 2020 in EU-27.

Table 3 Environmental bioenergy potential in Europe

Sector		2010	2020	2030
		Mtoe		
Agriculture		47.0	95.0	144.0
Forestry	Total without comp.	42.6	39.2	39.0
	Regular felling residues	*14.9*	*15.9*	*16.3*
	Additional fellings and their residues	*27.7*	*23.3*	*22.7*
	Competitive use of wood		*2.0*	*16.0*
Waste		99	100.0	102.0
TOTAL		**188.6**	**234.2**	**285.0**

Source: EEA 2006

According to the estimates of the Employ-RES project, energy generation from solid biomass and biowaste is projected to be 58% of the total renewable energy generation in 2020 (140 Mtoe of 240 Mtoe). Therefore biomass will cover 12% of the gross energy demand in the EU. The biomass energy generation will require 195 Mtoe that will be mainly produced from domestic biomass, i.e. 173 Mtoe of domestic solid biomass will be used in 2020, which is equal to 78% of the domestic EU potential. The remaining 22 Mtoe will be imported, divided into 5 Mtoe of forest products and residues and 16.9 Mtoe of biofuels.

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[5] "Biomass data has been cross checked with DG TREN, EEA and the GEMIS database" (Ragwitz et al. 2009)

When looking at global biomass potentials, Howes et al. 2007 report that biomass production potential varies between 33 and 1,135 EJ yr^{-1} (786-27,024 Mtoe yr^{-1}). The high variability is due to the assumptions that are made of land availability and yields. The actual biomass resource depends on several factors (accessibility, costs, etc.). The global technical potential of land-based biomass supply in 2050 is estimated to be 60-1,100 EJ yr^{-1} (1,430-26,190 Mtoe yr^{-1}) (Bauen et al. 2009). A significant contribution to the total biomass use in developed countries is given by biomass imports. In North-West Europe and Scandinavia biomass imports are 21-43% of the total use, including intra-European trade. In the longer term, the total traded biomass commodities could reach a total amount of more than 100 EJ, with Europe as a net importer (Bauen et al. 2009). These data suggest that the contribution of biomass imported from non-European countries could play a more relevant role than what suggested by the projections considered by the European Commission.

4 The mitigation potential of bioenergy

According to the principle of carbon neutrality, the GHG emissions produced by combustion of plant biomass are assumed to be re-captured instantaneously by new growing plants. When the raw material is wood, the time needed to re-absorb the CO_2 emitted in the atmosphere can be long, depending very much on the source of wood. Therefore bioenergy can create an atmospheric "carbon debt".

The research studies on bioenergy potential and the potential deployment of RES calculate the CO_2 emissions avoided by renewables based on the amount of displaced fossil fuels. The assessment is usually based only on the conversion efficiency of RES technologies.

An exhaustive GHG emission estimate should apply the principles of a Life Cycle Assessment (LCA) that take into account both direct and upstream emissions, like transport and the use of materials and energy for manufacture at all stages (EEA 2008). The calculations are made for both the original fossil fuel system (reference system or baseline) and the renewable energy system and the results from the two systems are compared to assess the GHG benefits or costs. Such an analysis should consider the emissions at all stages (Figure 2).

A type of emission that has been rarely taken into account is the carbon that is released in the atmosphere when the biomass is combusted. These emissions are usually neglected because they are only temporarily released in the atmosphere and later recaptured by re-growing biomass. Therefore biomass is considered carbon neutral. According to the principle of carbon neutrality, the GHG emissions produced by combustion of plant biomass are assumed to be re-captured instantaneously by new growing plants. This assumption is acceptable when the same amount of biomass that was burned will re-grow in a very short time as for annual crops. When the raw material is wood, the time needed to recover the CO_2 emitted in the atmosphere can be quite long, on the order of magnitude of decades. It is the same principle valid for a bank loan. The borrowed money is used in the first year to buy a product, but it is repaid to the bank in a certain time frame. The time needed to re-absorb the "carbon debt" from woody biomass depends very much on the source of wood. Factors to be considered are: the previous land use and management, the productivity of the trees that influences the time needed to biomass re-growth and the previous use of the raw material, if any.

The new climate change policies and the EU Renewable Energy Directive (D on RES) could be a strong driver for an increased use of biomass. Biomass resources, which would not have been used without the new policies, will be used to produce energy. This means that carbon that would have been stored in the biosphere in a 'without policy' baseline scenario will be released into the atmosphere as CO_2 as soon as the biomass is combusted. In the very short term, this amount of emissions going to the atmosphere would be the same as the emissions produced by a fossil fuel based energy system with similar conversion efficiency (C_{eff}) and similar emissions per unit of energy. The fossil fuel with emissions per unit of energy most similar to biomass is coal.[6]

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[6] However, most of the fossil fuel systems are more efficient than biomass energy systems, i.e. for the same amount of fuel used they produce more energy. In addition, fossil fuels other than coal produce more emissions per unit of energy derived from the fuel. Oil produces 20% less emissions than biomass to produce the same amount of energy (C_{eff}=0.8), while natural gas produces 40% less emissions (C_{eff}=0.6).

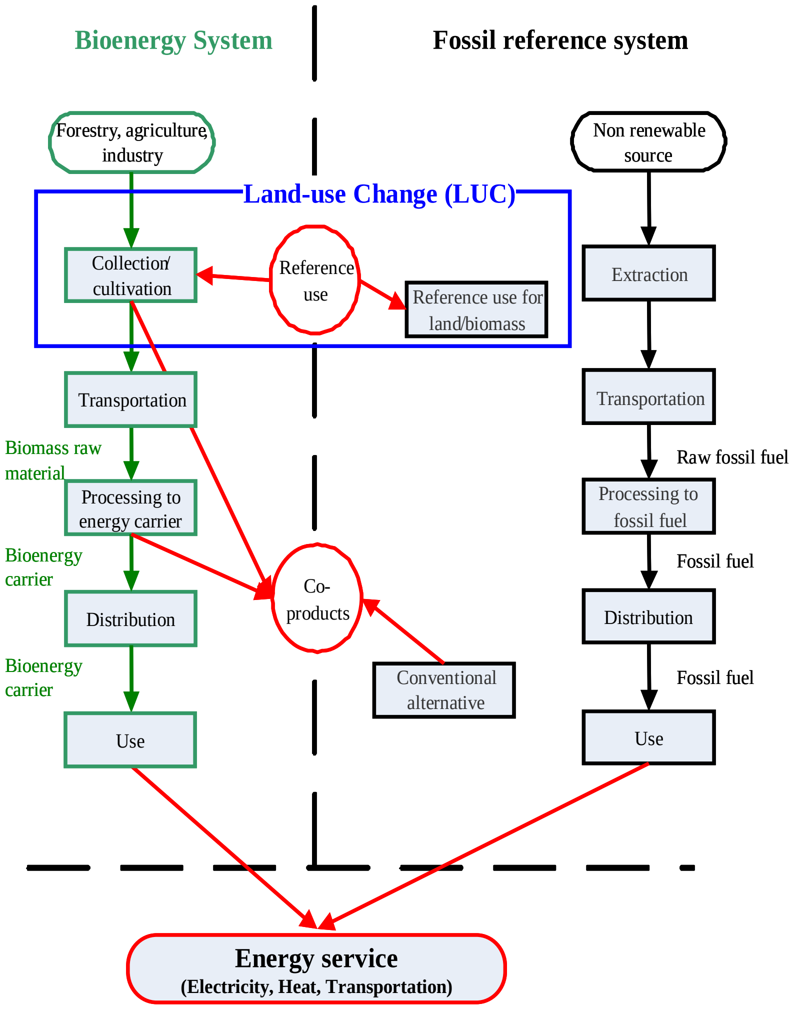

Figure 2: Processes in bioenergy and fossil reference systems

With time the emissions may be recaptured by re-growing biomass, but in the context of EU and KP climate change targets, a short term benefit, in terms of emission reductions, needs to be achieved.

It is estimated that the RES deployment considered by the European Commission will require 173 Mtoe of domestic solid biomass and 22 Mtoe of imported biomass in 2020. The sources of biomass will vary a lot, from agricultural residues to additional fellings from forest. In the short and the medium term, the real climate mitigation potential of the different materials will depend a lot on the time frame needed to recapture the emissions released from the combusted biomass.

4.1 Carbon neutrality factor

The extent to which the use of bioenergy reduces GHG emission can be quantified with a Carbon Neutrality (*CN*) factor. The *CN* factor is defined as the ratio between the net reduction/increase of carbon emissions in the bioenergy system and the carbon emissions from the substituted reference energy system, over a certain period of time. The *CN* is time dependent and it includes emissions from carbon stock changes.

Schlamadinger and Spitzer (1994) introduced 15 years ago the concept of a Carbon Neutrality Factor (*CN*) to quantify to the extent to which the use of biomass for energy reduces GHG emissions.

A similar approach is used in the D on RES. The D on RES provides instructions on how to calculate the GHG emission savings from the use of biofuels (EC 2009). The D on RES simplifies the calculation of emissions due to carbon stock changes in the biosphere. For one thing, it takes into account only emissions from land use changes, but not from management changes. In addition, it assumes constant land use change emissions over a 20 year period and therefore an unchanging relative improvement over use of fossil fuels, regardless of the time horizon of targets.

The *CN* factor is defined as the ratio between the net reduction/increase of carbon emissions in the bioenergy system and the carbon emissions from the substituted reference energy system, over a certain period of time:

[1]
$$CN(t) = \frac{[E_r(t) - E_n(t)]}{E_r(t)} = 1 - \frac{E_n(t)}{E_r(t)}$$

Where:
$E_r(t)$: carbon emissions of the fossil energy reference system, between 0 and t years
$E_n(t)$: carbon emissions of the new bioenergy system, between 0 and t years.

a) *CN* <0, if the emissions from the bioenergy system are higher than the emissions from the fossil fuel system.

b) *CN* =0, if the emissions from the new bioenergy system are equal to the emissions from the reference system.

c) *CN* =1, if the bioenergy system produces zero emissions in comparison to the reference system.

d) *CN* >1, when the bioenergy system produce a carbon sink in the biosphere.

Production chain emissions (e.g. cultivation, transport, processing, etc.) are not included in the *CN* concept. In the *CN*, the emissions produced by changes in carbon stocks (E_C) when biomass is removed are compared to the emissions produced by the fossil fuel burnt.

The E_C component (tCO_2eq.) is given by the difference in C stock in living biomass, both above and below ground[7], and in non-living biomass (dead wood, litter and soil) over a specified time period. Carbon stocks are measured before removal of biomass (C_0, tC -

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[7] Live fine-roots are normally considered part of the soil pool because they can not be distinguished from soil carbon.

baseline) and then after removal at some specified time t (C_t, tC – bioenergy system)[8]. A constant factor is used to convert the carbon into CO_2 emissions (a=3.664)

[3] $$E_C = (C_0 - C_t) \times a = \Delta C_t \times a$$

When carbon in biomass replaces the same amount of carbon in fossil fuels (biomass replacing coal), the *CN* factor is equal to:

[4] $$CN(t) = 1 - \frac{\Delta C_t \times a}{E_r(t)} = 1 - \frac{\Delta C_t}{C_{bioenergy}}$$

Where $C_{bioenergy}$ is the amount of carbon in the biomass used for bioenergy after t years.

The E_C is time dependent. When a new management – such as increased harvesting or removal of residues – is introduced or a land-use change occurs, the C stock in the system is modified until a new equilibrium is reached (Figure 3). The long-term E_C is the difference of carbon stock in biomass and soil between the baseline and the new equilibrium. However, most of the emissions due to management or land-use changes occur in the initial years. In a forest system, where additional biomass is harvested and burnt to produce bioenergy, there is an immediate loss of biomass carbon stocks equal to the amount of biomass extracted ($\Delta CB_t = C_{bioenergy} = CB_0 - CS_0$) as shown in Figure 3. The re-growth of biomass reduces, over time, the initial carbon loss (at year t_1, $\Delta CB_t = CB_0 - CB_1$). At the same time the reduced dead wood and litter inputs results in a loss of carbon in the soil and litter pools (ΔCS_t). The total E_C at time t is equal to the total carbon loss in the biomass and the soil at time t in comparison to the baseline ($\Delta CB_t + \Delta CS_t$) .

The time-dependency of E_C results in a time dependent *CN* factor (Figure 4):

1) $CN(t_0) = 1 - \dfrac{C_{bioenergy}}{C_{bioenergy}} = 0$

2) $CN(t_1) = 1 - \dfrac{\Delta CB_{t1} + \Delta CS_{t1}}{C_{bioenergy}}$

If in Figure 3 at time t_1, the carbon stock loss compared to the baseline ($\Delta CB_{t1} + \Delta CS_{t1}$) is assumed to be 40% of the amount of biomass used for bioenergy ($C_{bioenergy}$), *CN* at time t_1 is equal to 0.6.

3) If the carbon stock change, $\Delta CB_{t1} + \Delta CS_{t1}$ is equal to or less than zero (no change or a carbon sink), *CN* would be equal to or greater than 1:

$$CN(t) \geq 1 \text{ if } \Delta CB_t + \Delta CS_t \leq 0$$

In the following sections the principle of bioenergy carbon neutrality is discussed with examples that will illustrate the development in time of the *CN* factor for different bioenergy sources. The following examples will be described:

- Residues from managed forests
- Additional fellings from managed forests
- Bioenergy from new tree plantations

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[8] Normally the litter is considered a separate pool, but for the purposes of this discussion we will consider litter as part of the soil carbon pool

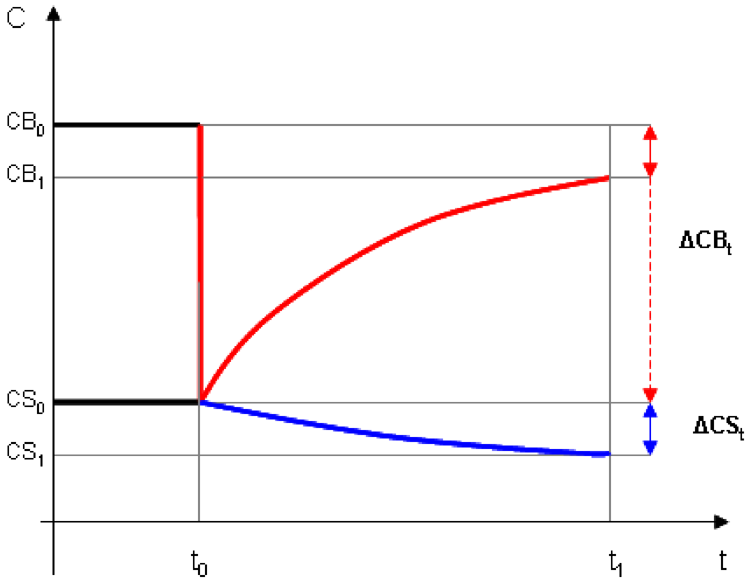

Figure 3 Carbon stock changes in biomass (*ΔCB*$_t$) and soil (*ΔCS*$_t$) due to additional biomass extraction and their change over time. Black lines: baseline carbon stock; Red lines: carbon stock in biomass when additional biomass is extracted; Blue line: carbon stock in soil and litter when additional biomass is extracted. *CB*$_0$=biomass C stock in the baseline; *CB*$_1$= biomass C stock after biomass re-growth at year *t*$_1$; *CS*$_0$ = soil C stock in the baseline; *CS*$_1$= soil C stock after *t*$_1$ years.

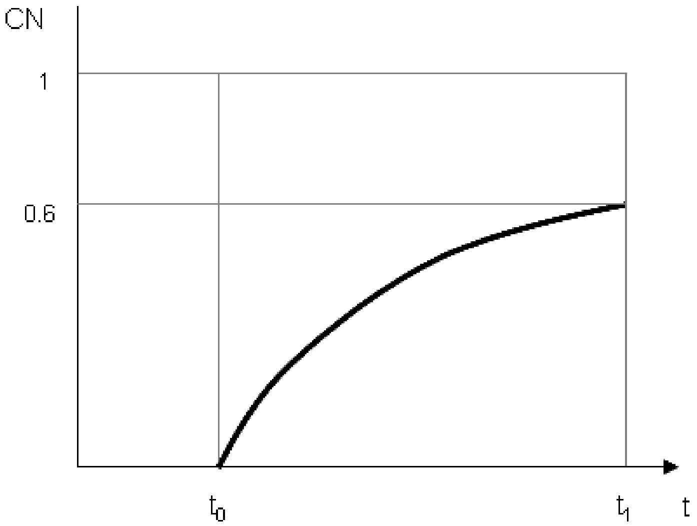

Figure 4 Development of the carbon neutrality factor (*CN*) over time, based on Figure 3

4.1.1 Residues from managed forests

When harvest residues, previously left on the forest floor, are extracted for bioenergy, there is a carbon stock loss in the dead wood, litter and soil pools. It was estimated that the mitigation potential of such bioenergy material in a 20 year time horizon is reduced by 10-40% by this loss (*CN*=0.6-0.9).

The following analysis is based on Schlamadinger et al. (1995) and Palosuo et al. (2001).

One of the possible strategies to increase the biomass available for bioenergy is to collect the forest residues that are usually left in the forest after harvesting. Depending on the site, a certain amount of residues can be extracted from the forest without compromising soil fertility and therefore forest production (EEA 2006). If this amount of residues is utilized as bioenergy source, the emissions due to the management change are limited to the carbon stock changes in the dead wood, litter and soil pools (Schlamadinger et al. 1995, Palosuo et al. 2001).

When residues are left on the forest floor, they gradually decompose. A great deal of the carbon contained in their biomass is released over time into the atmosphere and a small fraction of the carbon is transformed into humus and soil carbon. When the residues are burnt as bioenergy, the carbon that would have been oxidized over a longer time and carbon that would have been stored in the soil is released immediately to the atmosphere. This produces a short term decrease of the dead wood and litter pools that is later translated into a decrease of soil carbon.

The following paragraphs present two published studies that analysed the effect of removing harvest residues from forests where the residues were previously left on site:

1) A constant annual removal of harvest residues from selective logging (Schlamadinger et al. 1995)
2) Removal of residues from clear cut at the end of a 100 year cycle (Palosuo et al. 2001)

In Schlamadinger et al. (1995) the effect of annual residue removal from a temperate or boreal forest was analysed. Every year 2/3 of harvesting residues (0.3 tC $ha^{-1}yr^{-1}$) are extracted from a forest where selective harvesting has been taking place. The soil carbon is assumed to be in equilibrium when removal of logging residues starts at time 0.

Figure 5 compares the carbon in the residues removed annually and used to replace fossil fuel to the annual loss of carbon in the litter and soil due to these removals. At time 0 the removed biomass for bioenergy corresponds to an equal loss of carbon in the litter (0.31 t ha^{-1}). With time the soil and litter carbon tends to reach a new equilibrium and the losses tend to zero.

Based on this figures, the Carbon Neutrality factor (*CN*) of logging residues used for bioenergy was calculated (Figure 6). The *CN* factor at a certain time (*t*) represents the average *CN* of all the residues that have been extracted from year zero to year *t*.

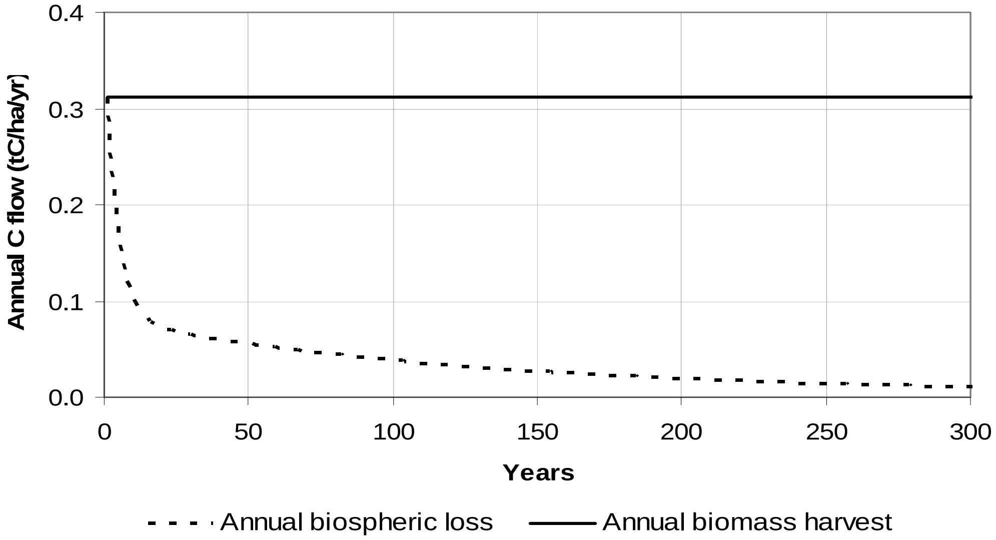

Figure 5 Carbon in removed biomass and carbon stock loss in litter and soil on a yearly basis (from Schlamadinger et al. 1995).

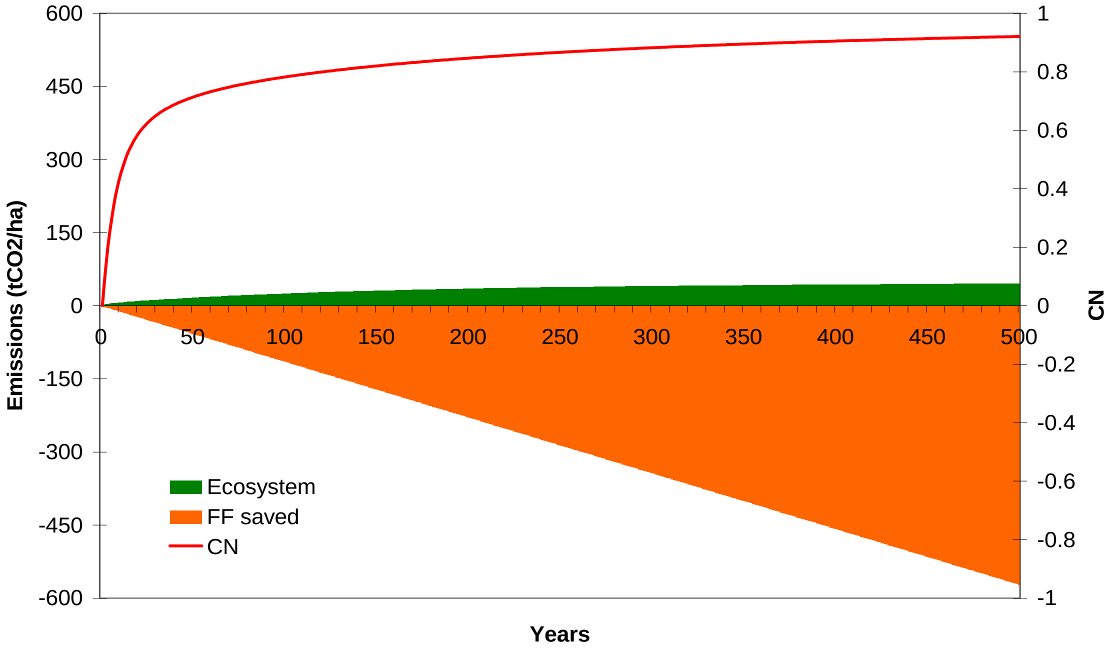

Figure 6 Carbon neutrality factor for burning logging residues for energy production (*CN*). The *CN* is calculated by comparing the carbon emissions in the soil ad litter due to the additional residue extraction (Ecosystem) to the total amount of saved emissions in the replaced fossil fuel (FF saved).

The *CN* is calculated by comparing the carbon loss in the soil ad litter due to the additional residue extraction to the total amount of carbon in the replaced fossil fuel. The replaced fossil fuel is assumed to be equal to the total biomass of residues that replaces it, i.e. the biomass replaces coal that has similar conversion efficiency and carbon emission rates. In this case,

[5]
$$CN = 1 - \frac{(C_0 - C_t)}{B_r \times t}$$

Where:
C_0= carbon stored in litter and soil at time 0 (baseline)
C_t = carbon stored in litter and soil at time t, when residues are extracted
B_r = carbon in the residues that are annually extracted

The results show that after 20-25 years the *CN* factor is about 0.6, meaning that 60% of the bioenergy used to replace fossil fuels is carbon neutral. In other words, it would be justified to assign no emissions to 60 percent of the bioenergy emissions, but in the case of the other 40 percent, an emission factor equal to that of coal would be appropriate.

The assumption used in equations [5] that the carbon emission rate or energy produced per ton of carbon of replaced fossil fuels is equal to the emission rate of residues used for energy is quite optimistic and is only approximately correct in the case of the substitution of coal. If we assume that 1 tC from residues can replace:

- 0.8 tC of oil, the *CN* of residues in the above case after 20 years would be equal to 0.5;
- 0.6 tC of natural gas, the *CN* of residues after 20 years would be equal to 0.3.

When wood waste is used for bioenergy instead of being discarded in landfills, the conclusions can be comparable if the decomposition rates in landfills are similar to the ones in forests soils. However, the wood in landfills usually decomposes slower than in the forest. In this case the *CN* of bioenergy would be lower in the short and medium term and, from the perspective of GHG emissions, it would be better to land-fill the waste wood.

A second case study was presented by Palosuo et al. (2001) for 1 ha of forest in Finland that is clear cut after a 100 year rotation cycle. The study assesses the effect of residue removal at the end of the rotation period on the litter and soil carbon. An average carbon decrease of 11% over the 100 year period was assessed, when the residues are removed. It was also calculated that 90% of the carbon in the residues left on site is released to the atmosphere after 20 years, i.e. the *CN* for a specific lot of residues removed at year 20 is equal to 0.9.

In Schlamadinger et al. the *CN* is calculated as the average for all residues annually removed over a certain period. When the *CN* is calculated for residues removed only once, by using the same modelling approach, the *CN* reaches a value of 0.8 by year 20. Therefore the figures are comparable to those presented in Palosuo et al. and they show how different chosen boundaries can influence the final results..

The calculations reported above refer to boreal or temperate forests. The decomposition rates (k) may vary substantially when the residues for bioenergy are imported from other regions. A review of litter decomposition rates shows that they increase with precipitation, temperature and latitude and they are lower for coarse dead wood than for fine litter (Zhang et al. 2008) (Table 4). In Schlamadinger et al. (1995) it was calculated that the same residue material with higher decomposition rates have a lower carbon neutrality factor.

When the residues extracted are coarse dead wood (e.g. stumps, branches), another factor needs to be considered. Part of the dead wood would not start decomposing immediately and the amount of carbon that is released in the atmosphere per year is not equal to $1-k$. Only a fraction of the carbon decomposes (e.g. 0.05 yr^{-1} for coarse dead wood, Palosuo et al. 2001) and the rest remains as a carbon pool in the forest. When the stumps are removed this slower decomposing pool must be accounted as a loss equivalent to the extraction of more logs. As a consequence the *CN* of stumps used for bioenergy will be much lower than *CN* of fast decomposing residues after the same time. The consequences of these slower rates are presented in the following section.

It is also assumed that the removal of residues does not affect soil fertility and therefore the growth of tree biomass. However, over a certain amount of residue extracted, soil fertility could be altered and negatively affect the overall forest carbon balance. Additional concerns to residue extraction are linked to the decrease of deadwood in the forest and the negative impacts that this decrease could have on biodiversity and water retention of the forest floor.

Table 4 Regression of litter decomposition with geographic, climatic factors and litter quality variables. T= mean annual temperature; P= mean annual precipitation; LAT= latitude; LIGN:N= lignin:N ratio; TN= total nutrient; C:N = carbon:nitrogen ratio

Variable/regression	N.	R^2
Climatic/geographic factors		
k = 0.0016 + 0.0447 T	163	0.288
k = -0.065 + 0.0001 P + 0.044 T	163	0.3
k = -0.4744 + 0.0081 LAT + 0.0586 T	163	0.301
k = -0.353 + 0.0063 LAT - 0.00005 P + 0.06 T	163	0.305
Litter quality variables		
k = 0.946 - 0.011 LIGN:N	141	0.131
k = -0.131 + 0.268 TN	68	0.388
k = -2.307 + 0.029 C:N + 0.524 TN	68	0.702
k = -2.132 + 0.031 C:N - 0.006 LIGN:N + 0.495 TN	68	0.733
Combination		
k = -0.308 + 0.026 T + 0.205 TN	68	0.467
k = -2.484 + 0.026 T + 0.0287 C:N + 0.461 TN	68	0.781
k = -2.935 + 0.0003 P + 0.021 T + 0.0315	68	0.805
k = -4.131 + 0.023 LAT + 0.063 T + 0.032 C:N + 0.517 TN	68	0.875

Source: Zhang et al. 2008

4.1.2 Additional fellings from managed forests

It was assessed that additional fellings for bioenergy can produce a decrease of the overall C stock in the forest that significantly affects the GHG balance of the bioenergy material. In the short-medium term (20-50 years), additional fellings could produce more emissions in the atmosphere than a fossil fuel system (*CN<0*). In such a case, the use of additional fellings would produce only very long term benefits, in the order of magnitude of 2-3 centuries.

An increased demand for biomass for bioenergy could require increasing the amount of fellings from managed forests (additional fellings). A EEA study (EEA 2006) assessed that 19.6 Mtoe of energy could come from additional fellings in the year 2020 in European forests. The potential corresponds to an additional biomass extraction of 44 Mt per year in 21 European countries (EU-21) in 2020 and takes into account environmental constraints.

European forestry statistics shows that currently the amount of annual fellings is lower than the net-annual increment (NAI). Fellings constitute on average 61% of the NAI in the EU-21 and a total amount of 433 Mm^3 was extracted in 2005 (MCPFE 2007)[9]. The FAO reported 425 Mm^3 of wood removals in EU-21 in 2005, 85% of which was industrial wood and the rest fuelwood (FAO 2006). By applying an average wood density of 0.45 t m^{-3}, 191-195 Mt of wood was removed in 2005 in EU-21 compared to a net-annual increment of about 320 Mt yr^{-1}. If an additional amount of wood, equal to 44 Mt yr^{-1}, is extracted every year, the annual fellings would increase to 75% of the NAI in EU-21.

This additional amount of extracted biomass could produce a decrease of the overall carbon stock in the forest biomass and in the soil in comparison to a “no increase in removals” baseline. The effect would be similar to the one described in the previous section for forest residues but it would be much greater. The carbon losses would not be limited to the soil and litter pools, but would include losses to the above ground live biomass pool.

The decrease of the biomass is initially equal to the amount of wood that is extracted. If we assume that every year the same amount of additional harvested wood is taken out of the forests (44 Mt yr^{-1}), forest growth and litter inputs to the soil would be modified. The forest system would slowly tend to a new equilibrium with a lower above ground biomass stock and lower soil carbon stock.

The following paragraphs illustrate what occurs when harvest thinning are increased on 1 ha of forest in Austria. The GORCAM model has been used to simulate the effects of increased thinnings against a baseline scenario. The baseline scenario is a forest on a 60 year rotation period. Wood is removed two times by thinnings at years 20 and 40. Each thinning operation extracts 18 t ha^{-1} of biomass, while the final harvest removes 270 t ha^{-1}. In the increased-thinnings scenario it is assumed that the amount of wood removed by thinnings is 30 t ha^{-1}, for a total of 60 t ha^{-1} in each rotation period. The final harvest remains the same (270t ha^{-1}).

Figure 7 presents the difference of the carbon stock in the two systems. The increase of thinnings produces a decrease of carbon stock in the forest pools. The decrease of stock

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[9] For Austria, Portugal and Spain the data of 2000 have been used

is greatest during the first 150 years and is partially and slowly compensated by the re-growth of trees. The soil is the slowest pool and it takes a very long time before it reaches a new equilibrium (approximately 300 years). In all, the total C stock is lower than in the baseline.

If the extracted biomass is used to replace fossil fuels, then there is a net benefit to the atmosphere if the cumulative emissions due to the management change are less than those would have occurred if the biomass were not used to substitute fossil fuels. Figure 8 shows the development of emissions in the forest ecosystem compared to the fossil fuel emissions avoided by using bioenergy. The first graph (A) assumes that the fossil fuel and the bioenergy system have the same conversion efficiency and the same CO_2 emissions per unit of energy produced. Even in this case, the bioenergy system will produce more emissions than the fossil fuel system for a long time. The bioenergy system will start to produce an atmospheric benefit only after 250 years ($CN \geq 0$). Bioenergy from additional fellings will produce an emission benefit even later if fossil fuels with fewer CO_2 emissions per unit of energy, like gas, are substituted (Figure 8B). In this case a benefit will be achieved only after 300 years.

Therefore in the short-medium term (20-50 years), additional fellings from already managed forests could produce more emissions in the atmosphere than a fossil fuel system and the *CN* will be negative for centuries. The use of additional fellings would produce only very long term benefits and it could be supported only when a long-term emission reduction target is considered, i.e. as an investment for future generations.

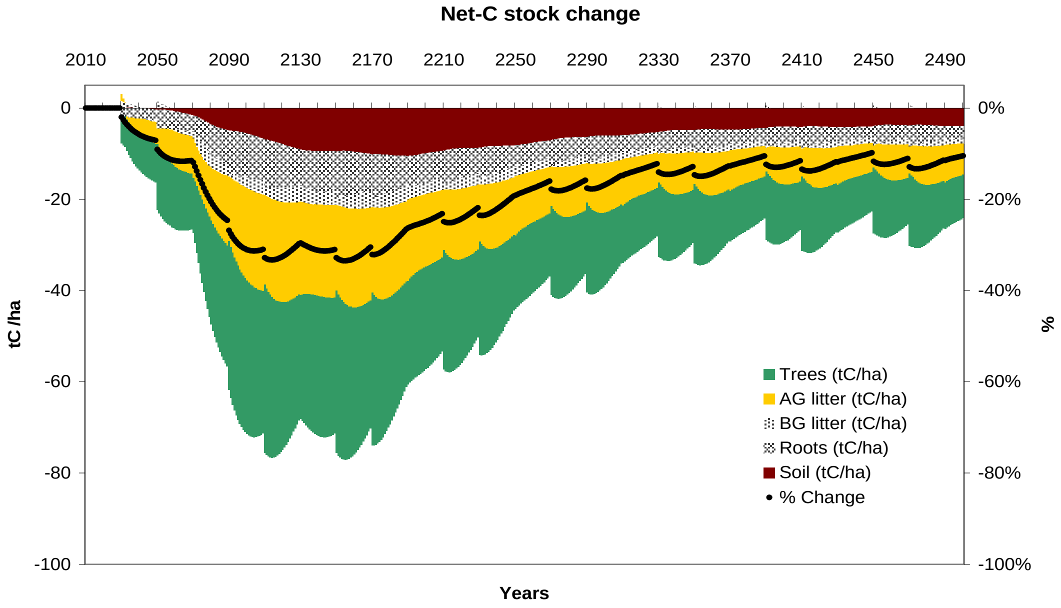
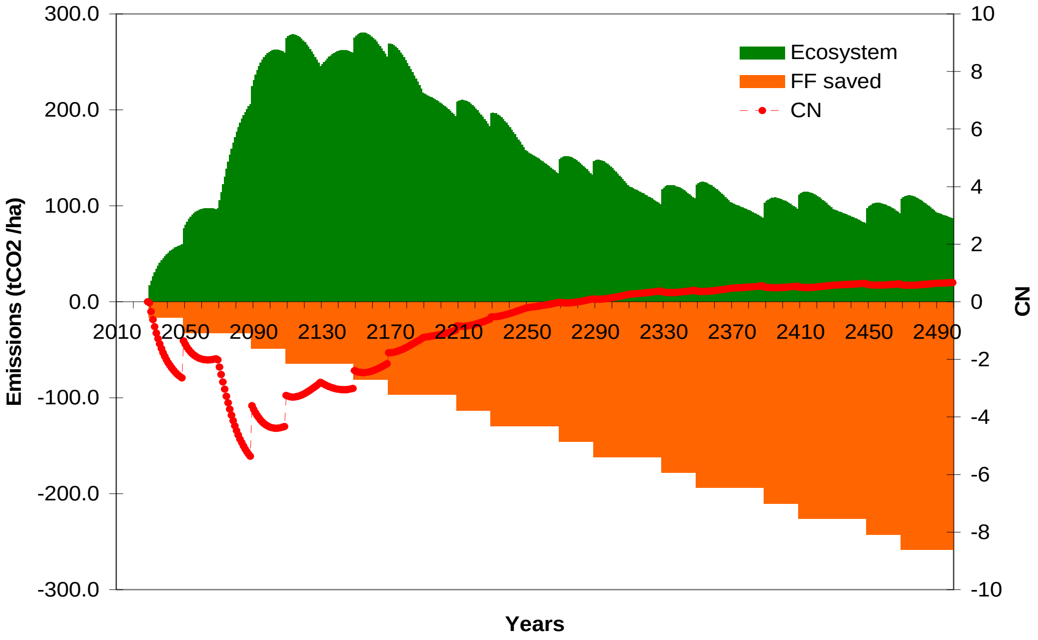


Figure 7 Decrease of carbon stock in the tree biomass, litter and soil when thinning removals are increased. Tree: aboveground tree biomass; AG litter: aboveground litter; BG litter: belowground litter; Roots: belowground tree biomass; Soil: soil carbon stock. The black line represents the percentage reduction of C stock in comparison to the baseline (% Change).

A



B

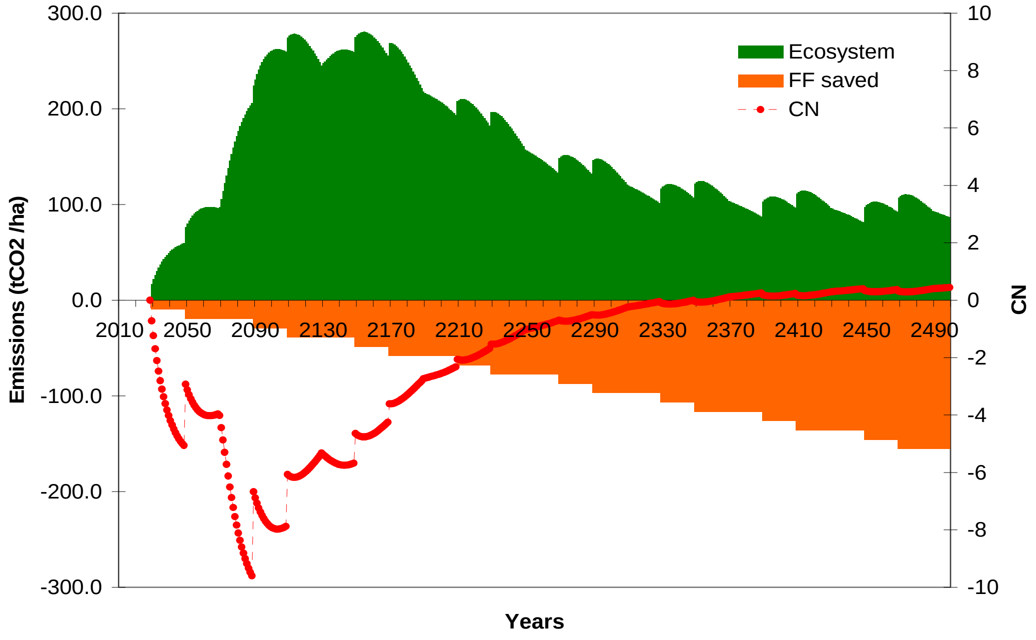


Figure 8 Additional CO_2 emissions, when additional harvesting is introduced in 1 ha of forest in Austria (Ecosystem). Cumulative emissions are shown and compared to the saved emissions in the substituted fossil fuel (FF saved). The *CN* factor shows when the emissions due to change of management are higher (*CN*<0) or lower (*CN*>0) than the baseline. (A) substitution of coal; (B) substitution of natural gas.

This example has illustrated the change of management on 1 ha of forest. When a rotation forest system is considered, each year a new patch of forest is cut to provide a constant supply of wood for bioenergy. The *CN* factor of this kind of system shows a similar development over time as the 1 hectare-system, but the *CN* is negative for a longer period. For bioenergy substituting coal, the *CN* will become positive about 25 years later (Figure 9).

This study does not take into account that the total forest carbon stock could stay unaffected when fellings are increased, because of a change of forest growth rate. To a certain extent, the forest can positively react to fellings when they reduce competition between trees and produce an increase of the net-annual increment per single tree. Additional fellings could also affect wood that, under a less intensive management, would be lost by disturbances as pests and storms and higher natural mortality rates (Nabuurs et al. 2008). It is also claimed that additional fellings can reduce forest fires. However, in European forests, where most of the fires are human-induced, it is difficult to assess to which extent this could happen.

In addition, the adoption of different management strategies in European forests could combine increased fellings for bioenergy in certain areas with afforestation and nature-oriented management in others. The result could be a shorter time period to recover the initial debt due to increased wood removals (e.g. 50 years) (Nabuurs et al. 2006).

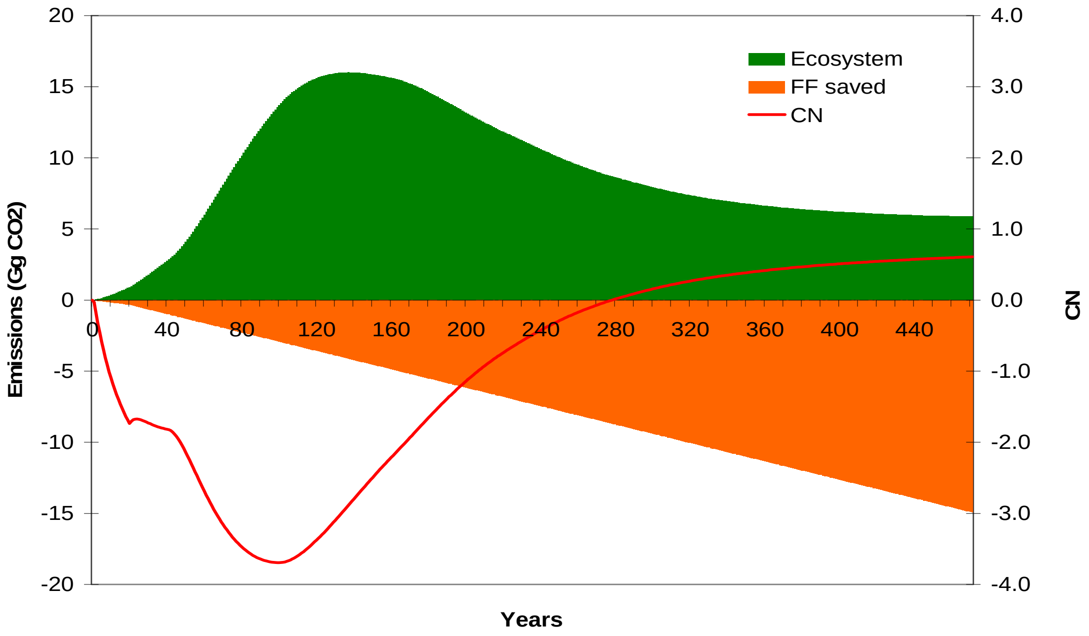


Figure 9 Additional CO_2 emissions, when additional harvesting is introduced in a rotation forest in Austria of 60 hectares (Ecosystem). In a 60 year rotation period, 1 ha of forest is cut each year to provide a constant wood supply. In comparison to Figure 8, the curve is smoothed and the *CN* line is continuous because of the constant annual wood extraction and the constant annual supply of bioenergy. Cumulative emissions are shown and compared to the saved emissions in the substituted fossil fuel (FF saved). The *CN* factor shows when the emissions due to change of management are higher (*CN*<0) or lower (*CN*>0) than the baseline. It is assumed that biomass substitutes coal.

4.1.3 Bioenergy from new plantations

The GHG balance of biomass from new plantations should include the C stock change due to the conversion from the previous land use (direct and indirect). The biomass source can be carbon neutral when the C stock change is zero or positive (e.g. conversion from abandoned croplands). If there is an initial carbon loss (e.g. conversion from a forest area), the biomass will produce an atmospheric benefit only after that the C stock change is fully compensated by the amount of avoided emissions in replaced fossil fuels.

New tree plantations established for the purpose of bioenergy production and climate change mitigation can be a third source of biomass (short rotation plantations or long-rotation forests). In this case, the trees would not have been there without the new policies and they are grown for the purpose of being used for energy at the end of the rotation period. Since the wood harvested is grown where there would not have been wood in a baseline scenario, there is no loss of biomass in comparison to the baseline when it is harvested and combusted.

On the other hand, C stock changes due to the conversion from the previous land use still occur and they can be positive (C sequestration) or negative (C loss). The C stock change assessment must include the difference between the carbon stock in the above and below ground biomass and soil before and after conversion. The effect of indirect land use changes should also be taken into account.

The C stock changes can vary a lot depending on the previous land use:

a) When cropland is converted to a tree plantation the “direct” carbon losses are limited to soil carbon losses due to site preparation. The temporary decrease of soil carbon stock, if any, is soon recovered and followed by a net increase of soil carbon due to higher litter inputs from trees than from crops (Guo and Gifford 2002). Therefore, the initial soil losses can be neglected. The belowground biomass stock increases, too. In this case, the biomass used for bioenergy will be carbon neutral or positive from the beginning ($CN \geq 1$). However, this positive “on-site” balance can be offset by carbon losses due to indirect land use change. For instance the crops previously grown on the land and used for food will be grown on other lands, possibly causing deforestation in other areas (see point c).

b) In permanent grasslands, the soil and the belowground biomass carbon stocks can be much higher than in croplands. Therefore, a few years are needed to recover the initial carbon loss (5-10 years). Depending on the initial carbon loss and the productivity of the new tree plantation, the carbon balance could be positive even during the first rotation period (e.g. conversion of degraded grassland) or it could be initially negative and then turn positive. In most of the cases, the biomass extracted to produce bioenergy will have an atmospheric benefit since the beginning ($CN \geq 0$)[10] and will become carbon neutral in a few decades ($CN \geq 1$).

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[10] An atmospheric benefit occurs as soon as the *CN* is greater than zero. When the biomass reaches, for example, a *CN* of 0.8, replaced fossil fuel emissions will be reduced by 80 percent. Full carbon neutrality – i.e., the condition where no emissions can be attributed to combustion of biomass, is not achieved until the *CN* reaches 1.

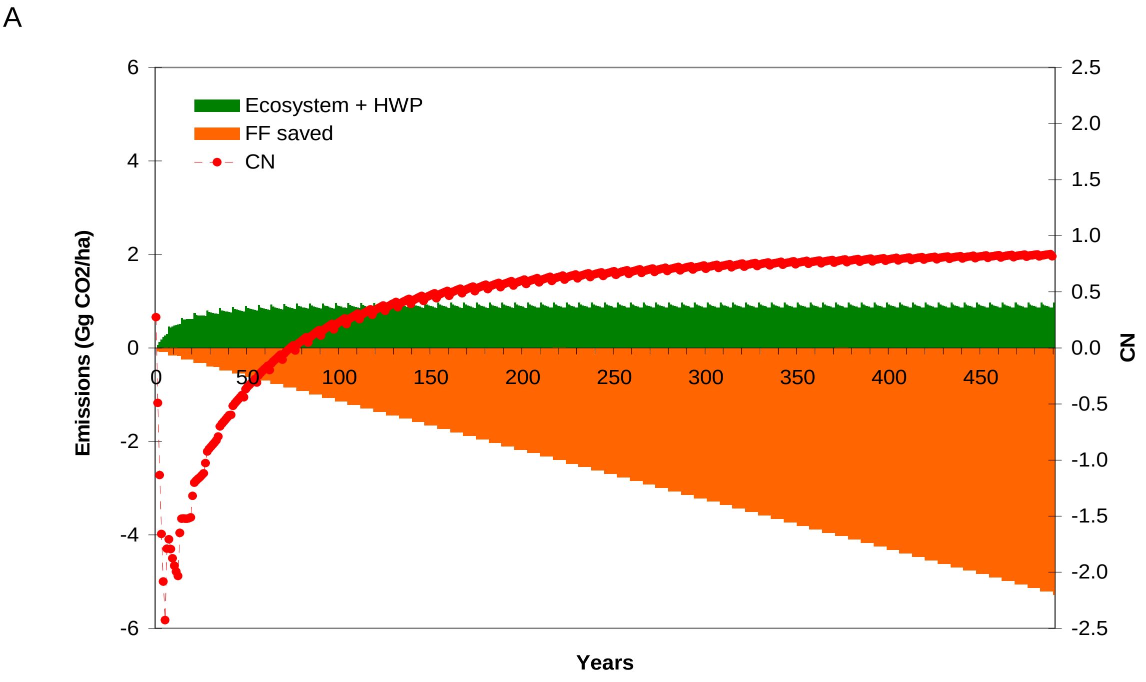
Different results could be linked to the conversion of grasslands with high carbon stocks.

c) If a forest area is clear cut to be replaced by a tree plantation used for bioenergy, an initial carbon loss equal to the forest biomass should be accounted for. The bioenergy produced from the clear cut forest and the new plantation has a GHG benefit only after that the carbon stock change is fully compensated by the same amount of avoided emissions in replaced fossil fuels. The changes in the litter and soil pools should also be added to the overall balance. In Schlamadinger and Marland (1996), the carbon loss from the conversion of 1 hectare of mature forest to short-rotation forestry (SRF) is compensated after 40 years, when natural gas is substituted. The example considers an initial forest C stock of 160 tC ha^{-1} and a new rotation period of 7 years in the SRF. Fossil fuels substituted by bioenergy and fossil fuels saved by substituting energy intensive materials with wood products are included to assess the compensation period. If only the fossil fuels substituted by bioenergy are accounted, the losses are compensated after 45 years, i.e. $CN \geq 0$ after 45 years. The paper adopts a simplified approach to calculate the carbon losses in soil (including roots) and litter. A constant decrease of soil and litter C pools for a certain time period is assumed.

   A similar case study has been developed here, using the GORCAM model, to include simple equations to simulate decomposition in litter and soil and the change of root biomass. As in Schlamadinger and Marland, the initial aboveground C stock of 160 tC ha^{-1} is harvested and used for long-lived and short-lived wood products (30% and 25% respectively) and for bioenergy (22%). The wood extracted every 7 years from the new short rotation forest is all used for bioenergy (80% of aboveground biomass). The improved simulation of the carbon stock changes in the soil, litter and roots, significantly changes the results presented in Schlamadinger and Marland (Figure 10). The bioenergy extracted from 1 ha of short rotation forest compensates the carbon losses due to the land use change after 70 years when natural gas is substituted (Figure 10A). Therefore, after 70 years, the bioenergy starts to produce an atmospheric benefit ($CN \geq 0$). When a rotation forest system is considered (each year a patch of forest is cut to provide a constant supply of bioenergy), the *CN* factor is negative for almost 80 years (Figure 10B).

   The results are strongly influenced by the assumptions made. When the conversion affects a forest with higher carbon stock, the period needed to compensate the land use change emissions is longer. For instance, if a mature forest of 275 tC ha^{-1} is cut and replaced by a SRF, the period of compensation is 170 years. Similarly, if the new plantation has a longer rotation period of 60 years, 150-200 years are needed to offset the initial C loss, depending if the wood from the plantation is all used for bioenergy (150 years) or if part of it is used for wood products (200 years).

In the Renewable Energy Directive, the sustainability criteria state that raw materials used for biofuels cannot be obtained from areas that were converted from land with high carbon stocks (forests, wetlands) or with high biodiversity values (highly biodiverse grasslands, primary forests). In addition, the land use change emissions are accounted for, when assessing the GHG emission performance of biofuels compared to fossil fuel.



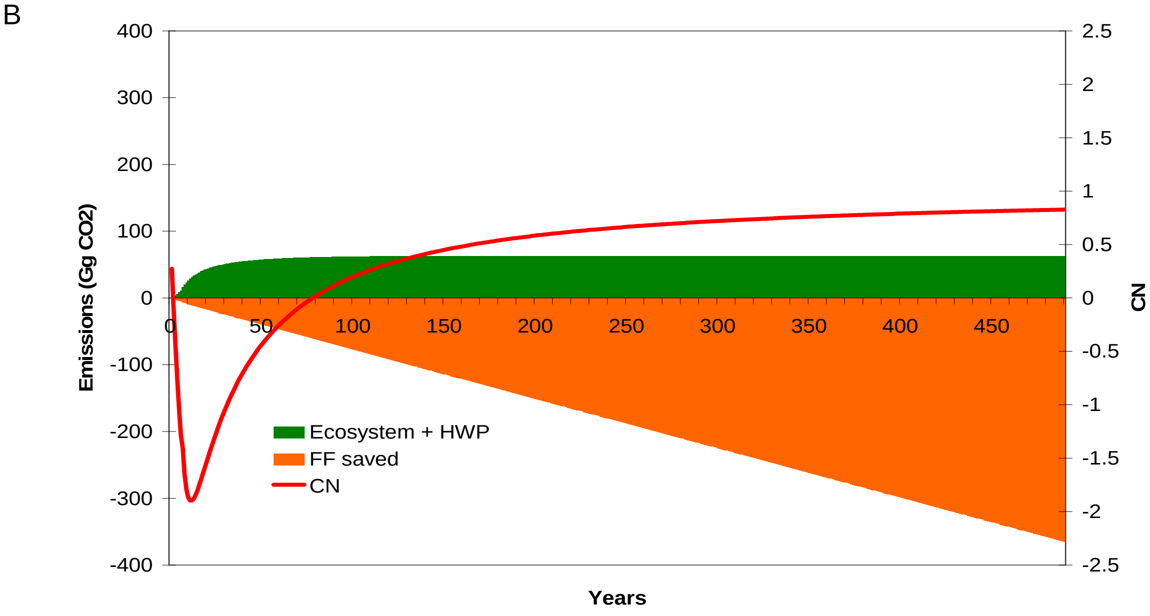


Figure 10 Cumulative CO$_2$ emissions when a mature forest is converted to a short-rotation forest on a 7 year rotation period (Ecosystem + HWP). The plantation follows harvest of a mature forest of 160 MgC ha·'. The wood from the initial harvest of the mature forest is used for wood products (HWP, 55%) and bioenergy (22%). Cumulative emissions are shown and compared to the saved emissions in the substituted fossil fuel (FF saved). The substituted fossil fuel is natural gas. The *CN* factor shows when the emissions due to land use change are compensated by the saved fossil fuel emissions (*CN*≥0). When *CN*>0, the bioenergy produces a net GHG benefit in the atmosphere. In diagram A, only 1 ha of forest is converted. Diagram B describes the conversion of 70 ha of forest to short-rotation plantation, when 10 ha are harvested each year.

In principle, if similar criteria would be applied to woody biomass, the land-use change emissions described above could be taken into account. Therefore, biomass that comes from areas converted from forests (or other lands) with high C stock would be discouraged or forbidden. However, in practice, not all the conversions can be classified as land-use changes because of the definitions adopted under the climate policy agreements. For instance, a SRF or a palm plantation usually complies with the definition of forest under the KP. Therefore, no land-use change may have to be reported when it replaces a forest with higher carbon stock if similar definitions would be applied under the Directive. This kind of problem could be solved by including management changes in the equation.

4.1.4 Summary of the mitigation effect of different sources of wood bioenergy

The previous sections explained that different sources of biomass for bioenergy can have very different climate change mitigation potentials according to the time horizon that is considered. Table 5 summarizes the *CN* factors of the previously illustrated examples for different time horizons. There is forest biomass that can produce a GHG benefit in the atmosphere from the beginning of its use but it is not carbon neutral (forest residues or wood from new plantations on lands with low carbon stocks previous to conversion). Other sources of woody biomass will require a long time before producing a GHG benefit in the atmosphere (additional fellings or new plantations in areas converted from high C stock ecosystems). Some other sources can be carbon neutral from their initiation (new plantations in areas converted from abandoned cropland that do not produce indirect land-use change).

Table 5 *CN* factors calculated in this study for different source of wood biomass on different time horizons, when biomass substitutes coal. When biomass substitutes oil the *CN* must be reduced by 0.2 and by 0.4 when it substitutes natural gas. The reported figures assume that no indirect land-use change occurs.

Source of biomass	*CN*			
	20 years	50 years	300 years	Notes
Forest residues (constant annual extraction)	0.6	0.7	0.9	Always positive, but not C neutral
Additional thinnings	<0	<0	0.2	Atmospheric benefit after 200-300 years
New forests:				
- conversion from cropland	≥1	>1	>1	C neutral
- conversion from grassland[a]	>0 to ≤1	≥1	≥1	Positive in the short-term, becomes C neutral in 1-2 decades
- conversion from managed forest to SRC	<0	<0	0.7	Atmospheric benefit after 70 years
- conversion from mature forest to SRC	<0	<0	0.4	Atmospheric benefit after 170 years
- conversion from managed forest to a 60 year rotation plantation	<0	<0	0.3-0.7	Atmospheric benefit after 150-200 years

[a] The conversion of natural grasslands with high C stock in soil and biomass can produce more emissions and reduce the mitigation potential of the bioenergy produced after conversion.

The illustrated examples are based on various assumptions and the values of *CN* can change as assumptions change. For instance, the biomass from areas converted from a forest to a bioenergy plantation can have a worse carbon balance and therefore a lower *CN* if the initial carbon stock is higher than the assumed 160 tC ha^{-1}, as in natural or mature forests. The calculated *CN* factors are not representative for all the woody biomass feedstocks that are planned to be used to meet the renewable energy targets of the EU. A more in-depth analysis that would consider average assumptions representative for the different feedstocks should be implemented. However, this study shows that some of the feedstocks included in the RES deployment projections should not enjoy a zero emission status in the accounting systems. In the short-medium term, wood material as forest residues could have a mitigation potential that need to be discounted by 30-40%, when only carbon stock changes are considered (41% of the bioenergy potential assessed by EEA). Additional fellings from existing forests could even produce more emissions than fossil fuels (59% of the bioenergy potential assessed by EEA).

In addition, results would be improved by including the positive effect that increased fellings can have on forest growth rates and on reducing natural mortality rates. The extent to which carbon stock changes could be counteracted by combined management strategies as forest conservation or afforestation should also be assessed.

The reported figures do not take into account the emissions in the production chain and their effect on the overall mitigation potential of bioenergy. The inclusion of production chain emissions would produce a further decrease of the emissions reductions attributable to bioenergy.

The study also does not take into account the impact of the change in surface albedo on climate change. The albedo of a surface is the extent to which it reflects light from the sun. Depending on its colour and brightness, a change in land surface can have a positive (cooling) or negative (warming) effect on climate change. Planting coniferous trees as a climate mitigation measure has been questioned in areas with snow since the darkening of the surface (decrease in albedo) may contribute to warming. Sequestration due to forest growth and albedo changes may compensate each other, tending towards a slight warming effect over the very long term (250 years) (Schwaiger and Bird 2010). Therefore the albedo effect might contribute to worsen the bioenergy climate change mitigation potential when the wood feedstock would come from new planted forests.

5 Policy Options to Address Current Accounting Gaps

A number of approaches currently under discussion in UNFCCC fora, the EU, and among concerned stakeholders and experts could address the spatial or temporal gaps identified in the previous chapters.

The previous sections have suggested that there are two major gaps in current accounting of GHG emissions due to the use of bioenergy. The first, discussed in Section 2, is a gap in spatial coverage. This gap resulted from adoption of an Inventory methodology designed for a system in which all nations report into systems in which only a small number of countries have emission obligations, i.e., the KP and the EU-ETS. The second is a failure to differentiate between a system in which very long time horizons are relevant – efforts to mitigate climate change over the long term – and systems concerned with shorter-term horizons such as the EU 2020 and 2050 targets. Since the KP adopted the UNFCCC Inventory Guidelines without considering these differences, current accounting systems' difficulties in addressing the time-dependency of biomass' carbon neutrality can also be traced to this decision.

Approaches currently under discussion that could address the spatial or temporal gaps, at least to a limited extent, include the following:

1. **More inclusive accounting of emissions from the land-use sector**
2. **Value Chain Approaches, including use of sustainability criteria**
3. **Point-of-use accounting**

The following sections briefly describe and evaluate each of these. While all of them are primarily intended to address problems that have emerged due to the difference in spatial boundaries, point-of-use accounting can address the time delay between use of biomass for energy and regrowth. Both value-chain and point-of-use accounting hold end-users responsible for emissions. Since the time horizon over which emissions due to land-use and management changes should be calculated is open to debate, *CN* factors offer an attractive avenue to address the time-variance of carbon neutrality with respect to targets. Adoption of *CN* factors in both the EU-ETS and the renewable energy Directive would result in market demand matching the true GHG profile of biomass used.

In the following review of options to address accounting gaps global accounting of land-use emissions is not included as it is not considered to be a realistic option within time frames of interest to current EU policy. Further, the discussion of sustainability criteria is confined to sustainability from the perspective of GHG emissions. Criteria and issues relevant to, e.g., sustainability of water supply or biodiversity are not considered.

5.1 Account for a wider range of land-sector emissions

Inclusion of a larger portion of the earth's land base in accounting system can reduce the areal gap identified in Section 2. However, short of full global inclusion, these approaches can only make limited contributions.

Two major avenues for fuller accounting of land-sector emissions have been under consideration in UNFCCC fora.

1. Increase the types of activities whose emissions must be accounted

2. Adopt a mechanism to support REDD+

These two mechanisms are appropriate for Annex-I (or countries adopting GHG obligations that include the land sector) and non Annex-I countries, respectively.

A third option is also reviewed:

3. Replace the current activity-based approach with unified carbon accounting (referred to in some papers as land-based accounting).

This approach is included due to the significant simplifications it would bring to accounting for land-sector emissions, the current openness of the climate agreement process, and its compatibility with atmospheric accounting approaches.

5.1.1 Widen mandatory accounting of land-sector activities

Widening the land-sector emissions that must be reported by Annex-I countries would be a useful step but would have only a limited impact.

Under the current KP, Annex-I countries are only obligated to include net emissions due to afforestation, reforestation and deforestation (ARD). They may also opt-in, on a voluntary basis, to include activities named in Article 3.4, e.g., emission reductions due to management of forests, croplands and grasslands. Widening the number of activities whose emissions must be counted would be a straightforward extension of the current regime. A first step might be to render Article 3.4 mandatory as has been proposed in meetings taking place within the UNFCCC process (UNFCCC 2008a). Stakeholders have also called for inclusion of wetland management.

From the perspective of biomass-for-energy, mandatory accounting of emissions due to forest, wetlands, and peatlands management would be the important additions and would close the primary gaps in areal coverage of land-sector emissions within the EU. However, the approach involves a continual series of agreements on which activities should become mandatory. For instance, currently inclusion of emissions from wetlands faces resistance, partly due to the comparative uncertainty in measurements. Consequently while agreement on mandatory inclusion of forest management might be reached in upcoming negotiations, each new activity requires new negotiations.

If bioenergy continues to enjoy the ‘zero emissions’ accounting procedure under the KP and EU-ETS, extension of the activities whose emissions must be reported would have the advantage that carbon-stock draw-downs attendant on dedication of biomass to energy would be reported. This would result in an accounting system more consistent with the emissions actually entering the atmosphere. However, this step would only address the gap in the EU – or in other Annex-I nations participating in an extension of the KP. It would not address the much larger areal gap that is the primary concern of Searchinger et al. (2009) and other stakeholders in the biofuels community. This larger gap results from the lack of GHG emission obligations in non-Annex-I countries where the vast majority of land-sector emissions originate[11]. A step towards addressing this gap may be taken with the adoption of REDD+.

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[11] As of 2008 approximately 1.2 billion tonnes (1.2 Pg) of carbon, or 12 percent of total CO_2 emissions were due to land use change. Brasil and Indonesia alone accounted for 0.9 million tonnes of these emissions (http://www.globalcarbonproject.org/carbonbudget).

5.1.2 REDD+ (Reduced Emissions from Deforestation, Degradation, and other activities)

Although REDD+ has garnered significant support and engendered considerable enthusiasm, its contribution to closing the accounting gap is likely to be limited to the reduction in biomass-for-energy demand it causes through price increases.

REDD+ is considered to be one of the few 'winners' from the recent COP-15 in Copenhagen (www.globalcanopy.org). Under the Copenhagen Agreement, Annex-I countries committed themselves to provide additional, predictable and adequate funding to developing countries, specifically mentioning REDD+ as an action to receive support (UNFCCC 2009). COP 11 in Montreal initiated a process to consider whether emissions from deforestation (RED) could be addressed within the KP. Initially focused on deforestation, in fall of 2008 a meeting of experts concluded that it would also be possible to include avoided degradation in a mechanism (UNFCCC 2008b), thus leading to the acronym REDD. As demonstrated by the text of the Copenhagen Accord (UNFCCC 2009) further stakeholder pressure, including by the United States, has led to expanding the mechanism to include forest conservation, the third activity generally understood to be designated by REDD+.

While REDD+ will encourage emission reduction efforts and lead to more robust estimates of land-sector emissions in non-Annex-I countries, its potential to reduce the accounting gap identified in section 2.1 is limited. Limitations stem from (1) the design of the mechanism itself, (2) from the unlikelihood that all developing countries will adopt or reach REDD+ targets, and (3) due to emission sources not included in the mechanism. From the point of view of bioenergy, it is also important to recognize that REDD+ will (4) directly compete with meeting bioenergy targets. REDD+ will raise both land costs and the cost of removing biomass from forests.

Looking at the first issue, the accounting gap could only be reduced to the extent that REDD+ play a role in accounting systems of nations having GHG emission obligations. That is, the carbon stock changes will have to enter into a system in which emissions are tallied. The most likely avenue for this is through issuance of credits for REDD+ achievements, credits that are then used by nations with GHG emission obligations to assist these. Such credits, even if issued and used, will only offer a 'soft' attempt to close the gap. Credits will almost certainly be based on reductions relative to a national baseline. Thus, REDD+ will, at best, only provide information about the difference between carbon stock changes at a national level under REDD+ and changes under a presumed business-as-usual case or historic emissions. There is no obvious way in which this information could be used to balance, or assess the degree of balance between, bioenergy emissions in Annex-I nations and carbon stock changes in developing countries.

Turning to issue (2), it is unlikely that REDD+ will be adopted across the globe. Consequently, international leakage will be a problem. Adoption of REDD+ in some nations can, and very likely would, be accompanied by increased deforestation and degradation, and decreased forest conservation in other nations. To the extent that this occurs, REDD+ would only address the gap in areal coverage to the extent that it lowers demand by raising prices. Since, however, both the United States and Europe drive bioenergy energy demand through mandates, it is more likely that land conversion will simply move around the globe and the cost of meeting biofuel or bioenergy mandates will increase. These mandates, in turn, will raise costs of REDD+ by increasing the opportunity costs of all lands with potential to produce biomass for energy.

Restricting imports of biomass-for-energy to nations that have adopted and achieved REDD+ goals is unlikely to reduce the leakage problem. Even if all major importing nations including, e.g., China, took part in such a ban – unlikely in itself – a ban would only lead to biomass-for-energy coming from 'REDD+' countries but increasing amounts of food, feed, and fiber would come from (with attendant land use changes) from non-REDD+ nations where land prices remain lower. The legality of such a ban under WTO regulations would, in any case, need to be established.

REDD+ will, as mentioned in (4), inevitably increase land prices (as well as costs of biomass extracted from forests). This is a direct result of money flowing into forest conservation, making conversion of forest land more expensive. Since land for food and feed often comes from conversion of forestlands, REDD+ will compete directly with meeting these, increasing, demands as well as with meeting bioenergy demand. The more successful REDD+ is, the more it will raise costs of these products. Similarly, the more countries adopt bioenergy goals or mandates, and the higher these are, the more expensive REDD+ itself will become.

If sufficient money flows into REDD+, the consequent food cost increases due to restrictions in conversion of forest land to agricultural land could render the cost increases attributed to U.S. ethanol mandates trivial in comparison. However, and particularly as land and food costs rise, nations are likely either to refuse to adopt REDD+ or will simply fail to achieve the targets unless these are set sufficiently low to accommodate rising food, feed, fiber and bioenergy demand. If set at such low levels, the targets will be meaningless. Thus, at best, REDD+ will dampen demand or supply of biomass-for-energy from developing countries. However, this dampening will most likely be due to rising prices.

Turning finally to (3), as currently understood, REDD+ falls well short of bringing the full range of land sector emissions into climate agreements. Key activities that are not covered include activities that cause emissions (or emission reductions) in wetlands, peatlands, and agricultural lands. Emissions from peatlands in non-Annex-I countries are a particular source of concern. Emissions from peatlands drained to grow palm trees or other crops are particularly high. A study by peatland expert Hans Joosten, for example, concluded that 580 million tonnes CO_2 were emitted from drained peatlands in Southeast Asia (Joosten 2009)[12]. Emissions from peatland drainage occur for decades to centuries once inaugurated. Consequently, this is another instance where taking account of emissions due carbon losses from lands remaining in a current use would be critical.

5.1.3 Unified Carbon Stock Accounting (UCSA)

Under unified carbon stock accounting, land-sector emissions would be estimated across all managed lands without restriction to specified activities. While having considerable advantages over the current approach, if only applied in Annex-I countries it will suffer the same major limitation as widening mandatory activities.

Currently, as mentioned in subsection 5.1.1, emissions from the land-use sector are calculated only insofar as they are linked to specific activities which cause them. This

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[12] Total CO_2 emissions in 2008 were 31.9 billion tonnes.

activity-based approach was, to a large extent, the result of the late acceptance of land use in the KP. The decision to allow reductions in emissions from land use to contribute to targets was made after targets had been set based only on emissions from other sectors. Due to the widely differing contributions that nations could expect from their land bases, it was agreed that only emissions and removals due to specified human activities were to be included. As a result, unlike all other emissions sources, the land sector is not listed as a Sector/Source in Annex A of the KP.

An alternative to the current activity-based accounting system would be to estimate, and include in accounting, all stock changes on managed lands without regard to the activity resulting in the emissions. Under this approach, carbon stock changes would be treated in the same manner regardless of whether they result from a land use or a management change. In effect, Articles 3.3 and 3.4 of the KP would be removed and the land sector would become a sector source as is the case for all other emission sources (UNFCCC 2008b). This approach is referred to hereafter as unified carbon stock accounting.

There is currently wide resistance to unified carbon stock accounting. However, it has a number of important advantages that, in the long run, might outweigh current resistance. From a bioenergy perspective, the most important advantage is that it would automatically, with one agreement, close the areal gaps in Annex-I countries. Other advantages include its relative simplicity and its high compatibility with atmospheric accounting (see section 5.3). Resistance seems to be grounded in the understandable reluctance to change from the current system as well as in the difficulties in, or rather range of uncertainties among, making estimates of emissions from the full use of land management and change options. That is, there is, for example, considerably greater ability to measure emissions due to deforestation than to do so for emissions due to draining wetlands or re-wetting them or to some agricultural land management changes.

UCSA simplifies accounting of land-sector emissions in a variety of ways. First it removes the need to define what constitutes specified human-induced activities such as deforestation or reforestation. Similarly it removes the need to define land categories such as forest land or wetland. All of these definitions have proved difficult and have led to the anomaly that what qualifies as deforestation in one nation does not qualify in another. Since IPCC Inventory guidelines are designed to provide for complete accounting of carbon stock changes across managed lands, the approach could be applied both in Annex-I and in developing countries. Further, a UCSA approach would provide an incentive to improve estimates of emissions from a range of sources in both Annex-I and developing countries.

UCSA would resolve the accounting gap attendant on the activity-based approach in Annex-I countries insofar as biomass originates in Annex-I countries. Emissions due to extraction of biomass can come from a very large array of activities, including activities that occur on lands remaining in the same use, and activities whose emissions are not currently included in Annex-I country accounting even within Article 3.4, e.g., peatland management. Under UCSA, emissions from all managed lands would enter the accounting system, and any land from which biomass were removed for bioenergy would automatically qualify as managed land. Thus, as long as the biomass originated in Annex-I countries, the reductions in carbon stocks would appear in accounts in the same time frame (actually before) the emissions due to their combustion. In fact, one way to tackle the gap caused by the current assignment of zero emissions to combustion of biomass is to combine UCSA in Annex-I countries with *CN* factors for biomass originating in nations not having GHG emission obligations (see section 5.3.3).

5.2 Value-chain accounting

Under value-chain approaches impacts along the entire series of steps - resource extraction or cultivation, transportation, and conversion to a final product – are taken into consideration. In the context of climate mitigation, only GHG emissions along this value chain are relevant. The EU RES Directive's requirements for biofuel are an example of a value-chain approach.

The increasing use of biofuels by Annex-I countries has, in particular, raised questions regarding of responsibility for impacts along biofuel value chains. Impacts due to land-use and management changes, including impacts on food prices, tropical forests, and GHG emissions have been of particular concern. Increased food prices in a range of developing countries in 2007 caused food riots which were attributed in part to dedication of U.S. corn to ethanol (www.environmentalgraffiti.com/business). Commodity price increases, or the reduced availability of U.S. soy due to switching from soy to corn production, were also believed to have triggered increases in land used to produce soybeans in Brazil. Production of oils for biodiesel to meet EU demand has also led to concerns. Oils often originate from drained peatlands in Southeast Asia. In this case concern stems from the very high emissions. Peatland contain up to 1,450 tonnes of soil carbon per hectare (Biello 2009),[13] carbon that is oxidized when the soils are drained. Questions about the advantage, from a GHG perspective, of ethanol from biomass other than sugar cane, have resulted in pressure to include consideration of GHG emissions that occur during conversion of biomass to fuel.

Stakeholder discussions have, as a result of these concerns, sought for ways to hold Annex-I country users of biofuels responsible for a range of impacts. As evidenced by the EU Renewable Energy Directive (D on RES) prohibitions on sourcing biomass from areas with high biodiversity, in addition to GHG emissions, stakeholders have, non-GHG concerns regarding impacts at the first step of the biofuel production chain – production or extraction of the biomass. However, as far as climate is concerned, only GHG impacts are relevant, i.e. the GHG emissions resulting from production, transport, and conversion of biomass. Holding users responsible for such 'value-chain' emissions can be referred to as end-user responsibility for embodied emissions.

End-user responsibility for embodied emissions represents a significantly different approach than the one taken in the UNFCCC Guidelines and KP. As mentioned in Section 2, under these reporting and accounting systems a nation is only responsible for emissions occurring within its borders, not for emissions embodied in imports. However, as shown by Figure 1, this approach fails to hold Annex-I nations responsible for their balance-of-trade in GHG emissions. Thus, an end-user approach potentially has application far beyond biofuels.

A system in which end-uses were responsible for emissions embodied in products might have considerable advantages. The production pathways – i.e. resource extraction or cultivation, processing, and transportation paths – with the lowest overall emissions would have an advantage in the global market and would presumably gain market share. Importing countries with GHG obligations would have a 'built-in' incentive to purchase goods with low GHG-profiles. The power of purchasers to alter production practices has been demonstrated in the forest sector. Sustainable forestry initiatives operate primarily

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[13] Some old growth forests on wetlands in the tropics and U.S. and Canadian Pacific Northwest have, for purposes of comparison some 500 to 700 tonnes per hectare.

through convincing purchasers to only buy wood certified as coming from sustainably managed forests, and some 90 percent of industrial forest land in the United States is now certified under the Sustainable Forestry Initiative (Richards et al. 2006). Placing responsibility for efficient or low-GHG production processes on the purchasers might prove an effective approach.

In spite of attractive features, there has been insufficient discussion of consumer-responsibility approaches in climate change discussions to enable a more in-depth evaluation of their pros and cons. The only products for which consumer-responsibility is currently required are bioenergy products. As yet these discussions are not occurring in the context of international climate agreements but only in the context of instruments such as the D on RES and a possible U.S. cap.

5.2.1 The EU Renewable Energy Directive (D on RES)

The Renewable Energy Directive's (D on RES) specifications regarding biofuels represent a value-chain approach. EU distributors of transportation fuels serve as the point for determining compliance with Directive specifications which prohibit use of lots that do not meet the specifications.

The Directive sets criteria with which biofuels must comply to satisfy national RES obligations. The criteria consist of a mix of prohibitions on origin of the biomass and GHG-emissions ratings which biofuels must satisfy to be eligible for use. The GHG-emission ratings include emissions throughout the value chain and entities importing and distributing biofuels are responsible for ensuring that the biofuels comply with the specifications. This is thus a system that places responsibility for emissions on the country using the product, not on the country where the emissions occur. The use of prohibitions within the D on RES – including the prohibitions on biomass origin and the specification of minimum GHG emissions – distinguishes it from value-chain approaches that simply hold end-users responsible for the emissions. Approaches that, by rendering end-users responsible, increase the price of products with high-embodied GHG emissions, but do not impose restriction on them may be more acceptable under WTO regulations. See sections 5.3.2 and 5.3.3 for further discussion of such approaches.

To be eligible for compliance with the D on RES, a biofuel consignment's GHG profile must be calculated. Emissions due to cultivation of biomass, direct land-use change, conversion to a fuel, and transportation must be included. No attempt is made to include emissions due to indirect land use change at this time. Only biofuels whose GHG emission profile is at least 35% (current) to 50-60% (2017-2018) lower than the fossil fuels they replace can be used. Emissions from direct land use change must be annualized over 20 years. This is a sufficiently short time frame so that biomass grown on land converted from forests, wetlands or recently drained peatlands would generally fail to meet the criteria as long as actual emissions are used.[14] However, this method of calculating GHG emissions does not address the problem of emissions from extraction of biomass where lands remain in the same land use. In particular, the formula does not address emissions due to increased extraction of wood from forests already used for wood supply. As shown in Section 4, the 'value' of such biomass from the perspective of its contribution to reductions in GHG emissions within the time frame relevant to the

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[14] Thus from a GHG perspective, the prohibitions on biofuels whose biomass originates from such lands, are most likely redundant with the time stipulations in the GHG emission calculation.

RES, e.g., the 2020 targets can vary greatly. Use of wood for energy from forests already in use is more likely to occur in the case of use of biomass for heat and power than for biomass for biofuels, at least in the near- to medium-term. Consequently, the formula would need to be expanded to cover emissions from lands remaining in the same use if it were to be applied more generally.

While GHG emission reductions are only one goal of the D on RES, this paper has shown that there are significant differences, from a GHG perspective, between use of forest residues, short-rotation plantations and increased harvests from forests typical of Europe. Some sources of wood, particularly increased harvests in European forests – or forests with similar growth rates – might make no significant contribution to reducing GHG emissions within the time frame of the RES targets. Thus, to the extent that GHG emissions are a concern for the EU, calculations of the GHG profiles of biomass-used-for-energy should reflect these differences. Particularly if guidelines are prepared covering use of biomass for energy more generally, i.e., for bioenergy pathways other than biofuels, inclusion of emissions from land remaining in the same use would be an important addition to the current approach. In effect, there is no justification, from a GHG perspective, of distinguishing between carbon losses, or emissions, that occur due to land use or land management changes.

5.2.2 Sustainability Criteria

One of the goals of the D on RES criteria for biofuels is to ensure the sustainability of biomass production. While theoretically attractive, application of sustainability criteria can run into hurdles due to information requirements and difficulty agreeing on specifics.

The RES applies specifications intended to insure sustainability to specific ‘lots’ to fuel. It is thus a ‘project-level’ approach. However, it is also possible to apply sustainability criteria at the national level. Both of these options are reviewed below.

GHG sustainability in the case of biomass is, essentially, a question of maintenance of carbon stocks. Except for biomass converted to extremely recalcitrant forms (e.g., fossil fuels or recalcitrant soil carbon), biomass oxidizes sooner or later, regardless of whether humans intervene or not. Thus, maintenance of carbon stocks entails sufficient biomass growth, over some time period and spatial area, to ‘make up for’ biomass oxidized. Requirements for biofuels to meet sustainability criteria consequently represent imposing responsibility for regrowth of biomass, e.g. for what occurs at the first step in a biofuel’s value chain – its cultivation.

It is important to note that the GHG sustainability of biomass is not the same as its *CN*. *CN* is determined in relation to a business-as-usual carbon stock scenario and represents the extent to which fossil fuel emissions are ‘neutralized’[15] through use of biomass. Particularly in the case of woody materials, biomass can be used in various energy pathways, substituting for fossil fuels with different emission profiles. In these cases, not only the time required for regrowth – including replacement of soil carbon losses – but also the fuel for which the biomass is substituted plays a role in its effectiveness in reducing GHG emissions. Moreover, as explained in Section 4, *CN* depends largely on time horizons. Woody biomass shipments that meet GHG

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[15] Neutralized is here used to express the concept that fossil fuel emissions are balanced by removals of CO_2 from the atmosphere, e.g., by increases in carbon stocks.

sustainability and *CN* criteria for a 2050 target might not meet similar criteria for a 2020 target. Thus, even if criteria can be employed that ensure sustainability, they will fail to ensure carbon neutrality.

Determining whether or not carbon stocks have been maintained depends, as mentioned, on the spatial and time boundaries selected. Globally, as has been the case at least since 1860 (Schlamadinger and Marland 2000), there is a net loss of terrestrial carbon stocks. While this loss is among the drivers for stakeholder interest in adoption of sustainability criteria, sustainability criteria that are being proposed do not operate at the global level. The two primary 'areal' boundaries most often proposed are project-level or national-level. Each of these has pros and cons.

Project-level Criteria

Requiring sustainability at the project level is attractive from the perspective of an individual entity in the business of producing and selling biomass for energy. Such an entity can usually ensure that, within the areas over which it has control or from which it is extracting carbon stocks, regrowth, over some time period, equals extraction. There are two problems with this approach: the difficulty of establishing what will qualify as sustainable and the problem of leakage.

A very large range of plants that can be used for energy can grow under many soil, climate, and management regimes. This could render impractical establishment and verification of numerical values, such as time for regrowth – including replacement of soil carbon oxidized – which would reflect the GHG sustainability of individual biomass shipments. Possibly due to partly the difficulties of numerical approaches, 'best practice' guidelines have been suggested for determining sustainability. Such guidelines, while often including quantitative elements, e.g., rates of fertilizer application or slope angle above which erosion control measures are required, only provides 'qualitative' assessments of sustainability. A best practice approach is attractive on a number of grounds, including that it forms the basis of both EU and U.S. agricultural policy. However, selection of best practices requires considerable knowledge of local conditions. Knowledge would be needed not only in regard to practices governing production of wood and crops but also in regard to removal of residues, an area in which very little reliable data is yet available even in Annex-I countries. A best-practice approach also requires regular monitoring to ensure that the practices are being employed. However, within a system in which information is required for each lot of biomass, such monitoring is likely to take place in a more systematic way than under EU cross-compliance where less than 5 percent of farmers are checked annually (Farmer et al. 2007).

Although best-practice approaches are not yet part of the KP, REDD+ discussions have highlighted the need to address underlying causes of deforestation and degradation (UNFCCC 2006b). Addressing such causes is likely to require policy changes or national measures, i.e. Policy & Measures (P&M) approaches. While best practices can be required at the project level, they also would fit well within national-level approaches including P&M, sectoral approaches, and NAMAs. All of these are under discussion and evaluation for inclusion in international climate agreements.

National-level criteria

National-level approaches have the primary advantage of being able to address the problem of leakage within a nation[16]. Criteria that would insure sustainable growth in a given project area – i.e. criteria applied at the project level – do not guarantee that carbon stocks will not be drawn down elsewhere. This problem – particularly in the case of forests where conservation in one area tends to lead to harvesting elsewhere – was a factor in not accepting avoided deforestation as eligible for crediting under the Clean Development Mechanism (CDM). The CDM is a project-level approach and acceptance of a national-level approach was an important element in building support for a mechanism to address emissions from deforestation in the KP.

Leakage is equally relevant where woody biomass that would have been used for some other purpose is to be used for bioenergy. Under these circumstances, the current RES criteria will not prevent leakage. The criteria in place – those that prevent biomass-for-energy from originating in primary forests or from conversion of forests, wetlands, or peatlands – are likely to simply shift the purposes for which lands are converted. Forests that would have been converted to produce biomass for energy can, instead, be converted to agricultural land to provide food and feed. Imposing sustainability criteria at the project level can not address this problem. Thus, a national-level approach to sustainable criteria for biomass-for-energy may also be appropriate.

Measuring sustainability at the national level is attractive both from the perspective of addressing domestic leakage[17] and from the perspective of an importing country. An importing nation would only need to know the national situation in order to assign a *CN* factor to imports. This would be equivalent, for example, to use of national averages to determine the GHG emissions of imported electricity or to determine the improvement over current emission rates represented by a new power generation station. However, as suggested above, land-uses are interchangeable and biomass-for energy is only one source of reductions in carbon stocks. In fact, in many developing nations the vast majority of carbon stock draw-down is to obtain land to meet internal food security or food export goals. Such draw-down is occurring on a considerable scale.

In the past decade, globally the area harvested for crops increased by some 70 million hectares while forest and pastureland decreased by over 100 million hectares (http://faostat.fao.org; http://www.fpl.fs.fed.us/documnts/pdf2000/young00a.pdf). Over the past decade world population increased by some 770 million and caloric intake per person is rising at some 0.35 percent per year. Demand for timber products has also increased in step with increasing population (http://faostat.fao.org.). It is thus reasonable to conclude that land use changes, and the resultant carbon stock reductions in many developing countries, are primarily a result of these drivers, not biofuel demand. Under these conditions, it can be questioned whether use of a national factor representing the carbon stock balance of a country to determine whether biomass-for-energy qualifies as sustainable is appropriate. The contribution of bioenergy demand to carbon stock reductions may be minor compared to other demands affecting land use. If the biomass for bioenergy comes from short rotation plantations established on lands that would not be used for agriculture it would in fact be contributing to carbon-stock increases.

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[16] A mechanism that addresses leakage within a nation is currently considered adequate because under the KP Annex-I nations are only held accountable for emissions within their borders.

[17] Since currently GHG emission obligations are confined to those occurring within national boundaries, proposed requirements to account for leakage are also confined to national boundaries.

5.3 Point-of-use Accounting (PoU)

Under point-of-use accounting, emissions due to combustion of biomass would be assigned a non-zero multiplier (i.e., emission factor). Under conditions where not all nations cap emissions in all sectors, point-of-use accounting is likely to provide better incentives and dis-incentives than other systems.

Just as inclusion of land use as a Sector/Source, i.e., UCSA, would bring the land-use sector into accord with how all other sectors are treated, assigning emissions from combustion of biomass their full CO_2 value when determining target compliance would bring emissions from use of biomass-for-energy into line with other energy-sector emission sources. In the form usually proposed, combustion of biomass would result in emissions based on an emission factor close to that of lignite coal, e.g. 2.47 kg CO_2 toe^{-1} (Hong and Slatick 1994). The resulting emissions would be counted in a GHG target in the same manner as emissions from combustion of coal, petroleum products, natural gas, and waste materials. After reviewing this approach, two alternative ways to calculate emission factors at point-of-use are reviewed: calculating net value-chain emissions not covered by caps and use of *CN* factors. While not currently being discussed in climate negotiations, the attention to problems that have arisen due to the 'zero emission' approach raised by recent papers, e.g., Searching et al. 2009 and DeCicco 2009, is likely to reopen the question of whether the 'zero' emission factor assigned to biomass approach should be abandoned.

Under an approach that assigns emissions to combustion of biomass, removals of CO_2 from the atmosphere by plants can continue to be tallied in the land-use sector. However, carbon stock losses due to use of biomass for energy would no longer be counted in the land-use sector. Under simple point-of-use, all biomass emissions and removals are counted where they occur. Under point-of-use plus, removals of CO_2 that are reported to end-users get credited in the energy sector, reducing the emission obligation for energy users. If *CN* factors are used, the time-pattern of both losses and removals is reflected in the factor.

5.3.1 Point-of-use

Under circumstances where many nations do not adopt emission caps, point-of-use accounting provides a straight-forward way to avoid undue encouragement of the use of biomass for energy. It can also provide advantages to countries which export more biomass for energy or wood products than they use domestically.

The pros and cons of accounting for biomass emissions and removals where they occur (referred to in the literature as the atmospheric flow approach in the context of harvested wood products) versus accounting for changes in carbon stocks (carbon stock approach) were investigated by a group of experts in 1997 (Apps et al. 1997). As long as a global perspective is adopted (i.e., stock changes are accounted for globally) and a long enough time horizon is contemplated, both approaches yield accurate accounts of emissions due to biomass oxidation and growth. This group of experts recommended use of the carbon stock change approach both on grounds of simplicity and because it seemed to result in a more desirable incentive system. They also recognized that selection between these two approaches determines in whose account emissions and removals would appear. At least partly due to their recommendation, the stock change approach was adopted. It is important to bear in mind that the recommendations were based on global accounting i.e., the assumption shared by the IPCC Reporting Guidelines.

Both the Searchinger and DeCicco papers focus on the real-world situation which has emerged since 1997. Under global accounting, Apps et al. showed that the stock-change approach would discourage deforestation, which was seen as one of the advantages of the stock-change system. However, since accounting does not, and in the foreseeable future will not, take place globally, the incentive system functions contrary to expectations. Since deforestation is primarily occurring in nations where accounting is not required, the system is failing to discourage it. Since, in addition, under the carbon-stock system no emissions are assigned at the point of combustion, the carbon-stock system encourages nations with accounting obligations to import and use of biomass to replace fossil-fuels. In contrast, the point-of-use as also recognized by Apps et al., discourages bioenergy use. Under partial accounting this may be preferable to a system that not only fails to discourage deforestation but actually incentivizes it by encouraging bioenergy use.

Moving to a point-of-use system would have both benefits and drawbacks. First, approach would have benefits for non Annex-I countries which grow more biomass than they use domestically. If point-of-use were adopted in conjunction with crediting in the land-use sector, developing nations could receive credits for the total amount of the biomass grown less the portion they use domestically. Loss of carbon stocks, and attendant emission, due to biomass exported would be the responsibility of the nation in which the biomass was combusted or otherwise oxidized. Thus, the system would represent a partial move toward user responsibility for emissions attendant on use of bioenergy. It is not a complete system because emissions due to processing, conversion, and transport outside of Annex-I countries would not be covered.

There are some consequences of adoption of a point-of-use approach about which little is yet known. In particular more information is needed regarding the distribution of benefits and losses. Point-of-use accounting would have impacts on international trade in biomass, but modelling will be necessary to determine, for instance, whether there would be negative impacts on EU nations currently exporting significant amounts of wood. Considerations are that point-of-use accounting would encourage reuse of wood but also sale of wood to other countries both for bioenergy and as waste after its final use to avoid responsibility for emissions due to oxidation. Again, the GHG balance of these effects is unknown.

Apps et al. pointed out one problem with a point-of-use approach. No system accounts, or envisions accounting, for CO_2 respired by people or animals. Thus, in the case of biomass used for food and feed – including in the case of food and feed exported from non-Annex-I to Annex-I nations – credits would accrue even for annual sequestration resulting from plant growth but the emissions due to its oxidation in the digestive-respiratory cycle would not be counted. Thus, statistics on food and feed consumption would need to be used to correct for this imbalance.

One drawback of a point-of-use system is that it does not, by itself, distinguish between biomass whose conversion and transportation emissions are high or low. That is, it only accounts for carbon stock losses. Insofar as conversion, processing, and transportation occur in nations without caps, these emissions would continue to lie outside of the accounting system. Further, the emissions due to combustion of a tonne of wood will be the same regardless of whether the wood is residues, from short-rotation plantations, from deforestation, or from increased harvests in forests already used for wood. In effect, there is no direct link between the user of biomass and source of carbon stock or other value-chain emissions. Thus, individual users of bioenergy – e.g., power plants or fuel blenders or distributors – have no incentive to select biomass with low embodied emissions or short regrowth cycle. The alternatives in the following two sections address these problems.

5.3.2 Point-of-use-plus

DeCicco (2009) proposes a system in which assignment of emissions to biomass used for energy is combined with tracking the emissions occurring along its value chain that occur in non-capped sectors or nations. One of his primary objectives is to create a system in which the emission cap on fossil fuels serves as the incentive to lower the GHG emission profiles of biofuels.

DeCicco (2009) proposes a system that combines:

1. An obligation on fuel distributors to submit permits to emit (allowances) based on the carbon content and use of biofuels.
2. The opportunity to use a lower emission factor to calculate obligations if it can be justified by net removals (removals minus GHG emissions) along the entire value chain.

For example, a distributor of biodiesel would calculate his obligation on the basis of 77 gCO_2 MJ^{-1} distributed. Reductions in this factor are allowed to the extent justified by net removals of CO_2. Net removal calculations must take into account GHG emissions at all steps along the value chain in addition to the carbon sequestered by plant growth. Emissions due to cultivation, land use change[18], conversion or other processing and transportation must be calculated. However, only those GHG emissions not covered by caps enter into reducing the emission factor.

DeCicco’s paper is focused on transportation fuels but the system he proposes would be applicable to any bioenergy pathway. He starts by pointing out that under cap-and-trade systems some fuel-related emissions fail to be counted because “markets cross the boundaries of capped and uncapped sectors both domestically and internationally.” He mentions that missed emissions include not only many biofuel-related emissions but also fossil fuel production and refining emissions insofar as these occur in developing countries. His proposal is directed at encouraging accounting, under a cap, for the all uncapped emissions and emission reductions along the biofuel value chain. His system encourages rather than requires such accounting because he proposes that the submission of value-chain information be voluntary.

DeCicco’s exclusive use of uncapped emission and sequestration emission sources to adjust the emission factor avoids double counting of both emissions and removals. Table 6 below illustrates how this works. In this example it is assumed that the agricultural sector is not part of a cap-and-trade system, so with respect to obligations under that cap, sequestration and emissions in agriculture play no role. However, fossil fuels, including both those used in transportation and electricity are capped, as well as most of the emission due to production of fertilizer. Thus, from the original credit (737 x 10^3

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[18] DeCicco does not provide information on how emissions due to land use change would be calculated. He does suggest a fund to purchase forestland to address indirect land use change. Since this is a form of REDD+, this is not further addressed here.

tonnes), after accounting for uncapped emissions, 637 x 10^3 credits remain at the first step in the value chain or 31.2 kg CO_2 per bushel.

Table 6: Example of credits for corn from some farm

Item	10^3 tonnes CO_2-eq.	
	all	uncapped
CO_2 absorbed	(737.0)	(737.0)
Conservation tillage	(12.7)	(12.7)
Fertilizer production	22.6	3.8
Diesel fuel	10.0	-
Propane	3.9	-
Electricity	4.0	-
N_2O emissions	97.6	97.6
Direct land-use	10.5	10.5
Totals	**(601.1)**	**(637.8)**
kg CO_2-eq. per bushel	(29.4)	(31.2)

Source: DeCicco, 2009.

Uncapped emissions from the conversion as well as from transportation, to the extent that this occurs in nations without caps, are further deducted. Table 7 shows the results for corn processed in a nation with caps on fossil fuels.

Table 7: GHG emission balance after refining

Item	10^3 tonnes CO_2-eq.	
	all	uncapped
Corn feedstock	(637.8)	(637.8)
Electricity	24.9	-
Natural gas	90.2	-
CO_2 from fermentation	240.5	240.5
Totals	**(282.2)**	**(397.3)**
kg CO_2e MJ^{-1} (LHV)	(63.0)	(88.8)

Source: DeCicco, 2009.

As shown, the net credits are converted into grams per MJ. In a final step, emissions due to use of biomass for ethanol at the rate of 71.5 gCO_2 MJ^{-1} are subtracted, leaving a credit of 17.3 gCO_2 MJ^{-1}. Credits equal to 17.3 gCO_2 MJ^{-1} in the ethanol he has purchased (i.e., 80.2 MJ $gallon^{-1}$) can then be used to reduce the fuel distributor's obligation for petroleum products he sells.

Since in DeCicco's system the submission of value-chain information is voluntary, only pathways where there would be a net credit would submit the information. However, a system could require submission of value-chain information.

DeCicco considers that this system has the following advantages:

- ✓ The cap itself functions to drive emission reductions along the entire chain. This occurs because distributors will offer higher prices for lower GHG-pathways as it reduces the number of allowances they need to submit.
- ✓ Biofuels suffer no market disadvantage compared to other fuels under the cap.

This is because biofuels 'non-reduced' emission factor is equivalent to their carbon content, on an energy equivalent basis, to the fuels they substitute.

- ✓ The rating system proposed avoids the need for full life-cycle analysis or information about multiple feedstock-fuel pathways.
  Information is only needed on GHG emissions throughout the value chain that are not accounted for elsewhere.
- ✓ There is no need to distinguish between acceptable or unacceptable fuels or pathways.

The system basically adds to the point-of-use approach an incentive to lower the GHG consequence of use of bioenergy. Since the system is voluntary it only closes the gap created by lack of caps in developing countries and lack of accounting across all managed lands in Annex-I countries to the extent that bioenergy pathways result in credits. However, if it were mandatory and if emissions due to indirect land use change were included, it would close the areal gap. Details of how carbon stock losses due to land use and management change were to be calculated would determine its completeness and impacts in relations to achievement of targets.

5.3.3 Mandatory *CN* factors

Use of a *CN* factor in Directives on renewable bioenergy could align bioenergy with its GHG consequences with respect to specified targets. *CN* factors could also be used to calculate biomass emissions within the EU-ETS, thus removing the undesirable effects of lack of coordination between the two systems.

A *CN* factor incorporates all emissions due to changes in carbon stocks. Moreover, it compares the biomass emissions to emissions resulting from combustion of fossil-fuels in a time-relevant manner. Thus, use of *CN* factors by bioenergy users could, in principal, address both the areal gaps and timing issues that have emerged as a result of the combination of the use of a 'zero emissions' factor at the point of biomass combustion under the KP and EU-ETS with the lack of accounting for emissions due to land use change both in some instances in Annex-I countries and to the lack of emission obligations in developing countries. A *CN* approach also includes the following elements not included in the D on RES approach:

- Emissions from land remaining in the same use
- The relative advantage over fossil fuels at any specified point in time

Currently neither *CN* factors nor the D on RES calculations incorporate emissions due to indirect land use change. If, or when, credible methodologies to estimate these become available, either approach could do so.

Under the current bioenergy accounting systems of the KP and EU-ETS, emission reductions appear in calculations determining target compliance well beyond those supported by the *CN* factors of the biomass. The compliance regime registers a 100 percent reduction in emissions compared to use of fossil fuels to produce the same amount of energy. As shown in Section 4, in the case of woody biomass, 100 percent reductions could occur only for certain types of biomass, namely from new plantations, or only occur in the case of fairly long time horizons. Where wood is used to replace petroleum or natural gas, emissions can actually be higher than they would be if the fossil fuel were used, at least in the short or medium term. Since *CN* factors calculate the relative emission savings for all sources of biomass, use of *CN*-factor labelled biomass – together with mandatory use of the factor to determine emissions that need to be covered by allowances – would provide a straightforward way to calculate emission benefits relative to use of fossil fuels. This could then be translated into a bioenergy user's allowance obligation. A user of bioenergy with a *CN* of 0.8, for example, would need to submit 20 allowances per 100 tonnes of CO_2 emitted.

As explained in Section 4, biomass removed for energy today will have a different *CN* factor in relation to a 2020 or 2030 target than biomass removed in 2018 or 2028. To address this problem within a *CN*-based system, one might use average *CN* factors over the time between the present and a selected target date for distinct sources of biomass. This would require reaching agreement on both the target date and what constituted a distinct biomass source. One problem that might arise, even if a single target date were agreed on within the EU, is that the acceptability of the date might be contested internationally.

Use of the same target date to assess the *CN* of biomass sources from Annex-I and developing countries would raise a set of difficult issues, issues shared by the D on RES requirement to average emissions from land use change over 20 years. Annex-I nations converted their native forest in the past. Consequently they can, in many cases, produce and extract biomass from lands whose land-use-change emissions no longer enter into either a *CN* or 20-year calculation. Thus, to use the same annualization period or target date can be viewed as a reversal of the normal interpretation of the 'differentiated responsibilities' concept: Annex-I countries do not have to account for emissions that developing countries do.

Since Annex-I lands that were converted from natural forests have been producing crops and wood products for hundreds of years, the same could be expected on lands currently being converted from natural forests or peatlands in developing countries. Particularly if forests are converted to short rotation plantations, positive *CN* factors can emerge within reasonable time spans (e.g., 60-70 years). This would support allowing annualization periods longer than the 20 years allowed in the EU-RED, or more distant dates for calculating annual emissions or *CN* factors. However, since such an approach within the D on RES would enable the EU to use biomass resulting from deforestation in developing countries it likely to be highly controversial.

Stakeholders may argue that short-term annualization periods are needed because GHG emissions must be reduced in the near term. REDD+, as well as prohibitions on extraction from currently high-carbon stock lands are also supported by this argument. Another common claim is that the objective of such mechanisms is to prevent developing countries from following the undesirable development path taken by the northern hemisphere. However, GHG emissions from land use change are an increasingly small percent of total GHG emissions, currently 12 percent (Marland 2009). The percent will almost certainly continue to fall as fossil fuel emissions from China in particular escalate. Lowering GHG emissions significantly within the next 50 years can thus only be accomplished by substantial reductions in the close to 90 percent of emissions due to combustion of fossil fuels. Until stakeholders concerned with deforestation also actively support carbon capture and sequestration (CCS), the only technology known today with this capability, the sincerity of their concern for near-term reductions is open to question. Similarly, the EU has shown no inclination to itself undertake to reforest a substantial portion of its agricultural land and thus both reduce emissions and undo the damage of its development path. Until it does so, the position that retaining large percents of land in forests is an attractive way to reduce GHG emissions and avoid the negative aspects of development represents an asymmetrical standard across nations. An alternative way for stakeholders advocating retention of forests in developing countries to increase their credibility would be to focus serious effort on the most critical contributors to deforestation: the low per hectare productivity of food and inefficiency with which biomass for food is used and the lack of robust growth in the industrial and service sectors.

As noted above, a further problem is that the *CN* factor as presented above does not incorporate emissions from indirect land use change. Further work would be necessary to do this. Use of *CN* factors could however, with this exception, close the current areal gap and address the time problem attendant on the lag between emissions due to combustion of biomass and the replenishment of carbon stocks. For the timing feature to function, however, the *CN*s will have to be related to specified time horizons or target dates.

It is very likely that accounting systems will remain partial through the foreseeable future. Not all nations will cap emissions from their land use sector and many of those that do are unlikely to adopt a UCSA approach. During this period a *CN* factor based only on emissions not falling under caps may be a useful approach. *CN* factors could be calculated under both the D on RES and the EU-ETS. Under both systems bioenergy users could use whatever mix of biomass sources enabled them to most cost-effectively meet their obligations. Under the EU-ETS, bioenergy users would have to submit allowances to emit for the fraction, if any, of fossil fuel emissions not neutralized. Such a system could be implemented as soon as agreements were reached on target dates. When methodologies for calculating indirect land use change were considered sufficiently well-established, these emissions could be incorporated. However, this is a new concept that has not as yet undergone discussion and review by experts and stakeholders. Such a review process is vital to identify problems and weakness that, in this first presentation of the concept, have not come to light. The authors encourage interested parties to inaugurate and support such a review process.

Table 8 Summary of the policy options to address emissions from the use of biomass for energy

Policy option	All direct LU emissions	iLUC emissions in:		non-LU emissions included	C stock recovery time	Market incentives to lower GHG pathways	Independent from WTO rules	Political Readiness	Cap needed
		Annex-I	Non-Annex I						
Expanded Activity Approach	-	F	-	-	-	-	✓	M	✓
UCSA: within Annex-I countries	✓	✓	-	-	✓	-	✓	L	✓
UCSA: all nations	✓	✓	✓	-	✓	-	✓	L	✓
Value-chain (basic)	✓	F	F	TP	-	✓	✓	H	-
• EU directive on RES	-	F	F	TP	-	-	-	H	-
• Sustainability criteria									
- Project level	✓	F	F	TP	-	-	-	H	-
- National level	✓	✓	F	TP	-	-	-	H	-
Point-of-use Accounting	-	-	-	C	-		✓	?	✓
Point of use Plus (voluntary)	✓	F	F	CTP	-	✓	✓	?	✓
Point of use Plus (mandatory)	✓	F	F	CTP	-	✓	✓	?	✓
Mandatory CN factors	✓	F	F	CTP	✓	✓	✓	?	✓

✓ yes, includes; or meets criteria
- no, does not include; fails to meet criteria
F: Future (i.e., when a credible method is available)
C, T, P: Combustion, Transport, Processing emissions
WTO: World Trade Organization
H, M, L: high, medium, low (high: already employed, medium: politically realistic in the near- to mid-term, low: unlikely to be politically accepted in the near term)
LU: land use
iLUC: indirect land use change

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Target Atmospheric CO_2: Where Should Humanity Aim?

James Hansen*[,1,2], Makiko Sato[1,2], Pushker Kharecha[1,2], David Beerling[3], Robert Berner[4], Valerie Masson-Delmotte[5], Mark Pagani[4], Maureen Raymo[6], Dana L. Royer[7] and James C. Zachos[8]

[1] *NASA/Goddard Institute for Space Studies, New York, NY 10025, USA*

[2] *Columbia University Earth Institute, New York, NY 10027, USA*

[3] *Department of Animal and Plant Sciences, University of Sheffield, Sheffield S10 2TN, UK*

[4] *Department of Geology and Geophysics, Yale University, New Haven, CT 06520-8109, USA*

[5] *Lab. Des Sciences du Climat et l'Environnement/Institut Pierre Simon Laplace, CEA-CNRS-Universite de Versailles Saint-Quentin en Yvelines, CE Saclay, 91191, Gif-sur-Yvette, France*

[6] *Department of Earth Sciences, Boston University, Boston, MA 02215, USA*

[7] *Department of Earth and Environmental Sciences, Wesleyan University, Middletown, CT 06459-0139, USA*

[8] *Earth & Planetary Sciences Dept., University of California, Santa Cruz, Santa Cruz, CA 95064, USA*

Abstract: Paleoclimate data show that climate sensitivity is ~3°C for doubled CO_2, including only fast feedback processes. Equilibrium sensitivity, including slower surface albedo feedbacks, is ~6°C for doubled CO_2 for the range of climate states between glacial conditions and ice-free Antarctica. Decreasing CO_2 was the main cause of a cooling trend that began 50 million years ago, the planet being nearly ice-free until CO_2 fell to 450 ± 100 ppm; barring prompt policy changes, that critical level will be passed, in the opposite direction, within decades. If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm, but likely less than that. The largest uncertainty in the target arises from possible changes of non-CO_2 forcings. An initial 350 ppm CO_2 target may be achievable by phasing out coal use except where CO_2 is captured and adopting agricultural and forestry practices that sequester carbon. If the present overshoot of this target CO_2 is not brief, there is a possibility of seeding irreversible catastrophic effects.

Keywords: Climate change, climate sensitivity, global warming.

1. INTRODUCTION

Human activities are altering Earth's atmospheric composition. Concern about global warming due to long-lived human-made greenhouse gases (GHGs) led to the United Nations Framework Convention on Climate Change [1] with the objective of stabilizing GHGs in the atmosphere at a level preventing "dangerous anthropogenic interference with the climate system."

The Intergovernmental Panel on Climate Change [IPCC, [2]] and others [3] used several "reasons for concern" to estimate that global warming of more than 2-3°C may be dangerous. The European Union adopted 2°C above preindustrial global temperature as a goal to limit human-made warming [4]. Hansen *et al*. [5] argued for a limit of 1°C global warming (relative to 2000, 1.7°C relative to preindustrial time), aiming to avoid practically irreversible ice sheet and species loss. This 1°C limit, with nominal climate sensitivity of ¾°C per W/m^2 and plausible control of other GHGs [6], implies maximum CO_2 ~ 450 ppm [5].

Our current analysis suggests that humanity must aim for an even lower level of GHGs. Paleoclimate data and ongoing global changes indicate that 'slow' climate feedback processes not included in most climate models, such as ice sheet disintegration, vegetation migration, and GHG release from soils, tundra or ocean sediments, may begin to come into play on time scales as short as centuries or less [7]. Rapid on-going climate changes and realization that Earth is out of energy balance, implying that more warming is 'in the pipeline' [8], add urgency to investigation of the dangerous level of GHGs.

A probabilistic analysis [9] concluded that the long-term CO_2 limit is in the range 300-500 ppm for 25 percent risk tolerance, depending on climate sensitivity and non-CO_2 forcings. Stabilizing atmospheric CO_2 and climate requires that net CO_2 emissions approach zero, because of the long lifetime of CO_2 [10, 11].

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*Address correspondence to this author at the NASA/Goddard Institute for Space Studies, New York, NY 10025, USA; E-mail: jhansen@giss.nasa.gov

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EXHIBIT 19

We use paleoclimate data to show that long-term climate has high sensitivity to climate forcings and that the present global mean CO_2, 385 ppm, is already in the dangerous zone. Despite rapid current CO_2 growth, ~2 ppm/year, we show that it is conceivable to reduce CO_2 this century to less than the current amount, but only *via* prompt policy changes.

1.1. Climate Sensitivity

A global climate forcing, measured in W/m^2 averaged over the planet, is an imposed perturbation of the planet's energy balance. Increase of solar irradiance (So) by 2% and doubling of atmospheric CO_2 are each forcings of about 4 W/m^2 [12].

Charney [13] defined an idealized climate sensitivity problem, asking how much global surface temperature would increase if atmospheric CO_2 were instantly doubled, assuming that slowly-changing planetary surface conditions, such as ice sheets and forest cover, were fixed. Long-lived GHGs, except for the specified CO_2 change, were also fixed, not responding to climate change. The Charney problem thus provides a measure of climate sensitivity including only the effect of 'fast' feedback processes, such as changes of water vapor, clouds and sea ice.

Classification of climate change mechanisms into fast and slow feedbacks is useful, even though time scales of these changes may overlap. We include as fast feedbacks aerosol changes, e.g., of desert dust and marine dimethylsulfide, that occur in response to climate change [7].

Charney [13] used climate models to estimate fast-feedback doubled CO_2 sensitivity of 3 ± 1.5°C. Water vapor increase and sea ice decrease in response to global warming were both found to be strong positive feedbacks, amplifying the surface temperature response. Climate models in the current IPCC [2] assessment still agree with Charney's estimate.

Climate models alone are unable to define climate sensitivity more precisely, because it is difficult to prove that models realistically incorporate all feedback processes. The Earth's history, however, allows empirical inference of both fast feedback climate sensitivity and long-term sensitivity to specified GHG change including the slow ice sheet feedback.

2. PLEISTOCENE EPOCH

Atmospheric composition and surface properties in the late Pleistocene are known well enough for accurate assessment of the fast-feedback (Charney) climate sensitivity. We first compare the pre-industrial Holocene with the last glacial maximum [LGM, 20 ky BP (before present)]. The planet was in energy balance in both periods within a small fraction of 1 W/m^2, as shown by considering the contrary: an imbalance of 1 W/m^2 maintained a few millennia would melt all ice on the planet or change ocean temperature an amount far outside measured variations [Table **S1** of 8]. The approximate equilibrium characterizing most of Earth's history is unlike the current situation, in which GHGs are rising at a rate much faster than the coupled climate system can respond.

Climate forcing in the LGM equilibrium state due to the ice age surface properties, i.e., increased ice area, different vegetation distribution, and continental shelf exposure, was -3.5 ± 1 W/m^2 [14] relative to the Holocene. Additional forcing due to reduced amounts of long-lived GHGs (CO_2, CH_4, N_2O), including the indirect effects of CH_4 on tropospheric ozone and stratospheric water vapor (Fig. **S1**) was -3 ± 0.5 W/m^2. Global forcing due to slight changes in the Earth's orbit is a negligible fraction of 1 W/m^2 (Fig. **S3**). The total 6.5 W/m^2 forcing and global surface temperature change of 5 ± 1°C relative to the Holocene [15, 16] yield an empirical sensitivity ~¾ ± ¼ °C per W/m^2 forcing, i.e., a Charney sensitivity of 3 ± 1 °C for the 4 W/m^2 forcing of doubled CO_2. This empirical fast-feedback climate sensitivity allows water vapor, clouds, aerosols, sea ice, and all other fast feedbacks that exist in the real world to respond naturally to global climate change.

Climate sensitivity varies as Earth becomes warmer or cooler. Toward colder extremes, as the area of sea ice grows, the planet approaches runaway snowball-Earth conditions, and at high temperatures it can approach a runaway greenhouse effect [12]. At its present temperature Earth is on a flat portion of its fast-feedback climate sensitivity curve (Fig. **S2**). Thus our empirical sensitivity, although strictly the mean fast-feedback sensitivity for climate states ranging from the ice age to the current interglacial period, is also today's fast-feedback climate sensitivity.

2.1. Verification

Our empirical fast-feedback climate sensitivity, derived by comparing conditions at two points in time, can be checked over the longer period of ice core data. Fig. (**1a**) shows CO_2 and CH_4 data from the Antarctic Vostok ice core [17, 18] and sea level based on Red Sea sediment cores [18]. Gases are from the same ice core and have a consistent time scale, but dating with respect to sea level may have errors up to several thousand years.

We use the GHG and sea level data to calculate climate forcing by GHGs and surface albedo change as in prior calculations [7], but with two refinements. First, we specify the N_2O climate forcing as 12 percent of the sum of the CO_2 and CH_4 forcings, rather than the 15 percent estimated earlier [7] Because N_2O data are not available for the entire record, and its forcing is small and highly correlated with CO_2 and CH_4, we take the GHG effective forcing as

$$Fe\ (GHGs) = 1.12\ [Fa(CO_2) + 1.4\ Fa(CH_4)], \qquad (1)$$

using published formulae for Fa of each gas [20]. The factor 1.4 accounts for the higher efficacy of CH_4 relative to CO_2, which is due mainly to the indirect effect of CH_4 on tropospheric ozone and stratospheric water vapor [12]. The resulting GHG forcing between the LGM and late Holocene is 3 W/m^2, apportioned as 75% CO_2, 14% CH_4 and 11% N_2O.

The second refinement in our calculations is to surface albedo. Based on models of ice sheet shape, we take the horizontal area of the ice sheet as proportional to the 4/5 power of volume. Fig. (**S4**) compares our present albedo forcing with prior use [7] of exponent 2/3, showing that this

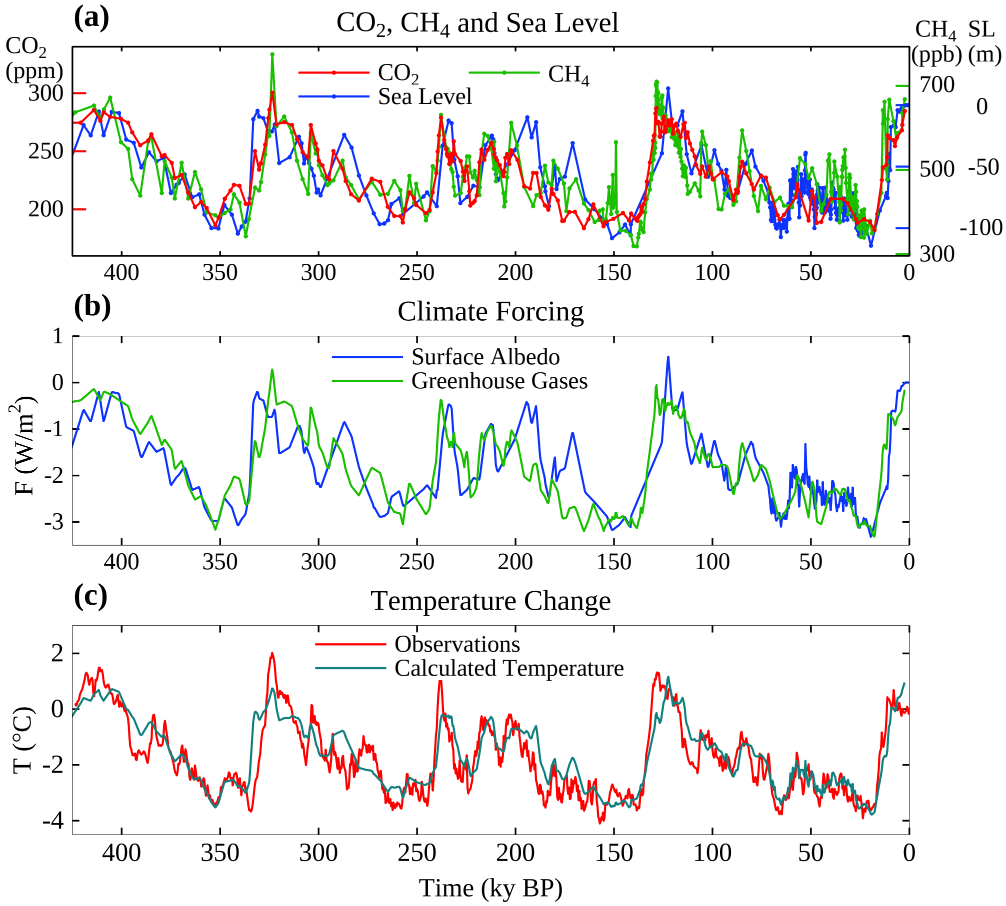


Fig. (1). (**a**) CO_2, CH_4 [17] and sea level [19] for past 425 ky. (**b**) Climate forcings due to changes of GHGs and ice sheet area, the latter inferred from sea level change. (**c**) Calculated global temperature change based on climate sensitivity of ¾°C per W/m^2. Observations are Antarctic temperature change [18] divided by two.

choice and division of the ice into multiple ice sheets has only a minor effect.

Multiplying the sum of GHG and surface albedo forcings by climate sensitivity ¾°C per W/m^2 yields the blue curve in Fig. (**1c**). Vostok temperature change [17] divided by two (red curve) is used to crudely estimate global temperature change, as typical glacial-interglacial global annual-mean temperature change is ~5°C and is associated with ~10°C change on Antarctica [21]. Fig. (**1c**) shows that fast-feedback climate sensitivity ¾°C per W/m^2 (3°C for doubled CO_2) is a good approximation for the entire period.

2.2. Slow Feedbacks

Let us consider climate change averaged over a few thousand years – long enough to assure energy balance and minimize effects of ocean thermal response time and climate change leads/lags between hemispheres [22]. At such temporal resolution the temperature variations in Fig. (**1**) are global, with high latitude amplification, being present in polar ice cores and sea surface temperature derived from ocean sediment cores (Fig. **S5**).

GHG and surface albedo changes are mechanisms causing the large global climate changes in Fig. (**1**), but they do not initiate these climate swings. Instead changes of GHGs and sea level (a measure of ice sheet size) lag temperature change by several hundred years [6, 7, 23, 24].

GHG and surface albedo changes are positive climate feedbacks. Major glacial-interglacial climate swings are instigated by slow changes of Earth's orbit, especially the tilt of Earth's spin-axis relative to the orbital plane and the precession of the equinoxes that influences the intensity of summer insolation [25, 26]. Global radiative forcing due to orbital changes is small, but ice sheet size is affected by changes of geographical and seasonal insolation (e.g., ice melts at both poles when the spin-axis tilt increases, and ice melts at one pole when perihelion, the closest approach to the sun, occurs in late spring [7]. Also a warming climate causes net release of GHGs. The most effective GHG feedback is release of CO_2 by the ocean, due partly to temperature dependence of CO_2 solubility but mostly to increased ocean mixing in a warmer climate, which acts to flush out

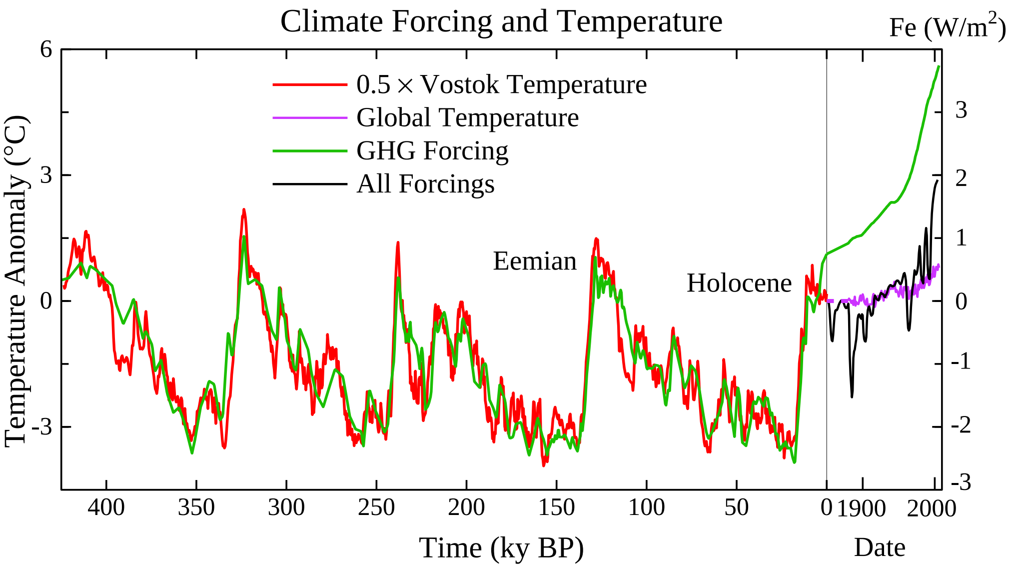


Fig. (2). Global temperature (left scale) and GHG forcing (right scale) due to CO_2, CH_4 and N_2O from the Vostok ice core [17, 18]. Time scale is expanded for the industrial era. Ratio of temperature and forcing scales is 1.5°C per W/m^2, i.e., the temperature scale gives the expected equilibrium response to GHG change including (slow feedback) surface albedo change. Modern forcings include human-made aerosols, volcanic aerosols and solar irradiance [5]. GHG forcing zero point is the mean for 10-8 ky BP (Fig. **S6**). Zero point of modern temperature and net climate forcing was set at 1850 [5], but this is also the zero point for 10-8 ky BP, as shown by the absence of a trend in Fig. (**S6**) and by the discussion of that figure.

deep ocean CO_2 and alters ocean biological productivity [27].

GHG and surface albedo feedbacks respond and contribute to temperature change caused by any climate forcing, natural or human-made, given sufficient time. The GHG feedback is nearly linear in global temperature during the late Pleistocene (Fig. **7** of [6, 28]). Surface albedo feedback increases as Earth becomes colder and the area of ice increases. Climate sensitivity on

Pleistocene time scales includes slow feedbacks, and is larger than the Charney sensitivity, because the dominant slow feedbacks are positive. Other feedbacks, e.g., the negative feedback of increased weathering as CO_2 increases, become important on longer geologic time scales.

Paleoclimate data permit evaluation of long-term sensitivity to specified GHG change. We assume only that, to first order, the area of ice is a function of global temperature. Plotting GHG forcing [7] from ice core data [18] against temperature shows that global climate sensitivity including the slow surface albedo feedback is 1.5°C per W/m^2 or 6°C for doubled CO_2 (Fig. **2**), twice as large as the Charney fast-feedback sensitivity. Note that we assume the area of ice and snow on the planet to be predominately dependent on global temperature, but some changes of regional ice sheet properties occur as part of the Earth orbital climate forcing (see Supplementary Material).

This equilibrium sensitivity of 6°C for doubled CO_2 is valid for specified GHG amount, as in studies that employ emission scenarios and coupled carbon cycle/climate models to determine GHG amount. If GHGs are included as a feedback (with say solar irradiance as forcing) sensitivity is still larger on Pleistocene time scales (see Supplementary Material), but the sensitivity may be reduced by negative feedbacks on geologic time scales [29, 30]. The 6°C sensitivity reduces to 3°C when the planet has become warm enough to lose its ice sheets.

This long-term climate sensitivity is relevant to GHGs that remain airborne for centuries-to-millennia. The human-caused atmospheric GHG increase will decline slowly if anthropogenic emissions from fossil fuel burning decrease enough, as we illustrate below using a simplified carbon cycle model. On the other hand, if the globe warms much further, carbon cycle models [2] and empirical data [6, 28] reveal a positive GHG feedback on century-millennia time scales. This amplification of GHG amount is moderate if warming is kept within the range of recent interglacial periods [6], but larger warming would risk greater release of CH_4 and CO_2 from methane hydrates in tundra and ocean sediments [29]. On still longer, geological, time scales weathering of rocks causes a negative feedback on atmospheric CO_2 amount [30], as discussed in section 3, but this feedback is too slow to alleviate climate change of concern to humanity.

2.3. Time Scales

How long does it take to reach equilibrium temperature with specified GHG change? Response is slowed by ocean thermal inertia and the time needed for ice sheets to disintegrate.

Ocean-caused delay is estimated in Fig. (**S7**) using a coupled atmosphere-ocean model. One-third of the response occurs in the first few years, in part because of rapid response over land, one-half in ~25 years, three-quarters in 250 years, and nearly full response in a millennium. The ocean-caused delay is a strong (quadratic) function of climate sensitivity and it depends on the rate of mixing of surface water and deep water [31], as discussed in the Supplementary Material Section.

Ice sheet response time is often assumed to be several millennia, based on the broad sweep of paleo sea level change (Fig. **1a**) and primitive ice sheet models designed to capture that change. However, this long time scale may reflect the slowly changing orbital forcing, rather than inherent inertia, as there is no discernable lag between maximum ice sheet melt rate and local insolation that favors melt [7]. Paleo sea level data with high time resolution reveal frequent 'suborbital' sea level changes at rates of 1 m/century or more [32-34].

Present-day observations of Greenland and Antarctica show increasing surface melt [35], loss of buttressing ice shelves [36], accelerating ice streams [37], and increasing overall mass loss [38]. These rapid changes do not occur in existing ice sheet models, which are missing critical physics of ice sheet disintegration [39]. Sea level changes of several meters per century occur in the paleoclimate record [32, 33], in response to forcings slower and weaker than the present human-made forcing. It seems likely that large ice sheet response will occur within centuries, if human-made forcings continue to increase. Once ice sheet disintegration is underway, decadal changes of sea level may be substantial.

2.4. Warming "in the Pipeline"

The expanded time scale for the industrial era (Fig. **2**) reveals a growing gap between actual global temperature (purple curve) and equilibrium (long-term) temperature response based on the net estimated climate forcing (black curve). Ocean and ice sheet response times together account for this gap, which is now 2.0°C.

The forcing in Fig. (**2**) (black curve, Fe scale), when used to drive a global climate model [5], yields global temperature change that agrees closely (Fig. **3** in [5]) with observations (purple curve, Fig. **2**). That climate model, which includes only fast feedbacks, has additional warming of ~0.6°C in the pipeline today because of ocean thermal inertia [5, 8].

The remaining gap between equilibrium temperature for current atmospheric composition and actual global temperature is ~1.4°C. This further 1.4°C warming still to come is due to the slow surface albedo feedback, specifically ice sheet disintegration and vegetation change.

One may ask whether the climate system, as the Earth warms from its present 'interglacial' state, still has the capacity to supply slow feedbacks that double the fast-feedback sensitivity. This issue can be addressed by considering longer time scales including periods with no ice.

3. CENOZOIC ERA

Pleistocene atmospheric CO_2 variations occur as a climate feedback, as carbon is exchanged among surface reservoirs: the ocean, atmosphere, soils and biosphere. The most effective feedback is increase of atmospheric CO_2 as climate warms, the CO_2 transfer being mainly from ocean to atmosphere [27, 28]. On longer time scales the total amount of CO_2 in the surface reservoirs varies due to exchange of carbon with the solid earth. CO_2 thus becomes a primary agent of long-term climate change, leaving orbital effects as 'noise' on larger climate swings.

The Cenozoic era, the past 65.5 My, provides a valuable complement to the Pleistocene for exploring climate sensitivity. Cenozoic data on climate and atmospheric composition are not as precise, but larger climate variations occur, including an ice-free planet, thus putting glacial-interglacial changes in a wider perspective.

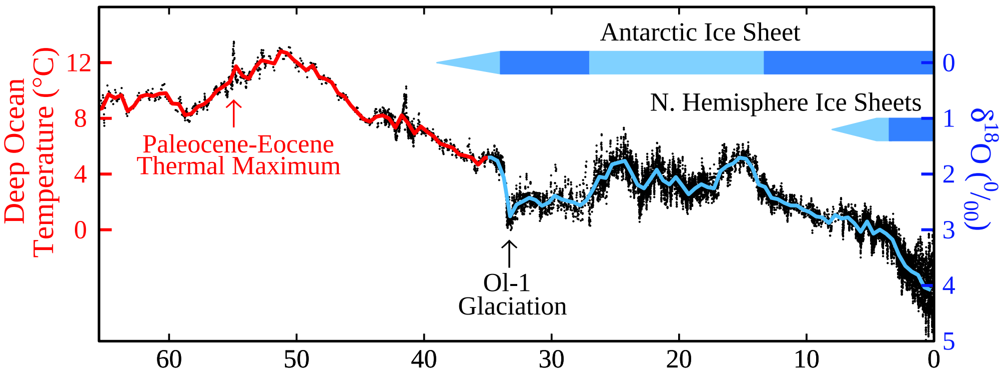
Oxygen isotopic composition of benthic (deep ocean dwelling) foraminifera shells in a global compilation of ocean sediment cores [26] provides a starting point for analyzing Cenozoic climate change (Fig. **3a**). At times with negligible ice sheets, oxygen isotope change, $\delta^{18}O$, provides a direct measure of deep ocean temperature (T_{do}). Thus T_{do} (°C) ~ -4 $\delta^{18}O$ + 12 between 65.5 and 35 My BP.

Rapid increase of $\delta^{18}O$ at about 34 My is associated with glaciation of Antarctica [26, 40] and global cooling, as evidenced by data from North America [41] and Asia [42]. From then until the present, ^{18}O in deep ocean foraminifera is affected by both ice volume and T_{do}, lighter ^{16}O evaporating preferentially from the ocean and accumulating in ice sheets. Between 35 My and the last ice age (20 ky) the change of $\delta^{18}O$ was ~ 3‰, change of T_{do} was ~ 6°C (from +5 to -1°C) and ice volume change ~ 180 msl (meters of sea level). Given that a 1.5‰ change of $\delta^{18}O$ is associated with a 6°C T_{do} change, we assign the remaining $\delta^{18}O$ change to ice volume linearly at the rate 60 msl per mil $\delta^{18}O$ change (thus 180 msl for $\delta^{18}O$ between 1.75 and 4.75). Equal division of $\delta^{18}O$ between temperature and sea level yields sea level change in the late Pleistocene in reasonable accord with available sea level data (Fig. **S8**). Subtracting the ice volume portion of $\delta^{18}O$ yields deep ocean temperature T_{do} (°C) = -2 ($\delta^{18}O$ -4.25‰) after 35 My, as in Fig. (**3b**).

The large (~14°C) Cenozoic temperature change between 50 My and the ice age at 20 ky must have been forced by changes of atmospheric composition. Alternative drives could come from outside (solar irradiance) or the Earth's surface (continental locations). But solar brightness increased ~0.4% in the Cenozoic [43], a linear forcing change of only +1 W/m^2 and of the wrong sign to contribute to the cooling trend. Climate forcing due to continental locations was < 1 W/m^2, because continents 65 My ago were already close to present latitudes (Fig. **S9**). Opening or closing of oceanic gateways might affect the timing of glaciation, but it would not provide the climate forcing needed for global cooling.

CO_2 concentration, in contrast, varied from ~180 ppm in glacial times to 1500 ± 500 ppm in the early Cenozoic [44]. This change is a forcing of more than 10 W/m^2 (Table **1** in [16]), an order of magnitude larger than other known forcings. CH_4 and N_2O, positively correlated with CO_2 and global temperature in the period with accurate data (ice cores), likely increase the total GHG forcing, but their forcings are much smaller than that of CO_2 [45, 46].

(a) Global Deep Ocean $\delta^{18}O$



(b) Global Deep Ocean Temperature

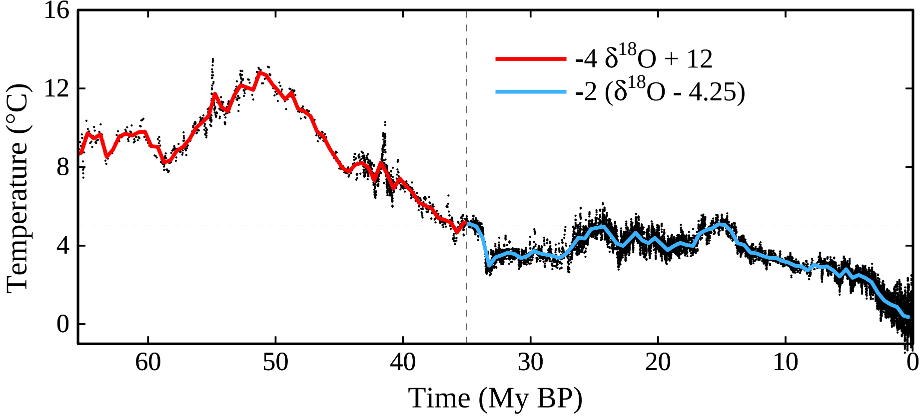


Fig. (3). Global deep ocean (**a**) $\delta^{18}O$ [26] and (**b**) temperature. Black curve is 5-point running mean of $\delta^{18}O$ original temporal resolution, while red and blue curves have 500 ky resolution.

3.1. Cenozoic Carbon Cycle

Solid Earth sources and sinks of CO_2 are not, in general, balanced at any given time [30, 47]. CO_2 is removed from surface reservoirs by: (1) chemical weathering of rocks with deposition of carbonates on the ocean floor, and (2) burial of organic matter; weathering is the dominant process [30]. CO_2 returns primarily *via* metamorphism and volcanic outgassing at locations where carbonate-rich oceanic crust is being subducted beneath moving continental plates.

Outgassing and burial of CO_2 are each typically 10^{12}-10^{13} mol C/year [30, 47-48]. At times of unusual plate tectonic activity, such as rapid subduction of carbon-rich ocean crust or strong orogeny, the imbalance between outgassing and burial can be a significant fraction of the one-way carbon flux. Although negative feedbacks in the geochemical carbon cycle reduce the rate of surface reservoir perturbation [49], a net imbalance ~10^{12} mol C/year can be maintained over thousands of years. Such an imbalance, if confined to the atmosphere, would be ~0.005 ppm/year, but as CO_2 is distributed among surface reservoirs, this is only ~0.0001 ppm/year. This rate is negligible compared to the present human-made atmospheric CO_2 increase of ~2 ppm/year, yet over a million years such a crustal imbalance alters atmospheric CO_2 by 100 ppm.

Between 60 and 50 My ago India moved north rapidly, 18-20 cm/year [50], through a region that long had been a depocenter for carbonate and organic sediments. Subduction of carbon-rich crust was surely a large source of CO_2 outgassing and a prime cause of global warming, which peaked 50 My ago (Fig. **3b**) with the Indo-Asian collision. CO_2 must have then decreased due to a reduced subduction source and enhanced weathering with uplift of the Himalayas/Tibetan Plateau [51]. Since then, the Indian and Atlantic Oceans have been major depocenters for carbon, but subduction of carbon-rich crust has been limited mainly to small regions near Indonesia and Central America [47].

Thus atmospheric CO_2 declined following the Indo-Asian collision [44] and climate cooled (Fig. **3b**) leading to Antarctic glaciation by ~34 My. Antarctica has been more or less glaciated ever since. The rate of CO_2 drawdown declines as atmospheric CO_2 decreases due to negative feedbacks, including the effect of declining atmospheric temperature and plant growth rates on weathering [30]. These negative feedbacks tend to create a balance between crustal outgassing and drawdown of CO_2, which have been equal within 1-2 percent over the past 700 ky [52]. Large fluctuations in the size of the Antarctic ice sheet have occurred in the past 34 My, possibly related to temporal variations of plate tectonics [53] and outgassing rates. The relatively constant atmospheric CO_2 amount of the past 20 My (Fig. **S10**) implies a near balance of outgassing and weathering rates over that period.

Knowledge of Cenozoic CO_2 is limited to imprecise proxy measures except for recent ice core data. There are discrepancies among different proxy measures, and even between different investigators using the same proxy method, as discussed in conjunction with Fig. (**S10**). Nevertheless, the proxy data indicate that CO_2 was of the order of 1000 ppm in the early Cenozoic but <500 ppm in the last 20 My [2, 44].

3.2. Cenozoic Forcing and CO_2

The entire Cenozoic climate forcing history (Fig. **4a**) is implied by the temperature reconstruction (Fig. **3b**), assuming a fast-feedback sensitivity of ¾°C per W/m^2. Subtracting the solar and surface albedo forcings (Fig. **4b**), the latter from Eq. S2 with ice sheet area *vs* time from $\delta^{18}O$, we obtain the GHG forcing history (Fig. **4c**).

We hinge our calculations at 35 My for several reasons. Between 65 and 35 My ago there was little ice on the planet, so climate sensitivity is defined mainly by fast feedbacks. Second, we want to estimate the CO_2 amount that precipitated Antarctic glaciation. Finally, the relation between global surface air temperature change (ΔT_s) and deep ocean temperature change (ΔT_{do}) differs for ice-free and glaciated worlds.

Climate models show that global temperature change is tied closely to ocean temperature change [54]. Deep ocean temperature is a function of high latitude ocean surface temperature, which tends to be amplified relative to global mean ocean surface temperature. However, land temperature change exceeds that of the ocean, with an effect on global temperature that tends to offset the latitudinal variation of ocean temperature. Thus in the ice-free world (65-35 My) we take $\Delta T_s \sim \Delta T_{do}$ with generous (50%) uncertainty. In the glaciated world ΔT_{do} is limited by the freezing point in the deep ocean. ΔT_s between the last ice age (20 ky) and the present

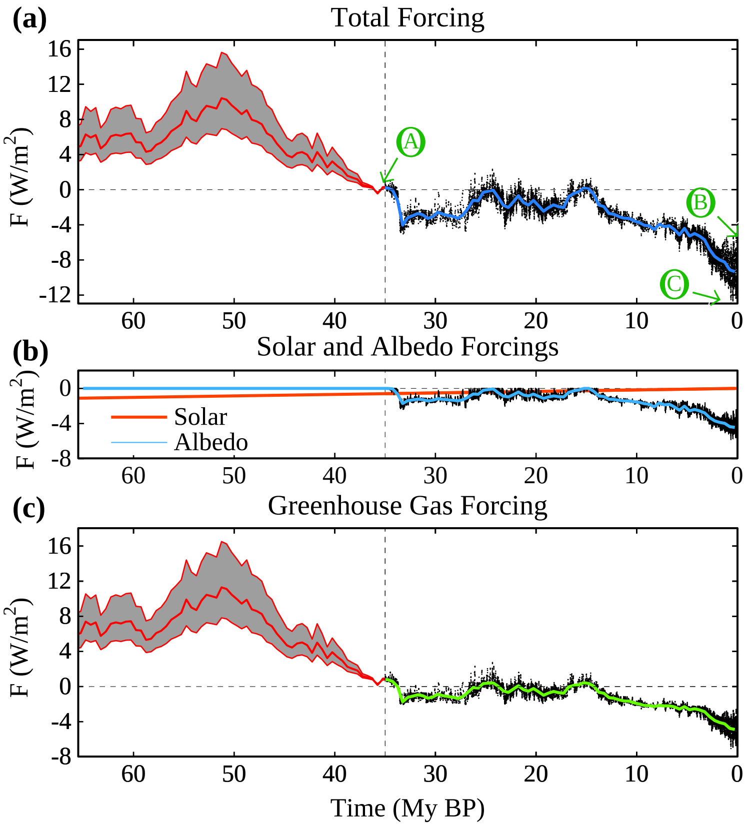
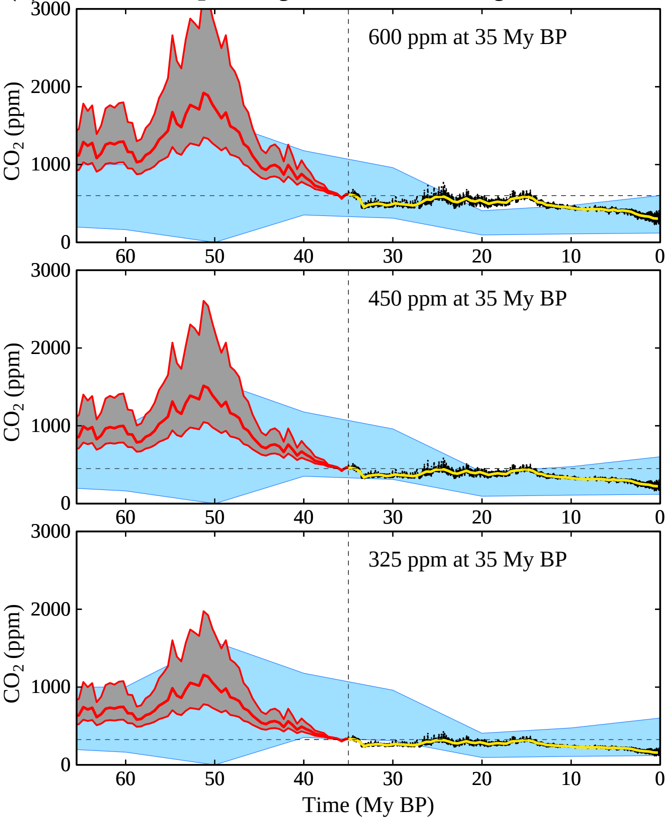


Fig. (4). (**a**) Total climate forcing, (**b**) solar and surface albedo forcings, and (**c**) GHG forcing in the Cenozoic, based on T_{do} history of Fig. (**3b**) and assumed fast-feedback climate sensitivity ¾°C per W/m^2. Ratio of T_s change and T_{do} change is assumed to be near unity in the minimal ice world between 65 and 35 My, but the gray area allows for 50% uncertainty in the ratio. In the later era with large ice sheets we take $\Delta T_s/\Delta T_{do} = 1.5$, in accord with Pleistocene data.

(a) CO_2 Forcing Converted to Mixing Ratio



(b) Observed and Calculated CO_2 in Last 425 kys

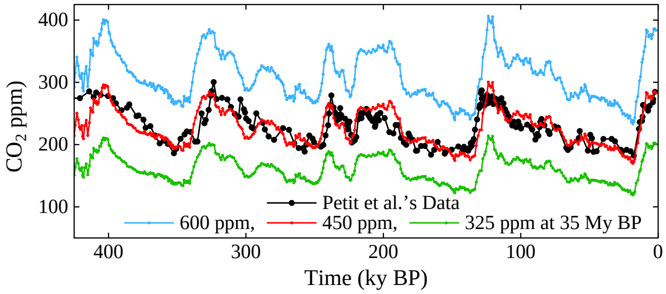


Fig. (5). (**a**) Simulated CO_2 amounts in the Cenozoic for three choices of CO_2 amount at 35 My (temporal resolution of black and colored curves as in Fig. (**3**); blue region: multiple CO_2 proxy data, discussed with Fig. (**S10**); gray region allows 50 percent uncertainty in ratio of global surface and deep ocean temperatures). (**b**) Expanded view of late Pleistocene, including precise ice core CO_2 measurements (black curve).

interglacial period (~5°C) was ~1.5 times larger than ΔT_{do}. In Fig. (**S5**) we show that this relationship fits well throughout the period of ice core data.

If we specify CO_2 at 35 My, the GHG forcing defines CO_2 at other times, assuming CO_2 provides 75% of the GHG forcing, as in the late Pleistocene. CO_2 ~450 ppm at 35 My keeps CO_2 in the range of early Cenozoic proxies (Fig. **5a**) and yields a good fit to the amplitude and mean CO_2 amount in the late Pleistocene (Fig. **5b**). A CO_2 threshold for Antarctic glaciation of ~500 ppm was previously inferred from proxy CO_2 data and a carbon cycle model [55].

Individual CO_2 proxies (Fig. **S10**) clarify limitations due to scatter among the measurements. Low CO_2 of some early Cenozoic proxies, if valid, would suggest higher climate sensitivity. However, in general the sensitivities inferred from the Cenozoic and Phanerozoic [56, 57, 58] agree well with our analysis, if we account for the ways in which sensitivity is defined and the periods emphasized in each empirical derivation (Table **S1**).

Our CO$_2$ estimate of ~450 ppm at 35 My (Fig. **5**) serves as a prediction to compare with new data on CO$_2$ amount. Model uncertainties (Fig. **S10**) include possible changes of non-CO$_2$ GHGs and the relation of ΔT_s to ΔT_{do}. The model fails to account for cooling in the past 15 My if CO$_2$ increased, as several proxies suggest (Fig. **S10**). Changing ocean currents, such as the closing of the Isthmus of Panama, may have contributed to climate evolution, but models find little effect on temperature [59]. Non-CO$_2$ GHGs also could have played a role, because little forcing would have been needed to cause cooling due to the magnitude of late Cenozoic albedo feedback.

3.3. Implication

We infer from Cenozoic data that CO$_2$ was the dominant Cenozoic forcing, that CO$_2$ was ~450 ± 100 ppm when Antarctica glaciated, and that glaciation is reversible. Together these inferences have profound implications.

Consider three points marked in Fig. (**4**): point A at 35 My, just before Antarctica glaciated; point B at recent interglacial periods; point C at the depth of recent ice ages. Point B is about half way between A and C in global temperature (Fig. **3b**) and climate forcings (Fig. **4**). The GHG forcing from the deepest recent ice age to current interglacial warmth is ~3.5 W/m^2. Additional 4 W/m^2 forcing carries the planet, at equilibrium, to the ice-free state. Thus equilibrium climate sensitivity to GHG change, including the surface albedo change as a slow feedback, is almost as large between today and an ice-free world as between today and the ice ages.

The implication is that global climate sensitivity of 3°C for doubled CO$_2$, although valid for the idealized Charney definition of climate sensitivity, is a considerable understatement of expected equilibrium global warming in response to imposed doubled CO$_2$. Additional warming, due to slow climate feedbacks including loss of ice and spread of flora over the vast high-latitude land area in the Northern Hemisphere, approximately doubles equilibrium climate sensitivity.

Equilibrium sensitivity 6°C for doubled CO$_2$ is relevant to the case in which GHG changes are specified. That is appropriate to the anthropogenic case, provided the GHG amounts are estimated from carbon cycle models including climate feedbacks such as methane release from tundra and ocean sediments. The equilibrium sensitivity is even higher if the GHG feedback is included as part of the climate response, as is appropriate for analysis of the climate response to Earth orbital perturbations. The very high sensitivity with both albedo and GHG slow feedbacks included accounts for the huge magnitude of glacial-interglacial fluctuations in the Pleistocene (Fig. **3**) in response to small forcings (section 3 of Supplementary Material).

Equilibrium climate response would not be reached in decades or even in a century, because surface warming is slowed by the inertia of the ocean (Fig. **S7**) and ice sheets. However, Earth's history suggests that positive feedbacks, especially surface albedo changes, can spur rapid global warmings, including sea level rise as fast as several meters per century [7]. Thus if humans push the climate system sufficiently far into disequilibrium, positive climate feedbacks may set in motion dramatic climate change and climate impacts that cannot be controlled.

4. ANTHROPOCENE ERA

Human-made global climate forcings now prevail over natural forcings (Fig. **2**). Earth may have entered the Anthropocene era [60, 61] 6-8 ky ago [62], but the net human-made forcing was small, perhaps slightly negative [7], prior to the industrial era. GHG forcing overwhelmed natural and negative human-made forcings only in the past quarter century (Fig. **2**).

Human-made climate change is delayed by ocean (Fig. **S7**) and ice sheet response times. Warming 'in the pipeline', mostly attributable to slow feedbacks, is now about 2°C (Fig. **2**). No additional forcing is required to raise global temperature to at least the level of the Pliocene, 2-3 million years ago, a degree of warming that would surely yield 'dangerous' climate impacts [5].

4.1. Tipping Points

Realization that today's climate is far out of equilibrium with current climate forcings raises the specter of 'tipping points', the concept that climate can reach a point where, without additional forcing, rapid changes proceed practically out of our control [2, 7, 63, 64]. Arctic sea ice and the West Antarctic Ice Sheet are examples of potential tipping points. Arctic sea ice loss is magnified by the positive feedback of increased absorption of sunlight as global warming initiates sea ice retreat [65]. West Antarctic ice loss can be accelerated by several feedbacks, once ice loss is substantial [39].

We define: (1) the *tipping level*, the global climate forcing that, if long maintained, gives rise to a specific consequence, and (2) the *point of no return*, a climate state beyond which the consequence is inevitable, even if climate forcings are reduced. A point of no return can be avoided, even if the tipping level is temporarily exceeded. Ocean and ice sheet inertia permit overshoot, provided the climate forcing is returned below the tipping level before initiating irreversible dynamic change.

Points of no return are inherently difficult to define, because the dynamical problems are nonlinear. Existing models are more lethargic than the real world for phenomena now unfolding, including changes of sea ice [65], ice streams [66], ice shelves [36], and expansion of the subtropics [67, 68].

The tipping level is easier to assess, because the paleoclimate quasi-equilibrium response to known climate forcing is relevant. The tipping level is a measure of the long-term climate forcing that humanity must aim to stay beneath to avoid large climate impacts. The tipping level does not define the magnitude or period of tolerable overshoot. However, if overshoot is in place for centuries, the thermal perturbation will so penetrate the ocean [10] that recovery without dramatic effects, such as ice sheet disintegration, becomes unlikely.

4.2. Target CO_2

Combined, GHGs other than CO_2 cause climate forcing comparable to that of CO_2 [2, 6], but growth of non-CO_2 GHGs is falling below IPCC [2] scenarios. Thus total GHG climate forcing change is now determined mainly by CO_2 [69]. Coincidentally, CO_2 forcing is similar to the net human-made forcing, because non-CO_2 GHGs tend to offset negative aerosol forcing [2, 5].

Thus we take future CO_2 change as approximating the net human-made forcing change, with two caveats. First, special effort to reduce non-CO_2 GHGs could alleviate the CO_2 requirement, allowing up to about +25 ppm CO_2 for the same climate effect, while resurgent growth of non-CO_2 GHGs could reduce allowed CO_2 a similar amount [6]. Second, reduction of human-made aerosols, which have a net cooling effect, could force stricter GHG requirements. However, an emphasis on reducing black soot could largely off-set reductions of high albedo aerosols [20].

Our estimated history of CO_2 through the Cenozoic Era provides a sobering perspective for assessing an appropriate target for future CO_2 levels. A CO_2 amount of order 450 ppm or larger, if long maintained, would push Earth toward the ice-free state. Although ocean and ice sheet inertia limit the rate of climate change, such a CO_2 level likely would cause the passing of climate tipping points and initiate dynamic responses that could be out of humanity's control.

The climate system, because of its inertia, has not yet fully responded to the recent increase of human-made climate forcings [5]. Yet climate impacts are already occurring that allow us to make an initial estimate for a target atmospheric CO_2 level. No doubt the target will need to be adjusted as climate data and knowledge improve, but the urgency and difficulty of reducing the human-made forcing will be less, and more likely manageable, if excess forcing is limited soon.

Civilization is adapted to climate zones of the Holocene. Theory and models indicate that subtropical regions expand poleward with global warming [2, 67]. Data reveal a 4-degree latitudinal shift already [68], larger than model predictions, yielding increased aridity in southern United States [70, 71], the Mediterranean region, Australia and parts of Africa. Impacts of this climate shift [72] support the conclusion that 385 ppm CO_2 is already deleterious.

Alpine glaciers are in near-global retreat [72, 73]. After a one-time added flush of fresh water, glacier demise will yield summers and autumns of frequently dry rivers, including rivers originating in the Himalayas, Andes and Rocky Mountains that now supply water to hundreds of millions of people. Present glacier retreat, and warming in the pipeline, indicate that 385 ppm CO_2 is already a threat.

Equilibrium sea level rise for today's 385 ppm CO_2 is at least several meters, judging from paleoclimate history [19, 32-34]. Accelerating mass losses from Greenland [74] and West Antarctica [75] heighten concerns about ice sheet stability. An initial CO_2 target of 350 ppm, to be reassessed as effects on ice sheet mass balance are observed, is suggested.

Stabilization of Arctic sea ice cover requires, to first approximation, restoration of planetary energy balance. Climate models driven by known forcings yield a present planetary energy imbalance of +0.5-1 W/m^2 [5]. Observed heat increase in the upper 700 m of the ocean [76] confirms the planetary energy imbalance, but observations of the entire ocean are needed for quantification. CO_2 amount must be reduced to 325-355 ppm to increase outgoing flux 0.5-1 W/m^2, if other forcings are unchanged. A further imbalance reduction, and thus CO_2 ~300-325 ppm, may be needed to restore sea ice to its area of 25 years ago.

Coral reefs are suffering from multiple stresses, with ocean acidification and ocean warming principal among them [77]. Given additional warming 'in-the-pipeline', 385 ppm CO_2 is already deleterious. A 300-350 ppm CO_2 target would significantly relieve both of these stresses.

4.3. CO_2 Scenarios

A large fraction of fossil fuel CO_2 emissions stays in the air a long time, one-quarter remaining airborne for several centuries [11, 78, 79]. Thus moderate delay of fossil fuel use will not appreciably reduce long-term human-made climate change. Preservation of a climate resembling that to which humanity is accustomed, the climate of the Holocene, requires that most remaining fossil fuel carbon is never emitted to the atmosphere.

Coal is the largest reservoir of conventional fossil fuels (Fig. **S12**), exceeding combined reserves of oil and gas [2, 79]. The only realistic way to sharply curtail CO_2 emissions is to phase out coal use except where CO_2 is captured and sequestered.

Phase-out of coal emissions by 2030 (Fig. **6**) keeps maximum CO_2 close to 400 ppm, depending on oil and gas reserves and reserve growth. IPCC reserves assume that half of readily extractable oil has already been used (Figs. **6**, **S12**). EIA [80] estimates (Fig. **S12**) have larger reserves and reserve growth. Even if EIA estimates are accurate, the IPCC case remains valid if the most difficult to extract oil and gas is left in the ground, *via* a rising price on carbon emissions that discourages remote exploration and environmental regulations that place some areas off-limit. If IPCC gas reserves (Fig. **S12**) are underestimated, the IPCC case in Fig. (**6**) remains valid if the additional gas reserves are used at facilities where CO_2 is captured.

However, even with phase-out of coal emissions and assuming IPCC oil and gas reserves, CO_2 would remain above 350 ppm for more than two centuries. Ongoing Arctic and ice sheet changes, examples of rapid paleoclimate change, and other criteria cited above all drive us to consider scenarios that bring CO_2 more rapidly back to 350 ppm or less.

4.4. Policy Relevance

Desire to reduce airborne CO_2 raises the question of whether CO_2 could be drawn from the air artificially. There are no large-scale technologies for CO_2 air capture now, but

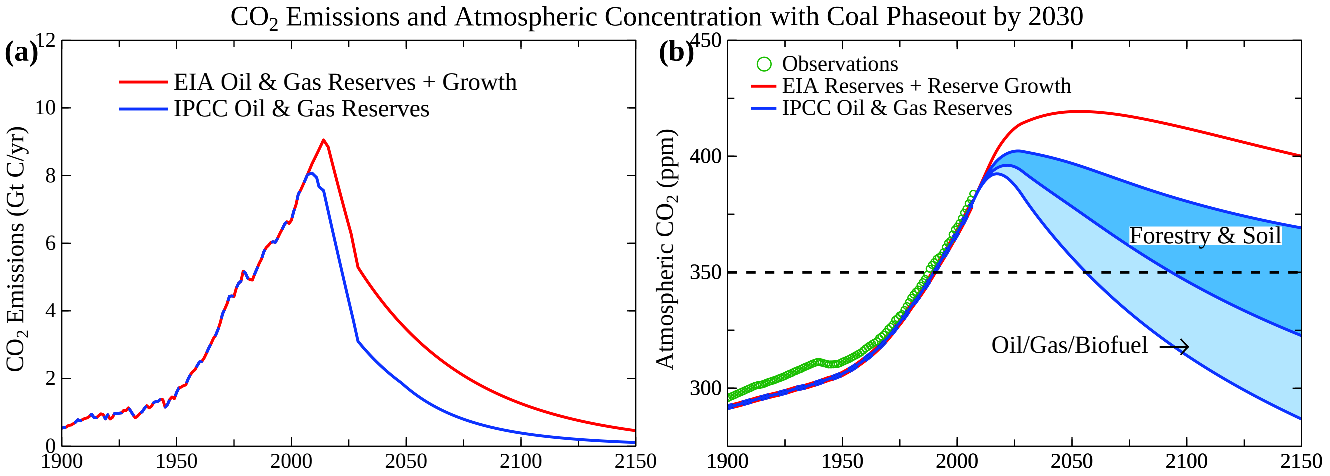


Fig. (6). (**a**) Fossil fuel CO_2 emissions with coal phase-out by 2030 based on IPCC [2] and EIA [80] estimated fossil fuel reserves. (**b**) Resulting atmospheric CO_2 based on use of a dynamic-sink pulse response function representation of the Bern carbon cycle model [78, 79].

with strong research and development support and industrial-scale pilot projects sustained over decades it may be possible to achieve costs ~\$200/tC [81] or perhaps less [82]. At \$200/tC, the cost of removing 50 ppm of CO_2 is ~\$20 trillion.

Improved agricultural and forestry practices offer a more natural way to draw down CO_2. Deforestation contributed a net emission of 60±30 ppm over the past few hundred years, of which ~20 ppm CO_2 remains in the air today [2, 83] (Figs. (**S12**, **S14**). Reforestation could absorb a substantial fraction of the 60±30 ppm net deforestation emission.

Carbon sequestration in soil also has significant potential. Biochar, produced in pyrolysis of residues from crops, forestry, and animal wastes, can be used to restore soil fertility while storing carbon for centuries to millennia [84]. Biochar helps soil retain nutrients and fertilizers, reducing emissions of GHGs such as N_2O [85]. Replacing slash-and-burn agriculture with slash-and-char and use of agricultural and forestry wastes for biochar production could provide a CO_2 drawdown of ~8 ppm or more in half a century [85].

In the Supplementary Material Section we define a forest/soil drawdown scenario that reaches 50 ppm by 2150 (Fig. **6b**). This scenario returns CO_2 below 350 ppm late this century, after about 100 years above that level.

More rapid drawdown could be provided by CO_2 capture at power plants fueled by gas and biofuels [86]. Low-input high-diversity biofuels grown on degraded or marginal lands, with associated biochar production, could accelerate CO_2 drawdown, but the nature of a biofuel approach must be carefully designed [85, 87-89].

A rising price on carbon emissions and payment for carbon sequestration is surely needed to make drawdown of airborne CO_2 a reality. A 50 ppm drawdown *via* agricultural and forestry practices seems plausible. But if most of the CO_2 in coal is put into the air, no such "natural" drawdown of CO_2 to 350 ppm is feasible. Indeed, if the world continues on a business-as-usual path for even another decade without initiating phase-out of unconstrained coal use, prospects for avoiding a dangerously large, extended overshoot of the 350 ppm level will be dim.

4.5. Caveats: Climate Variability, Climate Models, and Uncertainties

Climate has great variability, much of which is unforced and unpredictable [2, 90]. This fact raises a practical issue: what is the chance that climate variations, e.g., a temporary cooling trend, will affect public recognition of climate change, making it difficult to implement mitigation policies? Also what are the greatest uncertainties in the expectation of a continued global warming trend? And what are the impacts of climate model limitations, given the inability of models to realistically simulate many aspects of climate change and climate processes?

The atmosphere and ocean exhibit coupled nonlinear chaotic variability that cascades to all time scales [91]. Variability is so large that the significance of recent decadal global temperature change (Fig. **7a**) would be very limited, if the data were considered simply as a time series, without further information. However, other knowledge includes information on the causes of some of the temperature variability, the planet's energy imbalance, and global climate forcings.

The El Nino Southern Oscillation (ENSO) [94] accounts for most low latitude temperature variability and much of the global variability. The global impact of ENSO is coherent from month to month, as shown by the global-ocean-mean SST (Fig. **7b**), for which the ocean's thermal inertia minimizes the effect of weather noise. The cool anomaly of 2008 coincides with an ENSO minimum and does not imply a change of decadal temperature trend.

Decadal time scale variability, such as predicted weakening of the Atlantic overturning circulation [95], could interrupt global warming, as discussed in section 18 of the Supplementary Material. But the impact of regional dynamical effects on global temperature is opposed by the planet's energy imbalance [96], a product of the climate system's thermal inertia, which is confirmed by increasing ocean heat

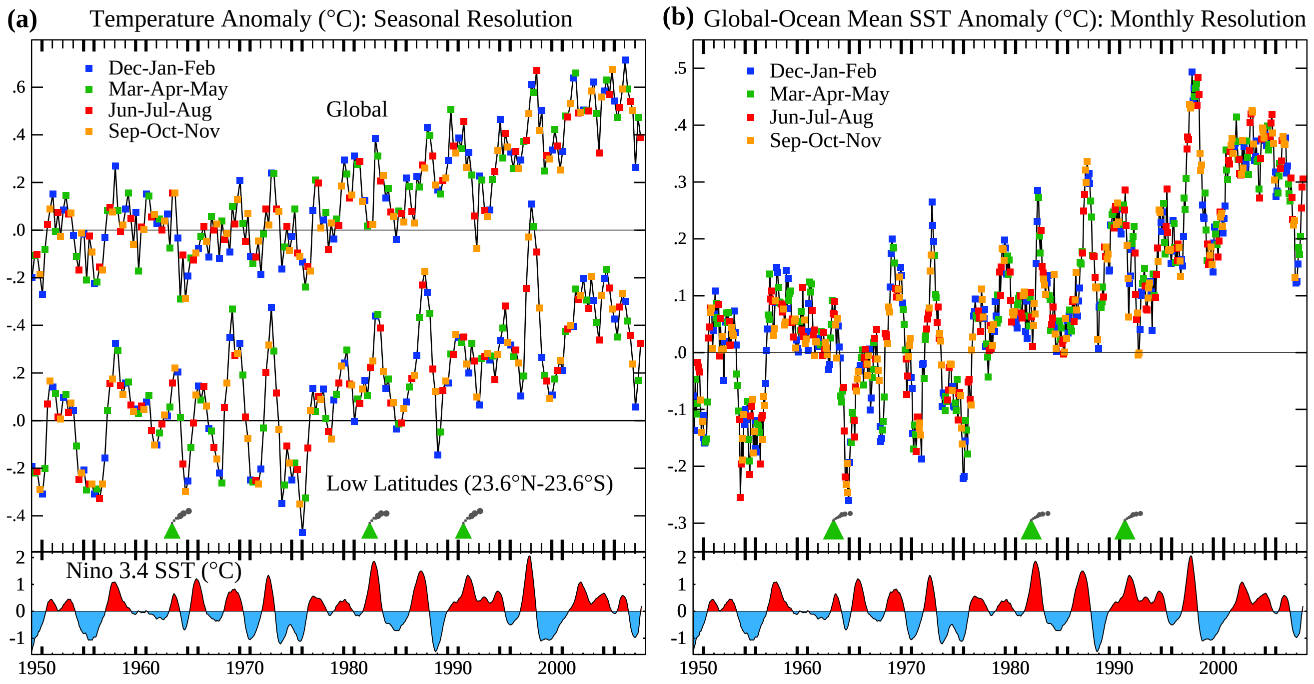


Fig. (7). (**a**) Seasonal-mean global and low-latitude surface temperature anomalies relative to 1951-1980, an update of [92], (**b**) global-ocean-mean sea surface temperature anomaly at monthly resolution. The Nino 3.4 Index, the temperature anomaly (12-month running mean) in a small part of the tropical Pacific Ocean [93], is a measure of ENSO, a basin-wide sloshing of the tropical Pacific Ocean [94]. Green triangles show major volcanic eruptions.

storage [97]. This energy imbalance makes decadal interruption of global warming, in the absence of a negative climate forcing, improbable [96].

Volcanoes and the sun can cause significant negative forcings. However, even if the solar irradiance remained at its value in the current solar minimum, this reduced forcing would be offset by increasing CO_2 within seven years (Supplementary Material section 18). Human-made aerosols cause a greater negative forcing, both directly and through their effects on clouds. The first satellite observations of aerosols and clouds with accuracy sufficient to quantify this forcing are planned to begin in 2009 [98], but most analysts anticipate that human-made aerosols will decrease in the future, rather than increase further.

Climate models have many deficiencies in their abilities to simulate climate change [2]. However, model uncertainties cut both ways: it is at least as likely that models underestimate effects of human-made GHGs as overestimate them (Supplementary Material section 18). Model deficiencies in evaluating tipping points, the possibility that rapid changes can occur without additional climate forcing [63, 64], are of special concern. Loss of Arctic sea ice, for example, has proceeded more rapidly than predicted by climate models [99]. There are reasons to expect that other nonlinear problems, such as ice sheet disintegration and extinction of interdependent species and ecosystems, also have the potential for rapid change [39, 63, 64].

5. SUMMARY

Humanity today, collectively, must face the uncomfortable fact that industrial civilization itself has become the principal driver of global climate. If we stay our present course, using fossil fuels to feed a growing appetite for energy-intensive life styles, we will soon leave the climate of the Holocene, the world of prior human history. The eventual response to doubling pre-industrial atmospheric CO_2 likely would be a nearly ice-free planet, preceded by a period of chaotic change with continually changing shorelines.

Humanity's task of moderating human-caused global climate change is urgent. Ocean and ice sheet inertias provide a buffer delaying full response by centuries, but there is a danger that human-made forcings could drive the climate system beyond tipping points such that change proceeds out of our control. The time available to reduce the human-made forcing is uncertain, because models of the global system and critical components such as ice sheets are inadequate. However, climate response time is surely less than the atmospheric lifetime of the human-caused perturbation of CO_2. Thus remaining fossil fuel reserves should not be exploited without a plan for retrieval and disposal of resulting atmospheric CO_2.

Paleoclimate evidence and ongoing global changes imply that today's CO_2, about 385 ppm, is already too high to maintain the climate to which humanity, wildlife, and the rest of the biosphere are adapted. Realization that we must reduce the current CO_2 amount has a bright side: effects that had begun to seem inevitable, including impacts of ocean acidification, loss of fresh water supplies, and shifting of climatic zones, may be averted by the necessity of finding an energy course beyond fossil fuels sooner than would otherwise have occurred.

We suggest an initial objective of reducing atmospheric CO_2 to 350 ppm, with the target to be adjusted as scientific understanding and empirical evidence of climate effects accumulate. Although a case already could be made that the eventual target probably needs to be lower, the 350 ppm target is sufficient to qualitatively change the discussion and drive fundamental changes in energy policy. Limited opportunities for reduction of non-CO_2 human-caused forcings are important to pursue but do not alter the initial 350 ppm CO_2 target. This target must be pursued on a timescale of decades, as paleoclimate and ongoing changes, and the ocean response time, suggest that it would be foolhardy to allow CO_2 to stay in the dangerous zone for centuries.

A practical global strategy almost surely requires a rising global price on CO_2 emissions and phase-out of coal use except for cases where the CO_2 is captured and sequestered. The carbon price should eliminate use of unconventional fossil fuels, unless, as is unlikely, the CO_2 can be captured. A reward system for improved agricultural and forestry practices that sequester carbon could remove the current CO_2 overshoot. With simultaneous policies to reduce non-CO_2 greenhouse gases, it appears still feasible to avert catastrophic climate change.

Present policies, with continued construction of coal-fired power plants without CO_2 capture, suggest that decision-makers do not appreciate the gravity of the situation. We must begin to move now toward the era beyond fossil fuels. Continued growth of greenhouse gas emissions, for just another decade, practically eliminates the possibility of near-term return of atmospheric composition beneath the tipping level for catastrophic effects.

The most difficult task, phase-out over the next 20-25 years of coal use that does not capture CO_2, is Herculean, yet feasible when compared with the efforts that went into World War II. The stakes, for all life on the planet, surpass those of any previous crisis. The greatest danger is continued ignorance and denial, which could make tragic consequences unavoidable.

ACKNOWLEDGMENTS

We thank H. Harvey and Hewlett Foundation, G. Lenfest, the Rockefeller Family Foundation, and NASA program managers D. Anderson and J. Kaye for research support, an anonymous reviewer, S. Baum, B. Brook, P. Essunger, K. Farnish, Q. Fu, L.D. Harvey, I. Horovitz, R. Keeling, C. Kutscher, J. Leventhal, C. McGrath, T. Noerpel, P. Read, J. Romm, D. Sanborn, S. Schwartz, J. Severinghaus, K. Ward and S. Weart for comments on a draft manuscript, G. Russell for the computations in Fig. (**S3**), and T. Conway and P. Tans of NOAA Earth System Research Laboratory and R. Andres, T. Boden and G. Marland of DOE CDIAC for data.

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Received: May 22, 2008 Revised: August 19, 2008 Accepted: September 23, 2008

Supplementary Material

1. ICE AGE CLIMATE FORCINGS

Fig. (**S1**) shows the climate forcings during the depth of the last ice age, 20 ky BP, relative to the Holocene [14]. The largest contribution to the uncertainty in the calculated 3.5 W/m^2 forcing due to surface changes (ice sheet area, vegetation distribution, shoreline movements) is due to uncertainty in the ice sheet sizes [14, S1]. Formulae for the GHG forcings [20] yield 2.25 W/m^2 for CO_2 (185 ppm → 275 ppm), 0.43 W/m^2 for CH_4 (350 → 675 ppb) and 0.32 W/m^2 for N_2O (200 → 270 ppb). The CH_4 forcing includes a factor 1.4 to account for indirect effects of CH_4 on tropospheric ozone and stratospheric water vapor [12].

The climate sensitivity inferred from the ice age climate change (~¾°C per W/m^2) includes only fast feedbacks, such as water vapor, clouds, aerosols (including dust) and sea ice. Ice sheet size and greenhouse gas amounts are specified boundary conditions in this derivation of the fast-feedback climate sensitivity.

It is permissible, alternatively, to specify aerosol changes as part of the forcing and thus derive a climate sensitivity that excludes the effect of aerosol feedbacks. That approach was used in the initial empirical derivation of climate sensitivity from Pleistocene climate change [14]. The difficulty with that approach is that, unlike long-lived GHGs, aerosols are distributed heterogeneously, so it is difficult to specify aerosol changes accurately. Also the forcing is a sensitive function of aerosol single scatter albedo and the vertical distribution of aerosols in the atmosphere, which are not measured. Furthermore, the aerosol indirect effect on clouds also depends upon all of these poorly known aerosol properties.

One recent study [S2] specified an arbitrary glacial-interglacial aerosol forcing slightly larger than the GHG glacial-interglacial forcing. As a result, because temperature, GHGs, and aerosol amount, overall, are positively correlated in glacial-interglacial changes, this study inferred a climate sensitivity of only ~2°C for doubled CO_2. This study used the correlation of aerosol and temperature in the Vostok ice core at two specific times to infer an aerosol forcing for a given aerosol amount. The conclusions of the study are immediately falsified by considering the full Vostok aerosol record (Fig. **2** of [17]), which reveals numerous large aerosol fluctuations without any corresponding temperature change. In contrast, the role of GHGs in climate change is confirmed when this same check is made for GHGs (Fig. **2**), and the fast-feedback climate sensitivity of 3°C for doubled CO_2 is confirmed (Fig. **1**).

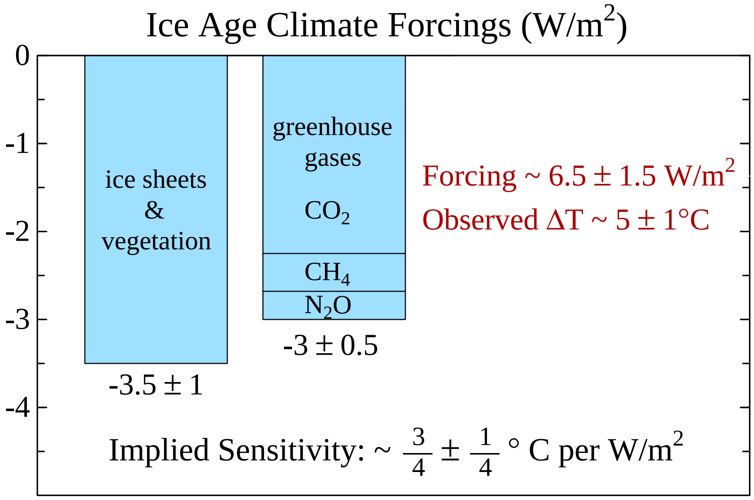


Fig. (S1). Climate forcings during ice age 20 ky BP, relative to the present (pre-industrial) interglacial period.

All the problems associated with imprecise knowledge of aerosol properties become moot if, as is appropriate, aerosols are included in the fast feedback category. Indeed, soil dust, sea salt, dimethylsulfide, and other aerosols are expected to vary (in regional, inhomogeneous ways) as climate changes. Unlike long-lived GHGs, global aerosol amounts cannot be inferred from ice cores. But the effect of aerosol changes is fully included in observed global temperature change. The climate sensitivity that we derive in Fig. (**S1**) includes the aerosol effect accurately, because both the climate forcings and the global climate response are known. The indirect effect of aerosol change on clouds is, of course, also included precisely.

2. CLIMATE FORCINGS AND CLIMATE FEEDBACKS

The Earth's temperature at equilibrium is such that the planet radiates to space (as heat, i.e., infrared radiation) the same amount of energy that it absorbs from the sun, which is ~240 W/m^2. A blackbody temperature of ~255°K yields a heat flux of 240 W/m^2. Indeed, 255°K is the temperature in the mid-troposphere, the mean level of infrared emission to space.

A climate forcing is a perturbation to the planet's energy balance, which causes the Earth's temperature to change as needed to restore energy balance. Doubling atmospheric CO_2 causes a planetary energy imbalance of ~4 W/m^2, with more energy coming in than going out. Earth's temperature would need to increase by ΔT_O = 1.2-1.3°C to restore planetary energy balance, if the temperature change were uniform throughout the atmosphere and if nothing else changed.

Actual equilibrium temperature change in response to any forcing is altered by feedbacks that can amplify or diminish the response, thus the mean surface temperature change is [14]

$$\begin{aligned}\Delta T_{eq} &= f\,\Delta T_O\\ &= \Delta T_O + \Delta T_{feedbacks}\\ &= \Delta T_O + \Delta T_1 + \Delta T_2 + \ldots,\end{aligned}$$

where f is the net feedback factor and the ΔT_i are increments due to specific feedbacks.

The role of feedback processes is clarified by defining the gain, g,

$$\begin{aligned}g &= \Delta T_{feedbacks}/\Delta T_{eq}\\ &= (\Delta T_1 + \Delta T_2 + \ldots)/\Delta T_{eq}\\ &= g_1 + g_2 + \ldots\end{aligned}$$

g_i is positive for an amplifying feedback and negative for a feedback that diminishes the response. The additive nature of the g_i, unlike f_i, is a useful characteristic of the gain. Evidently

$$f = 1/(1 - g)$$

The value of g (or f) depends upon the climate state, especially the planetary temperature. For example, as the planet becomes so warm that land ice disappears, the land ice albedo feedback diminishes, i.e. $g_{\text{land ice albedo}} \rightarrow 0$.

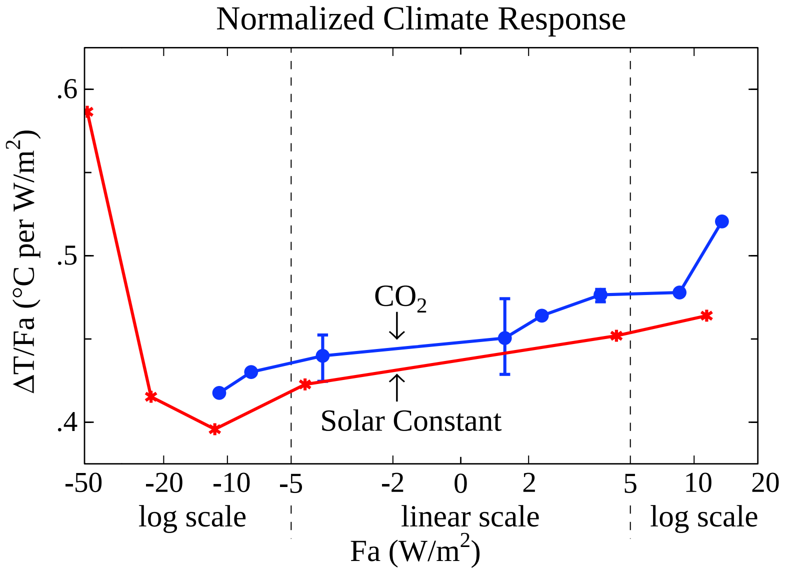


Fig. (S2). Global surface air temperature change [12] after 100 years in simulations with the Goddard Institute for Space Studies modelE [S3, 5] as a function of climate forcing for changes of solar irradiance and atmospheric CO_2. Fa is the standard adjusted climate forcing [12]. Results are extracted from Fig. (**25a**) of [12]. Curves terminate because the climate model 'bombs' at the next increment of forcing due to failure of one or more of the parameterizations of processes in the model as extreme conditions are approached.

'Fast feedbacks', such as water vapor, clouds and sea ice, are the mechanisms usually included in the 'Charney' [13] climate sensitivity. Climate models yield a Charney (fast feedback) sensitivity of about 3°C for doubled CO_2 [2, 12], a conclusion that is confirmed and tightened by empirical evidence from the Pleistocene (Section 2.1). This sensitivity implies

$$g_{\text{fast feedbacks}} \sim 0.5\text{-}0.6.$$

This fast feedback gain and climate sensitivity apply to the present climate and climate states with global temperatures that are not too different than at present.

If g approaches unity, f → ∞, implying a runaway climate instability. The possibility of such instability is anticipated for either a very warm climate (runaway greenhouse effect [S4]) or a very cold climate (snowball Earth [S5]). We can investigate how large a climate forcing is needed to cause g → 1 using a global climate model that includes the fast feedback processes, because both of these instabilities are a result of the temperature dependence of 'fast feedbacks' (the water vapor and ice/snow albedo feedbacks, respectively).

Fig. (**S2**) suggests that climate forcings ~10-25 W/m^2 are needed to approach either runaway snowball-Earth conditions or the runaway greenhouse effect. More precise quantification requires longer simulations and improved parameterizations of physical processes as extreme climates are approached. The processes should include slow feedbacks that can either amplify or diminish the climate change.

Earth has experienced snowball conditions [S5], or at least a 'slushball' state [S6] with ice reaching sea level in the tropics, on at least two occasions, the most recent ~640 My BP, aided by reduced solar irradiance [43] and favorable continental locations. The mechanism that allowed Earth to escape the snowball state was probably reduced weathering in a glaciated world, which allowed CO_2 to accumulate in the atmosphere [S5]. Venus, but not Earth, has experienced the runaway greenhouse effect, a state from which there is no escape.

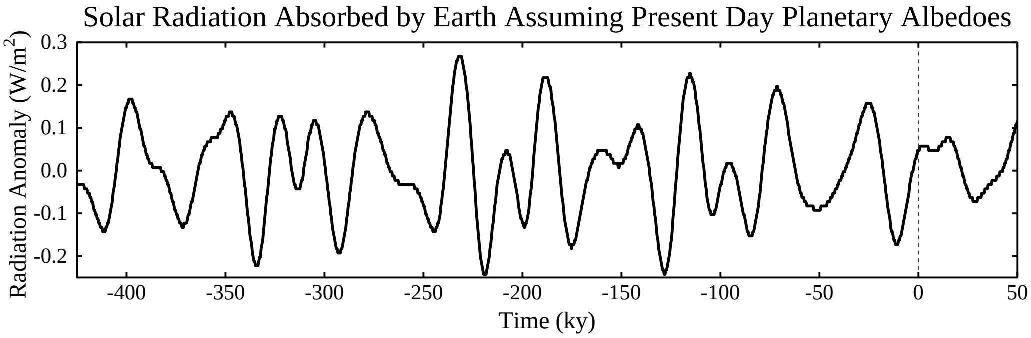


Fig. (S3). Annual-mean global-mean perturbation of the amount of solar radiation absorbed by the Earth, calculated by assuming present-day seasonal and geographical distribution of albedo.

3. PLEISTOCENE FORCINGS AND FEEDBACKS

Fig. (**S3**) shows the perturbation of solar radiation absorbed by the Earth due to changes in Earth orbital elements, i.e., the tilt of the Earth's spin axis relative to the orbital plane, the eccentricity of the Earth's orbit, and the time of year at which the Earth is closest to the sun (precession of equinoxes). This perturbation is calculated using fixed (present day) seasonal and geographical distribution of planetary albedo.

The global-mean annual-mean orbital (Milankovitch) forcing is very weak, at most a few tenths of 1 W/m^2. Our procedure in calculating the forcing, keeping ice sheet properties (size and albedo) fixed, is appropriate for 'instantaneous' and 'adjusted' radiative forcings [12].

Further, successive, definitions of the orbital 'forcing', e.g., allowing some regional response to the seasonal insolation perturbations, may be useful for the purpose of understanding glacial-interglacial climate change. For example, it may be informative to calculate the 'forcing' due to insolation-induced changes of ice-she*et al*bedo, because increased insolation can 'age' (increase snow crystal size and thus darken) an ice surface and also spur the date of first snow-melt [7]. However, one merit of the standard forcing definition is the insight that glacial-interglacial climate swings are almost entirely due to feedbacks.

Indeed, the gain during the Pleistocene is close to unity. Climate models and empirical evaluation from the climate change between the last ice age (Section 2.1 above) yield $g_{\text{fast feedbacks}}$ ~0.5-0.6 (the gain corresponding to fast feedback climate sensitivity 3°C for doubled CO_2). GHGs and surface albedo contribute about equally to glacial-interglacial 'forcings' and temperature change, with each having gain ~0.2 [14]. Thus

$$g = g_{\text{fast feedbacks}} + g_{\text{surface albedo}} + g_{\text{GHG}}$$

$$= \sim 0.5\text{-}0.6 + \sim 0.2 + \sim 0.2.$$

Thus climate gain in the Pleistocene was greater than or of the order of 0.9. It is no wonder that late Cenozoic climate fluctuated so greatly (Fig. **3b**). When substantial ice is present on the planet, g is close to unity, climate is sensitive, and large climate swings occur in response to small orbital forcings. Indeed, with g near unity any forcing or climate noise can cause large climate change, consistent with the conclusion that much of climate variability is not due to orbital forcings [S7]. In the early Cenozoic there was little ice, $g_{\text{surface albedo}}$ was small, and thus climate oscillations due to insolation perturbations were smaller.

It may be useful to divide inferences from Pleistocene climate change into two categories: (1) well-defined conclusions about the nature of the climate change, (2) less certain suggestions about the nature and causes of the climate change. The merit of identifying well-defined conclusions is that they help us predict likely consequences of human-made climate forcings. Less certain aspects of Pleistocene climate change mainly concern the small forcings that instigated climate swings. The small forcings are of great interest to paleoclimatologists, but they need not prevent extraction of practical implications from Pleistocene climate change.

Two fundamental characteristics of Pleistocene climate change are clear. First, there is the high gain, at least of the order of 0.9, i.e., the high sensitivity to a climate forcing, when the planet is in the range of climates that existed during the Pleistocene. Second, we have a good knowledge of the amplifying feedbacks that produce this high gain. Fast feedbacks, including water vapor, clouds, aerosols, sea ice and snow, contribute at least half of this gain. The remainder of the amplification is provided almost entirely by two factors: surface albedo (mainly ice sheets) and GHGs (mainly CO_2).

Details beyond these basic conclusions are less certain. The large glacial-interglacial surface albedo and GHG changes should lag global temperature, because they are feedbacks on global temperature on the global spatial scale and millennial time scale. The lag of GHGs after temperature change is several hundred years (Fig. **6** of [6]), perhaps determined by the ocean overturning time. Ice sheet changes may lag temperature by a few millennia [24], but it has been argued that there is no discernible lag between insolation forcing and the maximum rate of change of ice sheet volume [7].

A complication arises from the fact that some instigating factors (forcing mechanisms) for Pleistocene climate change also involve surface albedo and GHG changes. Regional anomalies of seasonal insolation are as much as many tens of W/m^2. The global forcing is small (Fig. **S3**) because the local anomalies are nearly balanced by anomalies of the opposite sign in either the opposite hemisphere or the opposite season. However, one can readily imagine climate change mechanisms that operate in such a way that cancellation does not occur.

For example, it has been argued [7] that a positive insolation anomaly in late spring is most effective for causing ice sheet disintegration because early ‘albedo flip’, as the ice becomes wet, yields maximum extension of the melt season. It is unlikely that the strong effect of albedo flip on absorbed solar energy could be offset by a negative insolation anomaly at other times of year.

A second example is non-cancellation of hemispheric insolation anomalies. A hemispheric asymmetry occurs when Earth is cold enough that ice sheets extend to Northern Hemisphere middle latitudes, due to absence of similar Southern Hemisphere land. It has been argued [7] that this hemispheric asymmetry is the reason that the orbital periodicities associated with precession of the equinoxes and orbit eccentricity became substantial about 1 million years ago.

Insolation anomalies also may directly affect GHG amounts, as well as surface albedo. One can readily imagine ways in which insolation anomalies affect methane release from wetlands or carbon uptake through biological processes.

Surface albedo and GHG changes that result immediately from insolation anomalies can be defined as climate forcings, as indirect forcings due to insolation anomalies. The question then becomes: what fractions of the known paleo albedo and GHG changes are immediate indirect forcings due to insolation anomalies and what fractions are feedbacks due to global temperature change?

It is our presumption that most of the Pleistocene GHG changes are a slow feedback in response to climate change. This interpretation is supported by the lag of several hundred years between temperature change and greenhouse gas amount (Fig. **6** of [6]). The conclusion that most of the ice area and surface albedo change is also a feedback in response to global temperature change is supported by the fact that the large climate swings are global (Section 5 of Appendix).

Note that our inferred climate sensitivity is not dependent on detailed workings of Pleistocene climate fluctuations. The fast feedback sensitivity of 3°C for doubled CO_2, derived by comparing glacial and interglacial states, is independent of the cause and dynamics of glacial/interglacial transitions.

Climate sensitivity including surface albedo feedback (~6°C for doubled CO_2) is the average sensitivity for the climate range from 35 My ago to the present and is independent of the glacial-interglacial ‘wiggles’ in Fig. (**3**). Note that climate and albedo changes occurred mainly at points with ‘ready’ [63] feedbacks: at Antarctic glaciation and (in the past three million years) with expansion of Northern Hemisphere glaciation, which are thus times of high climate sensitivity.

The entire ice albedo feedback from snowball-Earth to ice-free planet (or vice versa) can be viewed as a response to changing global temperature, with wiggles introduced by Milankovitch (orbital) forcings. The average $g_{\text{surface albedo}}$ for the range from today’s climate through Antarctic deglaciation is close to $g_{\text{surface albedo}} \sim 0.2$, almost as large as in the Pleistocene. Beyond Antarctic deglaciation (i.e., for an ice-free planet) $g_{\text{surface albedo}} \rightarrow 0$, except for vegetation effects.

For the sake of specificity, let us estimate the effect of slow feedbacks on climate sensitivity. If we round ΔT_O to 1.2°C for doubled CO_2 and the fast feedback gain to $g_{\text{fast feedbacks}} = 0.6$, then for fast feedbacks alone $f = 2.5$ and the equilibrium warming is $\Delta T_{eq} = 3°C$. Inclusion of $g_{\text{surface albedo}} = 0.2$ makes $f = 5$ and $\Delta T_{eq} = 6°C$, which is the sensitivity if the GHG amount is specified from observations or from a carbon cycle model.

The feedback factor f can approach infinity, i.e., the climate can become unstable. However, instabilities are limited except at the snowball Earth and runaway greenhouse extremes. Some feedbacks have a finite supply, e.g., as when Antarctica becomes fully deglaciated. Also climate change can cause positive feedbacks to decrease or negative feedbacks to come into play.

For example, Fig. (**S2**) suggests that a cooling climate from the present state first reduces the fast feedback gain. This and reduced weathering with glaciation may be reasons that most ice ages did not reach closer to the iceball state. Also there may be limitations on the ranges of GHG (CO_2, CH_4, N_2O) feedbacks. Empirical values g_{GHG} ~ 0.2 and $g_{surface\ albedo}$ ~ 0.2 were derived as averages relevant to the range of climates that existed in the past several hundred thousand years, and they may not be valid outside that range.

On the other hand, if the forcing becomes large enough, global instabilities are possible. Earth did become cold enough in the past for the snowball-Earth instability. Although the runaway greenhouse effect has not occurred on Earth, solar irradiance is now at its highest level so far, and Fig. (**S2**) suggests that the required forcing for runaway may be only 10-20 W/m^2. If all conventional and unconventional fossil fuels were burned, with the CO_2 emitted to the atmosphere, it is possible that a runaway greenhouse effect could occur, with incineration of life and creation of a permanent Venus-like hothouse Earth. It would take time for the ice sheets to melt, but the melt rate may accelerate as ice sheet disintegration proceeds.

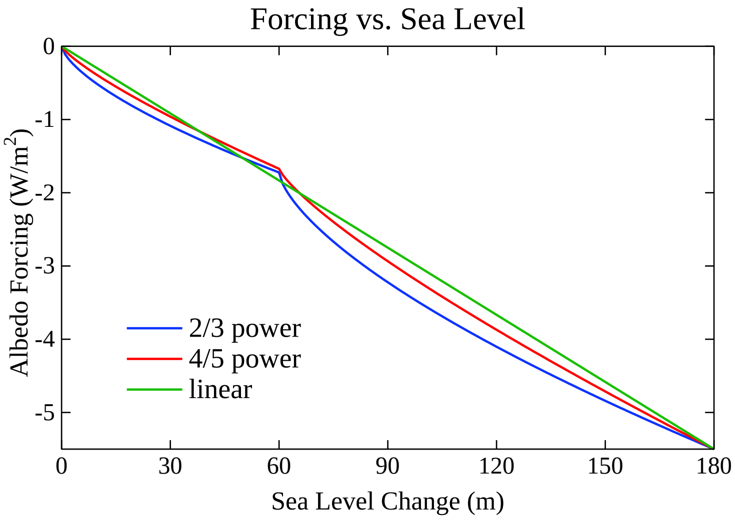


Fig. (S4). Surface albedo climate forcing as a function of sea level for three approximations of the ice sheet area as a function of sea level change, from an ice free planet to the last glacial maximum. For sea level between 0 and 60 m only Antarctica contributes to the albedo change. At the last glacial maximum Antarctica contains 75 m of sea level and the Northern Hemisphere contains 105 m.

4. ICE SHEE*T AL*BEDO

In the present paper we take the surface area covered by an ice sheet to be proportional to the 4/5 power of the volume of the ice sheet, based on ice sheet modeling of one of us (VM-D). We extend the formulation all the way to zero ice on the planet, with separate terms for each hemisphere. At 20 ky ago, when the ice sheets were at or near their maximum size in the Cenozoic era, the forcing by the Northern Hemisphere ice sheet was -3.5 W/m^2 and the forcing by the Southern Hemisphere ice sheet was -2 W/m^2, relative to the ice-free planet [14]. It is assumed that the first 60 m of sea level fall went entirely into growth of the Southern Hemisphere ice sheet. The water from further sea level fall is divided proportionately between hemispheres such that when sea level fall reaches -180 m there is 75 m in the ice sheet of the Southern Hemisphere and 105 m in the Northern Hemisphere.

The climate forcing due to sea level changes in the two hemispheres, SL_S and SL_N, is

$$F_{Albedo}\ (W/m^2) = -\ 2\ (SL_S/75\ m)^{4/5} - 3.5\ (SL_N/105\ m)^{4/5}, \qquad (S1)$$

where the climate forcings due to fully glaciated Antarctica (-2 W/m^2) and Northern Hemisphere glaciation during the last glacial maximum (-3.5 W/m^2) were derived from global climate model simulations [14].

Fig. (**S4**) compares results from the present approach with results from the same approach using exponent 2/3 rather than 4/5, and with a simple linear relationship between the total forcing and sea level change. Use of exponent 4/5 brings the results close to the linear case, suggesting that the simple linear relationship is a reasonably good approximation. The similarity of Fig. (**1c**) in our present paper and Fig. (**2c**) in [7] indicates that change of exponent from 2/3 to 4/5 did not have a large effect.

5. GLOBAL NATURE OF MAJOR CLIMATE CHANGES

Climate changes often begin in a specific hemisphere, but the large climate changes are invariably global, in part because of the global GHG feedback. Even without the GHG feedback, forcings that are located predominately in one hemisphere, such as ice sheet changes or human-made aerosols, still evoke a global response [12], albeit with the response being larger in the hemisphere of the forcing. Both the atmosphere and ocean transmit climate response between hemispheres. The deep ocean can carry a temperature change between hemispheres with little loss, but because of the ocean's thermal inertia there can be a hemispheric lag of up to a millennium (see Ocean Response Time, below).

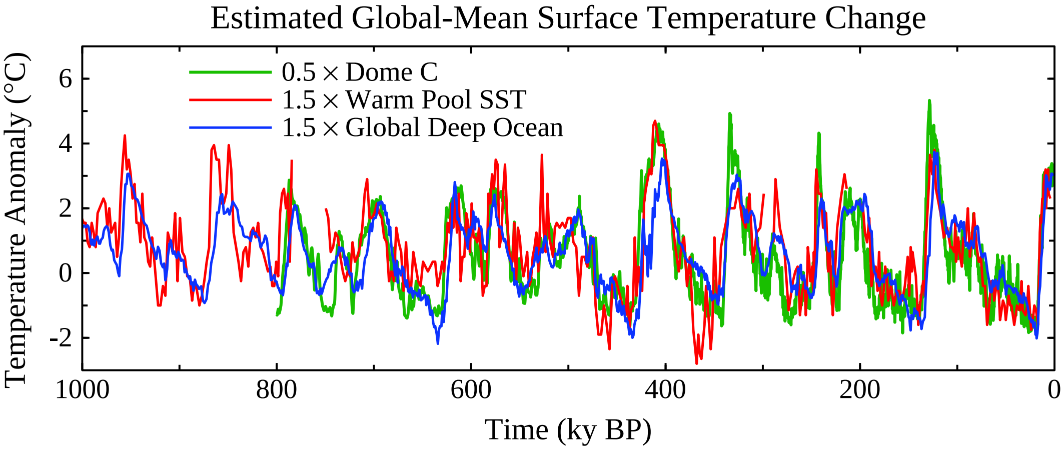


Fig. (S5). Estimated global temperature change based on measurements at a single point or, in the case of the deep ocean, a near-global stack of ocean drilling sites: Antarctica Dome C [S8], Warm Pool [S9], deep ocean [26].

Fig. (**S5**) compares temperature change in Antarctica [S8], the tropical sea surface [S9], and the global deep ocean [26]. Temperature records are multiplied by factors that convert the temperature record to an estimate of global temperature change. Based on paleoclimate records, polar temperature change is typically twice the global average temperature change, and tropical temperature change is about two-thirds of the global mean change. This polar amplification of the temperature change is an expected consequence of feedbacks [14], especially the snow-ice albedo feedback. The empirical result that deep ocean temperature changes are only about two-thirds as large as global temperature change is obtained from data for the Pleistocene epoch, when deep ocean temperature change is limited by its approach to the freezing point.

6. HOLOCENE CLIMATE FORCINGS

The GHG zero-point for the paleo portion of Fig. (**2**) is the mean for 10-8 ky BP, a time that should precede any significant anthropogenic effect on GHG amount. It has been suggested that the increase of CO_2 that began 8000 years ago is due to deforestation and the increase of CH_4 that began 6000 years ago is caused by rice agriculture [62]. This suggestion has proven to be controversial, but regardless of whether late Holocene CO_2 and CH_4 changes are human-made, the GHG forcing is anomalous in that period relative to global temperature change estimated from ocean and ice cores. As discussed elsewhere [7], the late Holocene is the only time in the ice core record in which there is a clear deviation of temperature from that expected due to GHG and surface albedo forcings.

The GHG forcing increase in the second half of the Holocene is ~3/4 W/m^2. Such a large forcing, by itself, would create a planetary energy imbalance that could not be sustained for millennia without causing a large global temperature increase, the expected global warming being about 1°C. Actual global temperature change in this period was small, perhaps a slight cooling. Fig. (**S6**) shows estimates of global temperature change obtained by dividing polar temperature change by two or multiplying tropical and deep ocean temperatures by 1.5. Clearly the Earth has not been warming rapidly in the latter half of the Holocene. Thus a substantial (negative) forcing must have been operating along with the positive GHG forcing.

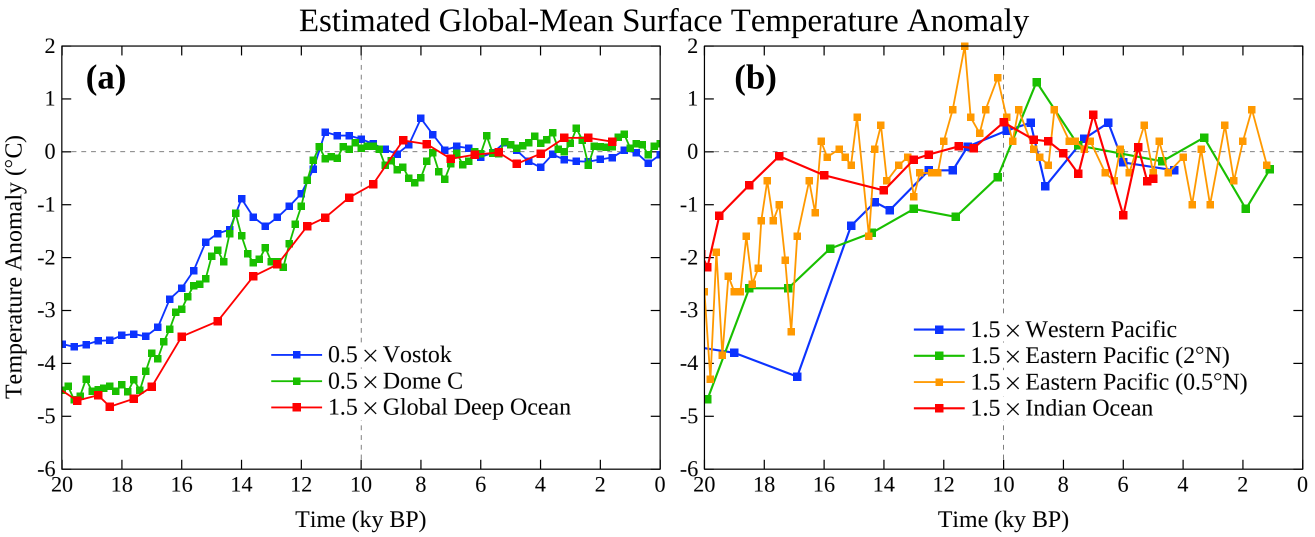


Fig. (S6). Estimates of global temperature change inferred from Antarctic ice cores [18, S8] and ocean sediment cores [S9-S13], as in Fig. (**S5**) but for a period allowing Holocene temperature to be apparent.

Deforestation causes a negative climate forcing [12], but an order of magnitude too small to balance GHG positive forcing. A much larger negative forcing is expected from human-made aerosols. Aerosol forcing is non-linear, especially the indirect effect on clouds, with aerosols added to a pristine atmosphere being more effective than those added to the current highly polluted atmosphere. Given estimates of a negative forcing of 1-2 W/m^2 for today's anthropogenic aerosols [2, 5, 12], a negative aerosol forcing at least of the order of 0.5 W/m^2 in 1850 is expected. We conclude that aerosols probably were the predominant negative forcing that opposed the rapid increase of positive GHG forcing in the late Holocene.

7. OCEAN RESPONSE TIME

Fig. (**S7**) shows the climate response function, defined as the fraction of equilibrium global warming that is obtained as a function of time. This response function was obtained [7] from a 3000-year simulation after instant doubling of atmospheric CO_2, using GISS modelE [S3, 12] coupled to the Russell ocean model [S14]. Note that although 40% of the equilibrium solution is obtained within several years, only 60% is achieved after a century, and nearly full response requires a millennium. The long response time is caused by slow uptake of heat by the deep ocean, which occurs primarily in the Southern Ocean.

This delay of the surface temperature response to a forcing, caused by ocean thermal inertia, is a strong (quadratic) function of climate sensitivity and it depends on the rate of mixing of water into the deep ocean [31]. The ocean model used for Fig. (**S7**) may mix somewhat too rapidly in the waters around Antarctica, as judged by transient tracers [S14], reducing the simulated surface response on the century time scale. However, this uncertainty does not qualitatively alter the shape of the response function (Fig. **S7**).

When the climate model used to produce Fig. (**S7**) is driven by observed changes of GHGs and other forcings it yields good agreement with observed global temperature and ocean heat storage [5]. The model has climate sensitivity ~3°C for doubled CO_2, in good agreement with the fast-feedback sensitivity inferred from paleoclimate data.

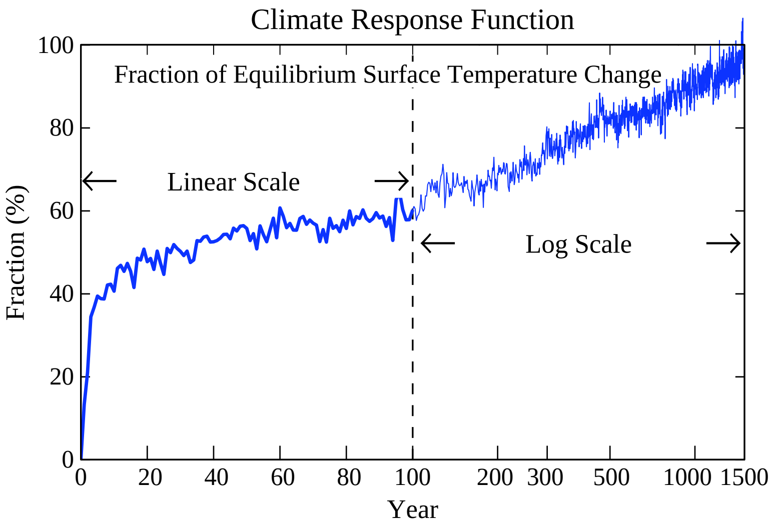


Fig. (S7). Fraction of equilibrium surface temperature response versus time in the GISS climate model [7, 12, S3] with the Russell [S14] ocean. The forcing was doubled atmospheric CO_2. The ice sheets, vegetation distribution and other long-lived GHGs were fixed.

8. SEPARATION OF Δ^{18}O INTO ICE VOLUME AND TEMPERATURE

δ^{18}O of benthic (deep ocean dwelling) foraminifera is affected by both deep ocean temperature and continental ice volume. Between 34 My and the last ice age (20 ky) the change of δ^{18}O was ~ 3, with T_{do} change ~ 6°C (from +5 to -1°C) and ice volume change ~ 180 msl (meters of sea level). Based on the rate of change of δ^{18}O with deep ocean temperature in the prior period without land ice, ~ 1.5 of δ^{18}O is associated with the T_{do} change of ~ 6°C, and we assign the remaining δ^{18}O change to ice volume linearly at the rate 60 msl per mil δ^{18}O change (thus 180 msl for δ^{18}O between 1.75 and 4.75).

Thus we assume that ice sheets were absent when δ^{18}O < 1.75 with sea level 75 msl higher than today. Sea level at smaller values of δ^{18}O is given by

$$\mathrm{SL\ (m)} = 75 - 60 \times (\delta^{18}\mathrm{O} - 1.75). \qquad \mathrm{(S2)}$$

Fig. (**S8**) shows that the division of δ^{18}O equally into sea level change and deep ocean temperature captures well the magnitude of the major glacial to interglacial changes.

9. CONTINENTAL DRIFT AND ATMOSPHERIC CO_2

At the beginning of the Cenozoic era 65 My ago the continents were already close to their present latitudes, so the effect of continental location on surface albedo had little direct effect on the planet's energy balance (Fig. **S9**). However, continental drift has a major effect on the balance, or imbalance, of outgassing and uptake of CO_2 by the solid Earth and thus a major effect on atmospheric composition and climate. We refer to the carbon in the air, ocean, soil and biosphere as the combined surface reservoir of carbon, and carbon in ocean sediments and the rest of the crust as the carbon in the 'solid' Earth. Sloshing of CO_2 among the surface reservoirs, as we have shown, is a primary mechanism for glacial-interglacial climate fluctuations. On longer time scales the total amount of carbon in the surface reservoirs can change as a result of any imbalance between outgassing and uptake by the solid Earth.

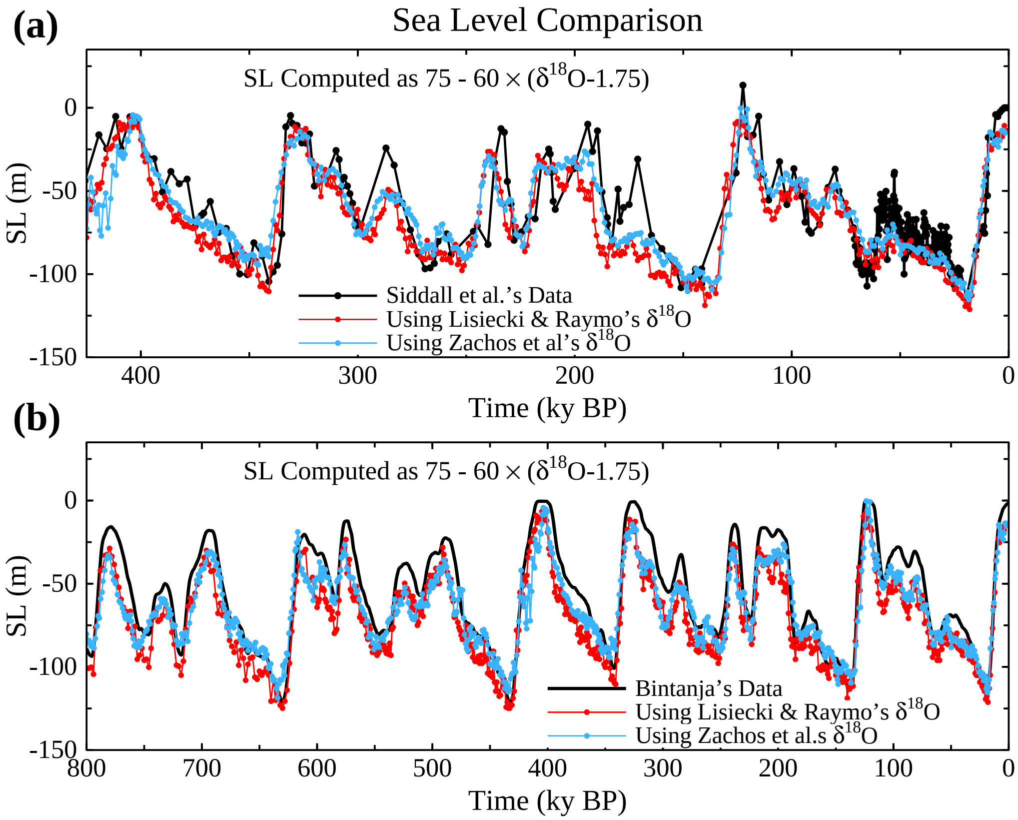
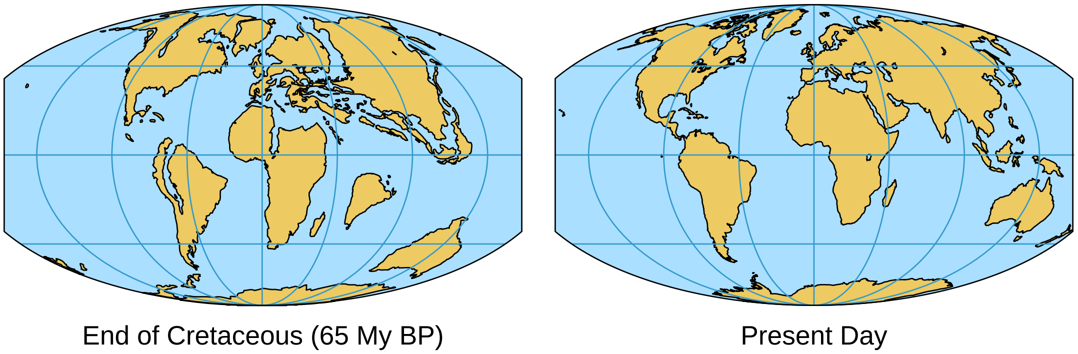


Fig. (S8). (**a**) Comparison of Siddall *et al.* [19] sea level record with sea level computed from $\delta^{18}O$ *via* Eq. S2 using two alternative global benthic stacks [26, S15]. (**b**) Comparison of Bintanja *et al.* [S16] sea level reconstruction with the same global benthic stacks as in (**a**).


End of Cretaceous (65 My BP)

Present Day

Fig. (S9). Continental locations at the beginning and end of the Cenozoic era [S17].

Outgassing, which occurs mainly in regions of volcanic activity, depends upon the rate at which carbon-rich oceanic crust is subducted beneath moving continental plates [30, 47]. Drawdown of CO_2 from the surface reservoir occurs with weathering of rocks exposed by uplift, with the weathering products carried by rivers to the ocean and eventually deposited as carbonates on the ocean floor [30] and by burial of organic matter. Both outgassing and drawdown of CO_2 are affected by changes in plate tectonics, which thus can alter the amount of carbon in the surface reservoir. The magnitude of the changes of carbon in the surface reservoir, and thus in the atmosphere, is constrained by a negative weathering feedback on the time scale of hundreds of thousands of years [30, 52], but plate tectonics can evoke changes of the surface carbon reservoir by altering the rates of outgassing and weathering.

At the beginning of the Cenozoic the African plate was already in collision with Eurasia, pushing up the Alps. India was still south of the equator, but moving north rapidly through a region with fresh carbonate deposits. It is likely that subduction of carbon rich crust of the Tethys Ocean, long a depocenter for sediments, caused an increase of atmospheric CO_2 and the early Cenozoic warming that peaked ~50 My ago. The period of rapid subduction terminated with the collision of India with Eurasia, whereupon uplift of the Himalayas and the Tibetan Plateau increased weathering rates and drawdown of atmospheric CO_2 [51].

Since 50 My ago the world's major rivers have emptied into the Indian and Atlantic Oceans, but there is little subduction of oceanic crust of these regions that are accumulating sediments [47]. Thus the collision of India with Asia was effective in both reducing a large source of outgassing of CO_2 as well as exposing rock for weathering and drawdown of atmospheric CO_2. The rate of CO_2 drawdown decreases as the CO_2 amount declines because of negative feedbacks, including the effects of temperature and plant growth rate on weathering [30].

10. PROXY CO_2 DATA

There are inconsistencies among the several proxy measures of atmospheric CO_2, including differences between results of investigators using nominally the same reconstruction method. We briefly describe strengths and weaknesses of the four paleo-CO_2 reconstruction methods included in the IPCC report [2], which are shown in Fig. (**S10**) and discussed in detail elsewhere [S18]. The inconsistencies among the different proxies constrain their utility for rigorously evaluating our CO_2 predictions. We also include a comparison of our calculated CO_2 history with results from a version of the Berner [30] geochemical carbon cycle model, as well as a comparison with an emerging CO_2 proxy based on carbon-isotope analyses of nonvascular plant (bryophyte) fossils [S19].

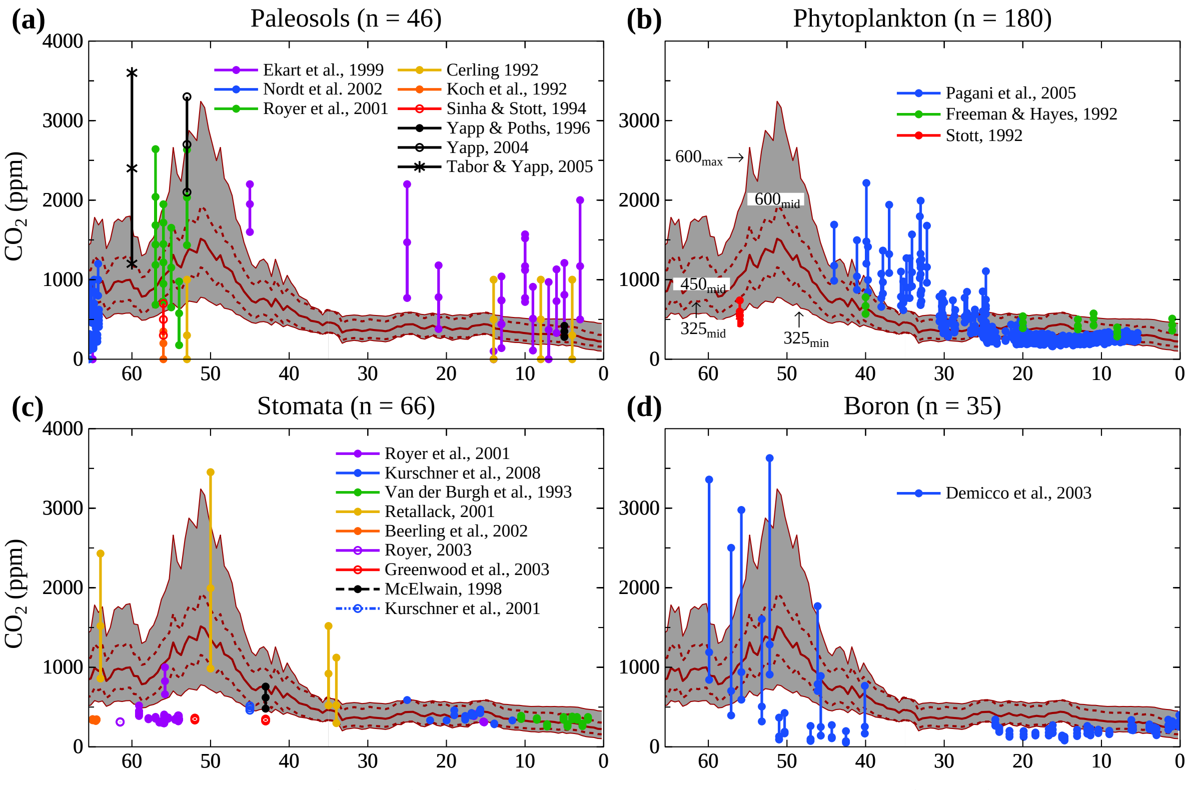


Fig. (S10). Comparison of proxy CO_2 measurements with CO_2 predictions based on deep-ocean temperature, the latter inferred from benthic $\delta^{18}O$. The shaded range of model results is intended mainly to guide the eye in comparing different proxies. The dark central line is for the standard case with CO_2 = 450 ppm at 35 My ago, and the dashed lines are the standard cases for CO_2 = 325 and 600 ppm at 35 My ago. The extremes of the shaded area correspond to the maximum range including a 50% uncertainty in the relation of ΔT_s and ΔT_{do}. Our assumption that CO_2 provides 75% of the GHG throughout the Cenozoic adds additional uncertainty to the predicted CO_2 amount. References for data sources in the legends are provided by Royer [55], except Kurshner *et al.* [S20].

The paleosol method is based on the $\delta^{13}C$ of pedogenic carbonate nodules, whose formation can be represented by a two end-member mixing model between atmospheric CO_2 and soil-derived carbon [S21]. Variables that need to be constrained or assumed include an estimation of nodule depth from the surface of the original soil, the respiration rate of the ecosystem that inhabits the soil, the porosity/diffusivity of the original soil, and the isotopic composition of the vegetation contribution of respired CO_2. The uncertainties in CO_2 estimates with this proxy are substantial at high CO_2 (±500-1000 ppm when CO_2 > 1000 ppm) and somewhat less in the lower CO_2 range (±400-500 ppm when CO_2 < 1000 ppm).

The stomatal method is based on the genetically-controlled relationship [S22] between the proportion of leaf surface cells that are stomata and atmospheric CO_2 concentrations [S23]. The error terms with this method are comparatively small at low CO_2 (< ±50 ppm), but the method rapidly loses sensitivity at high CO_2 (> 500-1000 ppm). Because stomatal-CO_2 relationships are often species-specific, only extant taxa with long fossil records can be used [S24]. Also, because the fundamental response of stomata is to the partial pressure of CO_2 [S25], constraints on paleoelevation are required.

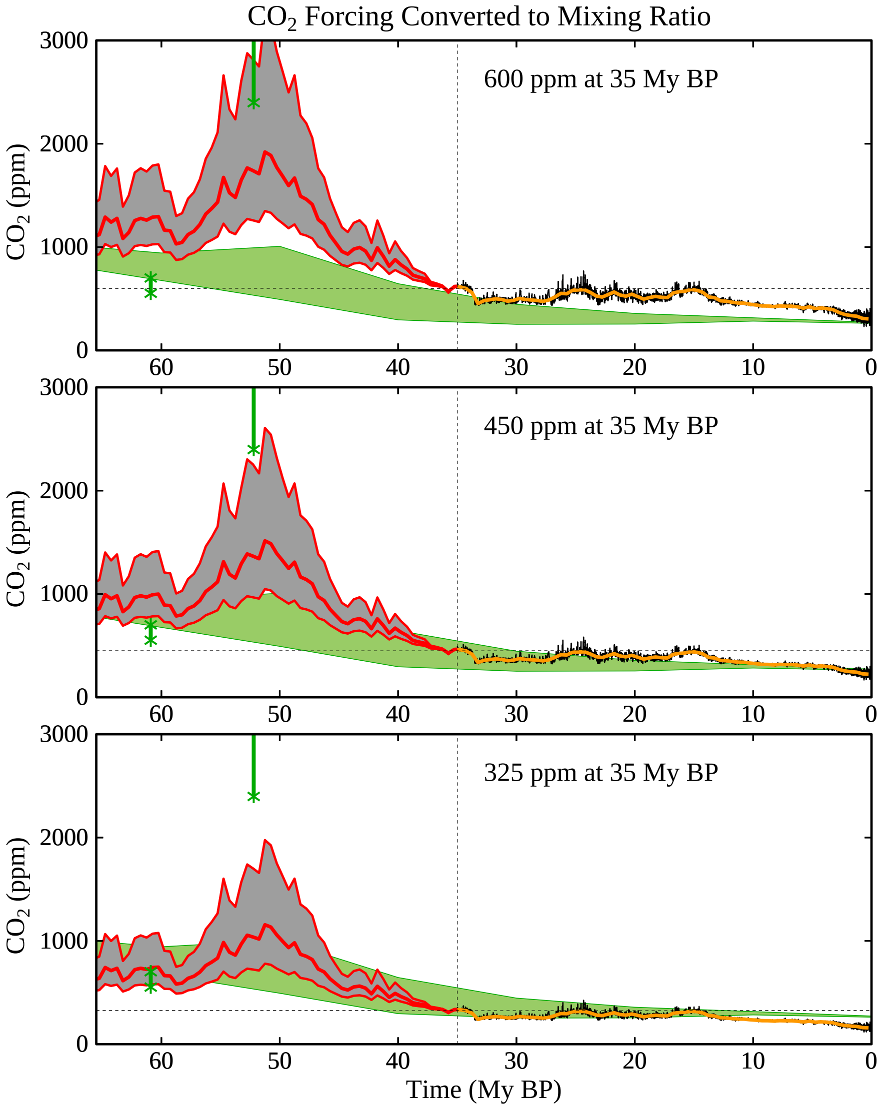


Fig. (S11). Simulated CO_2 in the Cenozoic for three choices of CO_2 amount at 35 My, as in Fig. (**5**), compared with the CO_2 history in a geochemical model [30], specifically the model version described by Fletcher *et al.* [S19]. The green vertical bars are a proxy CO_2 measure [S19] obtained from fossils of non-vascular plants (bryophytes) that is not included among the proxies shown in Fig. (**S10**).

The phytoplankton method is based on the Rayleigh distillation process of fractionating stable carbon isotopes during photosynthesis [S26]. In a high CO_2 environment, for example, there is a higher diffusion rate of CO_2 through phytoplankton cell membranes, leading to a larger available intercellular pool of $CO_{2[aq]}$ and more depleted $\delta^{13}C$ values in photosynthate. Cellular growth rate and cell size also impact the fractionation of carbon isotopes in phytoplankton and thus fossil studies must take these factors into account [S27]. This approach to reconstructing CO_2 assumes that the diffusional transport of CO_2 into the cell dominates, and that any portion of carbon actively transported into the cell remains constant with time. Error terms are typically small at low CO_2 (< ±50 ppm) and increase substantially under higher CO_2 concentrations [S27].

The boron-isotope approach is based on the pH-dependency of the $\delta^{11}B$ of marine carbonate [S28]. This current method assumes that only borate is incorporated in the carbonate lattice and that the fractionation factor for isotope exchange between boric acid and borate in solution is well-constrained. Additional factors that must be taken into account include test dissolution and size, species-specific physiological effects on carbonate $\delta^{11}B$, and ocean alkalinity [S29-S31]. As with the stomatal and phytoplankton methods, error terms are comparatively small at low CO_2 (< ±50 ppm) and the method loses sensitivity at higher CO_2 (> 1000 ppm). Uncertainty is unconstrained for extinct foraminiferal species.

Fig. (**S10**) illustrates the scatter among proxy data sources, which limits inferences about atmospheric CO_2 history. Given the large inconsistency among different data sets in the early Cenozoic, at least some of the data or their interpretations must be flawed. In the range of proxy data shown in Fig. (**5**) we took all data sources as being of equal significance. It seems likely that the low CO_2 values in the early Cenozoic are faulty, but we avoid omission of any data until the matter is clarified, and thus the range of proxy data shown in Fig. (**5**) is based on all data. Reviews of the proxy data [S19, 55] conclude that atmospheric CO_2 amount in the early Cenozoic reached values of at least 500-1000 ppm.

Fig. (**S11**) shows that geochemical carbon cycle modeling [30, S19] is reasonably consistent with our calculated long-term trend of atmospheric CO_2 for the cases with CO_2 at 34 My ago being in the range from about 325 to 450 ppm. The geochemical modeling does not yield a strong maximum of CO_2 at 50 My ago, but the temporal resolution of the modeling (10 My) and the absence of high resolution input data for outgassing due to variations in plate motions tends to mitigate against sharp features in the simulated CO_2.

Fig. (**S11**) also shows (vertical green bars) an emerging CO_2 proxy based on the isotopic composition of fossil liverworts. These non-vascular plants, lacking stomatal pores, have a carbon isotopic fractionation that is strongly CO_2 dependent, reflecting the balance between CO_2 uptake by photosynthesis and inward CO_2 diffusion [S19].

11. CLIMATE SENSITIVITY COMPARISONS

Other empirical or semi-empirical derivations of climate sensitivity from paleoclimate data (Table **S1**) are in reasonable accord with our results, when account is taken of differences in definitions of sensitivity and the periods considered.

Royer *et al.* [56] use a carbon cycle model, including temperature dependence of weathering rates, to find a best-fit doubled CO_2 sensitivity of 2.8°C based on comparison with Phanerozoic CO_2 proxy amounts. Best-fit in their comparison of model and proxy CO_2 data is dominated by the times of large CO_2 in the Phanerozoic, when ice sheets would be absent, not by the times of small CO_2 in the late Cenozoic. Their inferred sensitivity is consistent with our inference of ~3°C for doubled CO_2 at times of little or no ice on the planet.

Higgins and Schrag [57] infer climate sensitivity of ~4°C for doubled CO_2 from the temperature change during the Paleocene-Eocene Thermal Maximum (PETM) ~55 My ago (Fig. **3**), based on the magnitude of the carbon isotope excursion at that time. Their climate sensitivity for an ice-free planet is consistent with ours within uncertainty ranges. Furthermore, recalling that we assume non-CO_2 to provide 25% of the GHG forcing, if one assumes that part of the PETM warming was a direct of effect of methane, then their inferred climate sensitivity is in even closer agreement with ours.

Pagani *et al.* [58] also use the magnitude of the PETM warming and the associated carbon isotopic excursion to discuss implications for climate sensitivity, providing a graphical relationship to help assess alternative assumptions about the origin and magnitude of carbon release. They conclude that the observed PETM warming of about 5°C implies a high climate sensitivity, but with large uncertainty due to imprecise knowledge of the carbon release.

Table S1. Climate Sensitivity Inferred Semi-Empirically from Cenozoic or Phanerozoic Climate Change

Reference	Period	Doubled CO_2 Sensitivity
Royer *et al.* [56]	0-420 My	~ 2.8°C
Higgins and Schrag [57]	PETM	~4°C
Pagani *et al.* [58]	PETM	High

12. GREENHOUSE GAS GROWTH RATES

Fossil fuel CO_2 emissions have been increasing at a rate close to the highest IPCC [S34] scenario (Fig. **S12b**). Increase of CO_2 in the air, however, appears to be in the middle of the IPCC scenarios (Fig. **S12c**, **d**), but as yet the scenarios are too close and interannual variability too large, for assessment. CO_2 growth is well above the "alternative scenario", which was defined with the objective of keeping added GHG forcing in the 21^{st} century at about 1.5 W/m^2 and 21^{st} century global warming less than 1°C [20].

Non-CO_2 greenhouse gases are increasing more slowly than in IPCC scenarios, overall at approximately the rate of the "alternative scenario", based on a review of data through the end of 2007 [69]. There is potential to reduce non-CO_2 forcings below the alternative scenario [69].

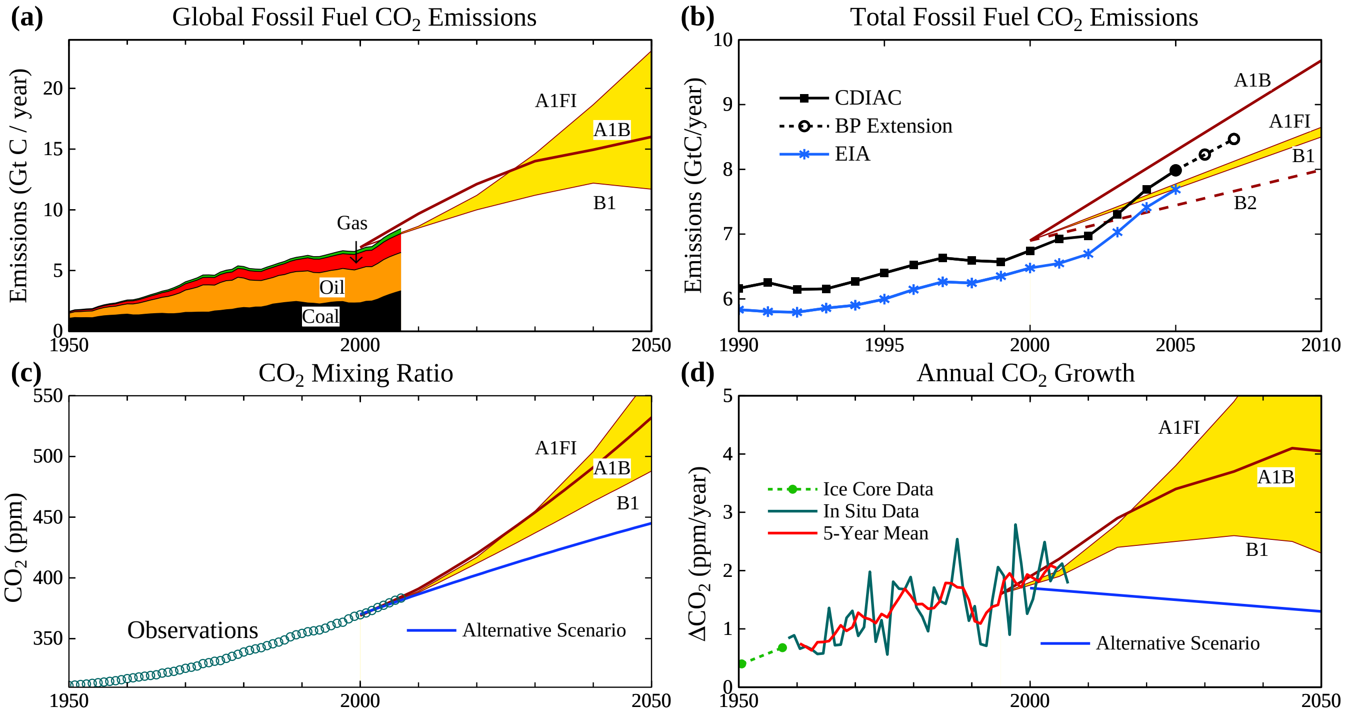


Fig. (S12). (**a**) Fossil fuel CO_2 emissions by fuel type [S32, S33], the thin green sliver being gas flaring plus cement production, and IPCC fossil fuel emissions scenarios, (**b**) expansion global emissions to show recent changes more precisely, the EIA values excluding CO_2 emissions from cement manufacture, (**c**) observed atmospheric CO_2 amount and IPCC and "alternative" scenarios for the future, (**d**) annual atmospheric CO_2 growth rates. Data here is an update of data sources defined in [6]. The yellow area is bounded by scenarios that are most extreme in the second half of the 21st century; other scenarios fall outside this range in the early part of the century.

13. FOSSIL FUEL AND LAND-USE CO_2 EMISSIONS

Fig. (**S13**) shows estimates of anthropogenic CO_2 emissions to the atmosphere. Although fossil emissions through 2006 are known with good accuracy, probably better than 10%, reserves and potential reserve growth are highly uncertain. IPCC [S34] estimates for oil and gas proven reserves are probably a lower limit for future oil and gas emissions, but they are perhaps a feasible goal that could be achieved *via* a substantial growing carbon price that discourages fossil fuel exploration in extreme environments together with national and international policies that accelerate transition to carbon-free energy sources and limit fossil fuel extraction in extreme environments and on government controlled property.

Coal reserves are highly uncertain, but the reserves are surely enough to take atmospheric CO_2 amount far into the region that we assess as being "dangerous". Thus we only consider scenarios in which coal use is phased out as rapidly as possible, except for uses in which the CO_2 is captured and stored so that it cannot escape to the atmosphere. Thus the magnitude of coal reserves does not appreciably affect our simulations of future atmospheric CO_2 amount.

Integrated 1850-2008 net land-use emissions based on the full Houghton [83] historical emissions (Fig. **S14**), extended with constant emissions for the past several years, are 79 ppm CO_2. Although this could be an overestimate by up to a factor of two (see below), substantial pre-1850 deforestation must be added in. Our subjective estimate of uncertainty in the total land-use CO_2 emission is a factor of two.

14. THE MODERN CARBON CYCLE

Atmospheric CO_2 amount is affected significantly not only by fossil fuel emissions, but also by agricultural and forestry practices. Quantification of the role of land-use in the uptake and release of CO_2 is needed to assess strategies to minimize human-made climate effects.

Fig. (**S15**) shows the CO_2 airborne fraction, AF, the annual increase of atmospheric CO_2 divided by annual fossil fuel CO_2 emissions. AF is a critical metric of the modern carbon cycle, because it is based on the two numbers characterizing the global carbon cycle that are well known. AF averages 56% over the period of accurate data, which began with the CO_2 measurements of Keeling in 1957, with no discernable trend. The fact that 44% of fossil fuel emissions seemingly "disappears" immediately provides a hint of optimism with regard to the possibility of stabilizing, or reducing, atmospheric CO_2 amount.

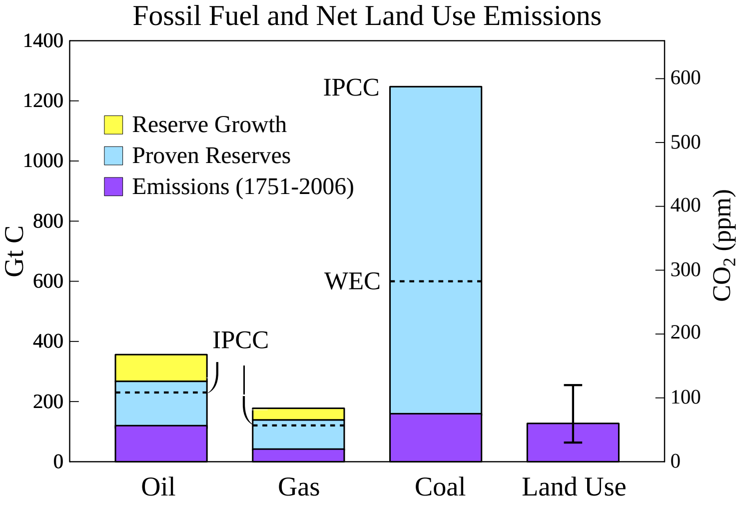


Fig. (S13). Fossil fuel and land-use CO_2 emissions, and potential fossil fuel emissions. Historical fossil fuel emissions are from the Carbon Dioxide Information Analysis Center [CDIAC, S32] and British Petroleum [BP, S33]. Lower limits on oil and gas reserves are from IPCC [S34] and higher limits are from the United States Energy Information Administration [EIA, 80]. Lower limit for coal reserves is from the World Energy Council [WEC, S35] and upper limit from IPCC [S34]. Land use estimate is from integrated emissions of Houghton/2 (Fig. **S14**) supplemented to include pre-1850 and post-2000 emissions; uncertainty bar is subjective.

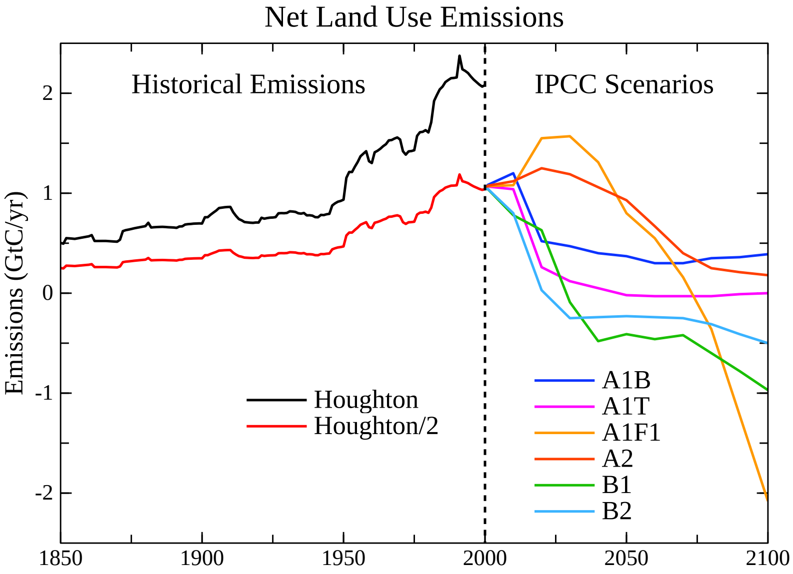


Fig. (S14). Left side: estimate by Houghton [83] of historical net land-use CO_2 emissions, and a 50 percent reduction of that estimate. Right side: IPCC [2] scenarios for land-use CO_2 emissions.

That optimism needs to be tempered, as we will see, by realization of the magnitude of the actions required to halt and reverse CO_2 growth. However, it is equally important to realize that assertions that fossil fuel emissions must be reduced close to 100% on an implausibly fast schedule are not necessarily valid.

A second definition of the airborne fraction, AF2, is also useful. AF2 includes the net anthropogenic land-use emission of CO_2 in the denominator. This AF2 definition of airborne fraction has become common in recent carbon cycle literature. However, AF2 is not an observed or accurately known quantity; it involves estimates of net land-use CO_2 emissions, which vary among investigators by a factor of two or more [2].

Fig. (**S15**) shows an estimate of net land-use CO_2 emissions commonly used in carbon cycle studies, labeled “Houghton” [83], as well as “Houghton/2”, a 50% reduction of these land-use emissions. An over-estimate of land-use emissions is one possible solution of the long-standing “missing sink” problem that emerges when the full “Houghton” land-use emissions are employed in carbon cycle models [2, S34, 79].

Principal competing solutions of the “missing sink” paradox are (1) land-use CO_2 emissions are over-estimated by about a factor of two, or (2) the biosphere is being “fertilized” by anthropogenic emissions, *via* some combination of increasing atmospheric CO_2, nitrogen deposition, and global warming, to a greater degree than included in typical carbon cycle models.

Reality may include contributions from both candidate explanations. There is also a possibility that imprecision in the ocean uptake of CO_2, or existence of other sinks such as clay formation, could contribute increased CO_2 uptake, but these uncertainties are believed to be small.

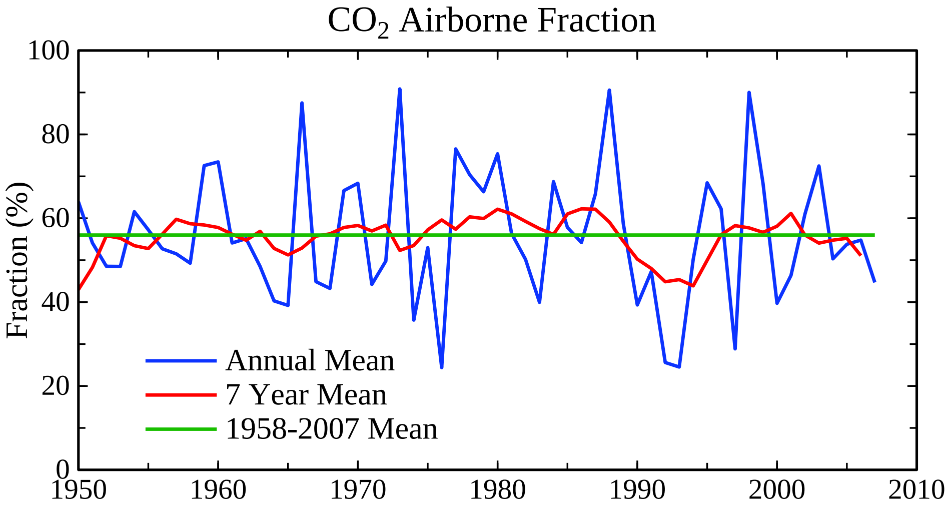


Fig. (S15). CO_2 airborne fraction, AF, the ratio of annual observed atmospheric CO_2 increase to annual fossil fuel CO_2 emissions.

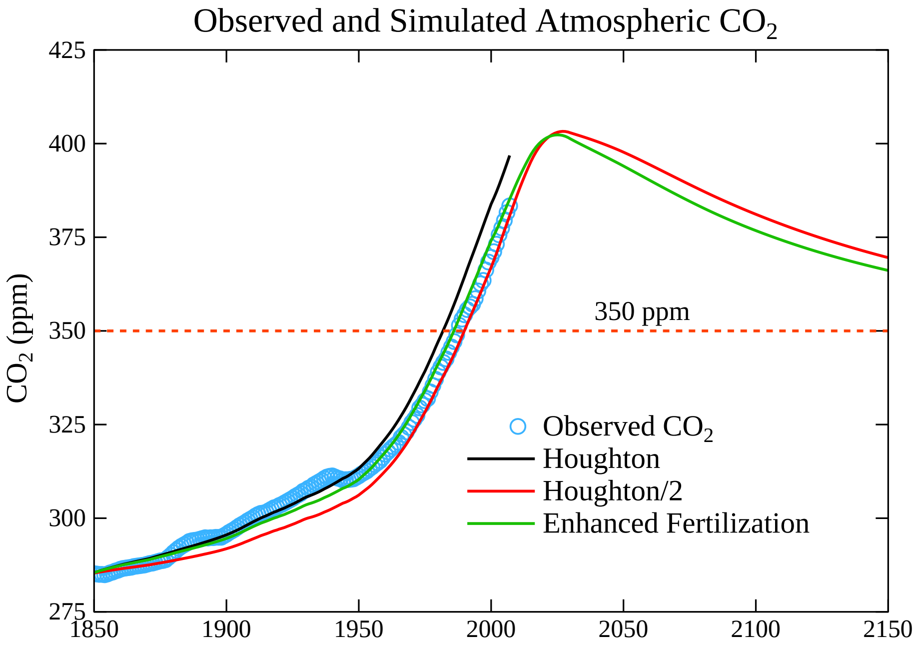


Fig. (S16). Computed and observed time evolution of atmospheric CO_2. "Enhanced Fertilization" uses the full "Houghton" land use emissions for 1850–2000. "Houghton/2" and "Enhanced Fertilization" simulations are extended to 2100 assuming coal phase-out by 2030 and the IPCC [2] A1T land-use scenario. Observations are from Law Dome ice core data and flask and in-situ measurements [6, S36, http://www.esrl.noaa.gov/gmd/ccgg/trends/].

Fig. (**S16**) shows resulting atmospheric CO_2, and Fig. (**S17**) shows AF and AF2, for two extreme assumptions: "Houghton/2" and " Enhanced Fertilization", as computed with a dynamic-sink pulse response function (PRF) representation of the Bern carbon cycle model [78, 79]. Fertilization is implemented *via* a parameterization [78] that can be adjusted to achieve an improved match between observed and simulated CO_2 amount. In the "Houghton/2" simulation the original value [78] of the fertilization parameter is employed while in the "Enhanced Fertilization" simulation the full Houghton emissions are used with a larger fertilization parameter. Both "Houghton/2" and "Enhanced Fertilization" yield good agreement with the observed CO_2 history, but Houghton/2 does a better job of matching the time dependence of observed AF.

It would be possible to match observed CO_2 to an arbitrary precision if we allowed the adjustment to "Houghton" land-use to vary with time, but there is little point or need for that. Fig. (**S16**) shows that projections of future CO_2 do not differ much even for the extremes of Houghton/2 and Enhanced Fertilization. Thus in Fig. (**6**) we show results for only the case Houghton/2, which is in better agreement with the airborne fraction and also is continuous with IPCC scenarios for land use.

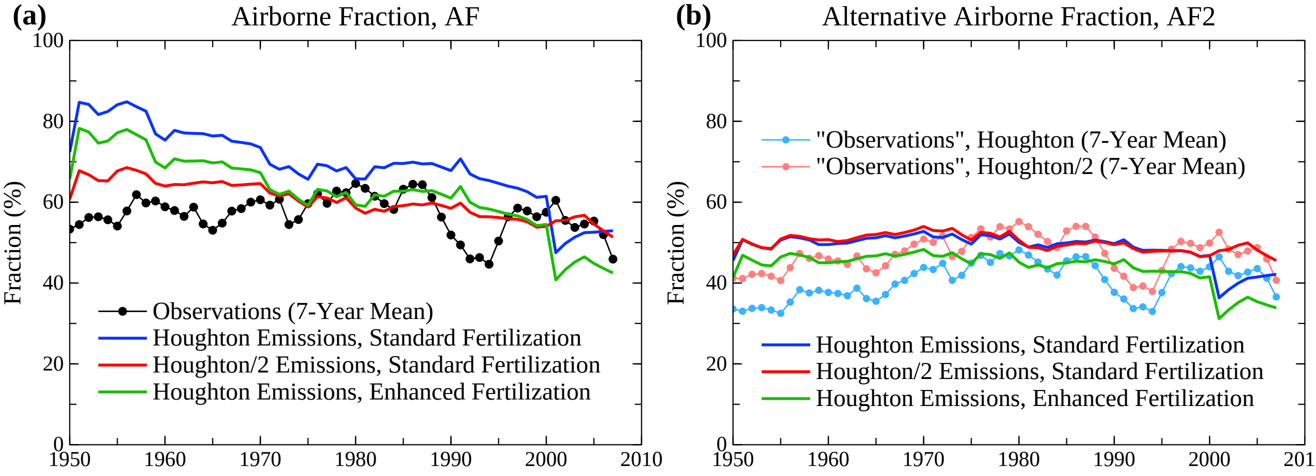


Fig. (S17). (**a**) Observed and simulated airborne fraction (AF), the ratio of annual CO_2 increase in the air over annual fossil fuel CO_2 emissions, (**b**) AF2 includes the sum of land use and fossil fuel emissions in the denominator in defining airborne fraction; thus AF2 is not accurately known because of the large uncertainty in land use emissions.

15. IMPLICATIONS OF FIG. (6): CO_2 EMISSIONS AND ATMOSPHERIC CONCENTRATION WITH COAL PHASE-OUT BY 2030

Fig. (**6**) provides an indication of the magnitude of actions that are needed to return atmospheric CO_2 to a level of 350 ppm or lower. Fig. (**6**) allows for the fact that there is disagreement about the magnitude of fossil fuel reserves, and that the magnitude of useable reserves depends upon policies.

A basic assumption underlying Fig. (**6**) is that, within the next several years, there will be a moratorium on construction of coal-fired power plants that do not capture and store CO_2, and that CO_2 emissions from existing power plants will be phased out by 2030. This coal emissions phase out is the sine qua non for stabilizing and reducing atmospheric CO_2. If the sine qua non of coal emissions phase-out is achieved, atmospheric CO_2 can be kept to a peak amount ~400-425 ppm, depending upon the magnitude of oil and gas reserves.

Fig. (**6**) illustrates two widely different assumptions about the magnitude of oil and gas reserves (illustrated in Fig. **S13**). The smaller oil and gas reserves, those labeled “IPCC”, are realistic if “peak oil” advocates are more-or-less right, i.e., if the world has already exploited about half of readily accessible oil and gas deposits, so that production of oil and gas will begin to decline within the next several years.

There are also “resource optimists” who dispute the “peakists’, arguing that there is much more oil (and gas) to be found. It is possible that both the “peakists” and “resource optimists” are right, it being a matter of how hard we work to extract maximum fossil fuel resources. From the standpoint of controlling human-made climate change, it does not matter much which of these parties is closer to the truth.

Fig. (**6**) shows that, if peak CO_2 is to be kept close to 400 ppm, the oil and gas reserves actually exploited need to be close to the “IPCC” reserve values. In other words, if we phase out coal emissions we can use remaining oil and gas amounts equal to those which have already been used, and still keep peak CO_2 at about 400 ppm. Such a limit is probably necessary if we are to retain the possibility of a drawdown of CO_2 beneath the 350 ppm level by methods that are more-or-less “natural”. If, on the other hand, reserve growth of the magnitude that EIA estimates (Figs. **6** and **S13**) occurs, and if these reserves are burned with the CO_2 emitted to the atmosphere, then the forest and soil sequestration that we discuss would be inadequate to achieve drawdown below the 350 ppm level in less than several centuries.

Even if the greater resources estimated by EIA are potentially available, it does not mean that the world necessarily must follow the course implied by EIA estimates for reserve growth. If a sufficient price is applied to carbon emissions it will discourage extraction of fossil fuels in the most extreme environments. Other actions that would help keep effective reserves close to the IPCC estimates would include prohibition of drilling in environmentally sensitive areas, including the Arctic and Antarctic.

National policies, in most countries, have generally pushed to expand fossil fuel reserves as much as possible. This might partially account for the fact that energy information agencies, such as the EIA in the United States, which are government agencies, tend to forecast strong growth of fossil fuel reserves. On the other hand, state, local, and citizen organizations can influence imposition of limits on fossil fuel extraction, so there is no guarantee that fossil resources will be fully exploited. Once the successors to fossil energy begin to take hold, there may be a shifting away from fossil fuels that leaves some of the resources in the ground. Thus a scenario with oil and gas emissions similar to that for IPCC reserves may be plausible.

Assumptions yielding the Forestry & Soil wedge in Fig. (**6b**) are as follows. It is assumed that current net deforestation will decline linearly to zero between 2010 and 2015. It is assumed that uptake of carbon *via* reforestation will increase linearly until 2030, by which time reforestation will achieve a maximum potential sequestration rate of 1.6 GtC per year [S37]. Waste-derived biochar application will be phased in linearly over the period 2010-2020, by which time it will reach a maximum uptake rate of 0.16 GtC/yr [85]. Thus after 2030 there will be an annual uptake of 1.6 + 0.16 = 1.76 GtC per year, based on the two processes described.

Thus Fig. (**6**) shows that the combination of (1) moratorium and phase-out of coal emissions by 2030, (2) policies that effectively keep fossil fuel reserves from significantly exceeding the IPCC reserve estimates, and (3) major programs to achieve carbon sequestration in forests and soil, can together return atmospheric CO_2 below the 350 ppm level before the end of the century.

The final wedge in Fig. (**6**) is designed to provide an indication of the degree of actions that would be required to bring atmospheric CO_2 back to the level of 350 ppm by a time close to the middle of this century, rather than the end of the century. This case also provides an indication of how difficult it would be to compensate for excessive coal emissions, if the world should fail to achieve a moratorium and phase-out of coal as assumed as our "sine qua non".

Assumptions yielding the Oil-Gas-Biofuels wedge in Fig. (**6b**) are as follows: energy efficiency, conservation, carbon pricing, renewable energies, nuclear power and other carbon-free energy sources, and government standards and regulations will lead to decline of oil and gas emissions at 4% per year beginning when 50% of the estimated resource (oil or gas) has been exploited, rather than the 2% per year baseline decline rate [79]. Also capture of CO_2 at gas- power plants (with CO_2 capture) will use 50% of remaining gas supplies. Also a linear phase-in of liquid biofuels is assumed between 2015 and 2025 leading to a maximum global bioenergy from "low-input/high-diversity" biofuels of ~23 EJ/yr, inferred from Tilman *et al*. [87], that is used as a substitute for oil; this is equivalent to ~0.5 GtC/yr, based on energy conversion of 50 EJ/GtC for oil. Finally, from 2025 onward, twice this number (i.e., 1 GtC/yr) is subtracted from annual oil emissions, assuming root/soil carbon sequestration *via* this biofuel-for-oil substitution is at least as substantial as in Tilman *et al.* [87]. An additional option that could contribute to this wedge is using biofuels in powerplants with CO_2 capture and sequestration [86].

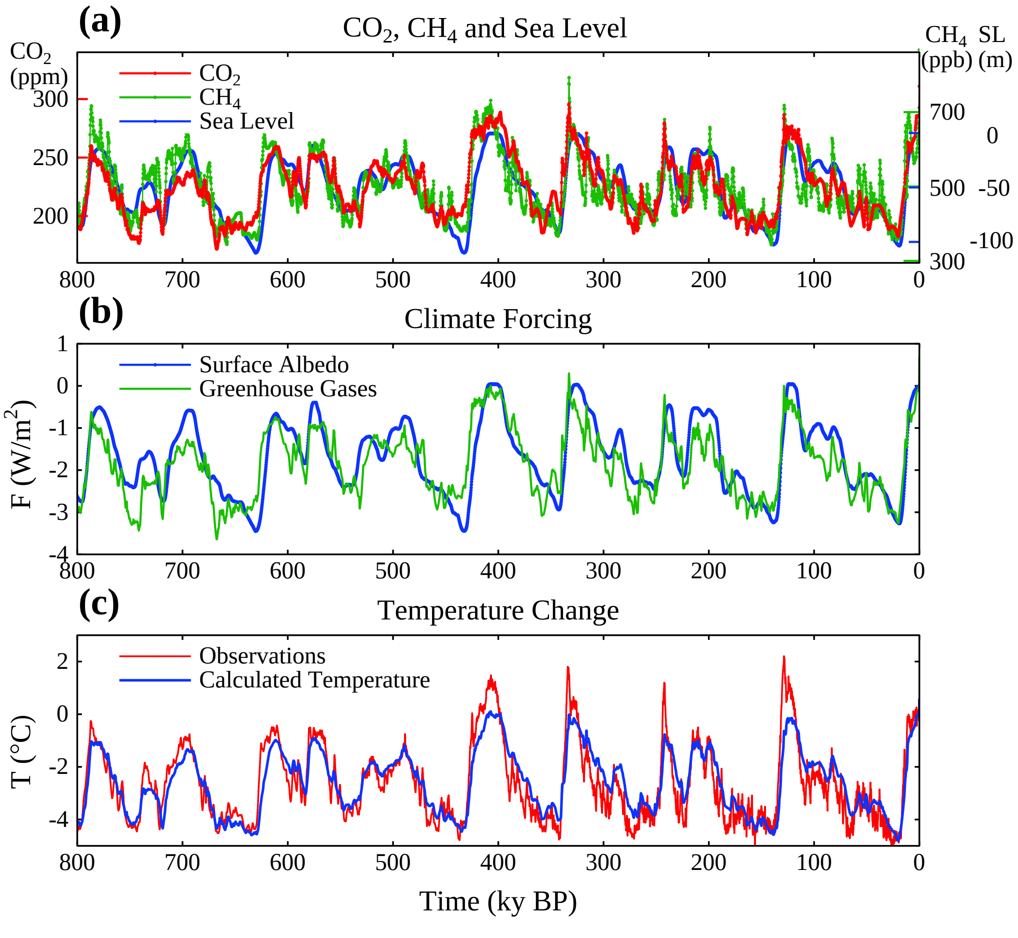


Fig. (S18). (**a**) CO_2 [S38], CH_4 [S39] and sea level [S16] for past 800 ky. (**b**) Climate forcings due to changes of GHGs and ice sheet area, the latter inferred from the sea level history of Bintanja *et al.* [S16]. (**c**) Calculated global temperature change based on the above forcings and climate sensitivity ¾°C per W/m^2. Observations are Antarctic temperature change from the Dome C ice core [S8] divided by two.

16. EPICA 800 KY DATA

Antarctic Dme C ice core data acquired by EPICA (European Project for Ice Coring in Antarctica) provide a record of atmospheric composition and temperature spanning 800 ky [S8], almost double the time covered by the Vostok data [17, 18] of Figs. (**1**) and (**2**). This extended record allows us to examine the relationship of climate forcing mechanisms and temperature change over a period that includes a substantial change in the nature of glacial-interglacial climate swings. During the first half of the EPICA record, the period 800-400 ky BP, the climate swings were smaller, sea level did not rise as high as the present level, and the GHGs did not increase to amounts as high as those of recent interglacial periods.

Fig. (**S18**) shows that the temperature change calculated exactly as described for the Vostok data of Fig. (**1**), i.e., multiplying the fast-feedback climate sensitivity ¾°C per W/m^2 by the sum of the GHG and surface albedo forcings (Fig. **S18b**), yields a remarkably close fit in the first half of the Dome C record to one-half of the temperature inferred from the isotopic composition of the ice. In the more recent half of the record slightly larger than ¾°C per W/m^2 would yield a noticeably better fit to the observed Dome C temperature divided by two (Fig. **S19**). However, there is no good reason to change our approximate estimate of ¾°C per W/m^2, because the assumed polar amplification by a factor of two is only approximate.

The sharper spikes in recent observed interglacial temperature, relative to the calculated temperature, must be in part an artifact of differing temporal resolutions. Temperature is inferred from the isotopic composition of the ice, being a function of the temperature at which the snowflakes formed, and thus inherently has a very high temporal resolution. GHG amounts, in contrast, are smoothed over a few ky by mixing of air in the snow that occurs up until the snow is deep enough for the snow to be compressed into ice. In the central Antarctic, where both Vostok and Dome C are located, bubble closure requires a few thousand years [17].

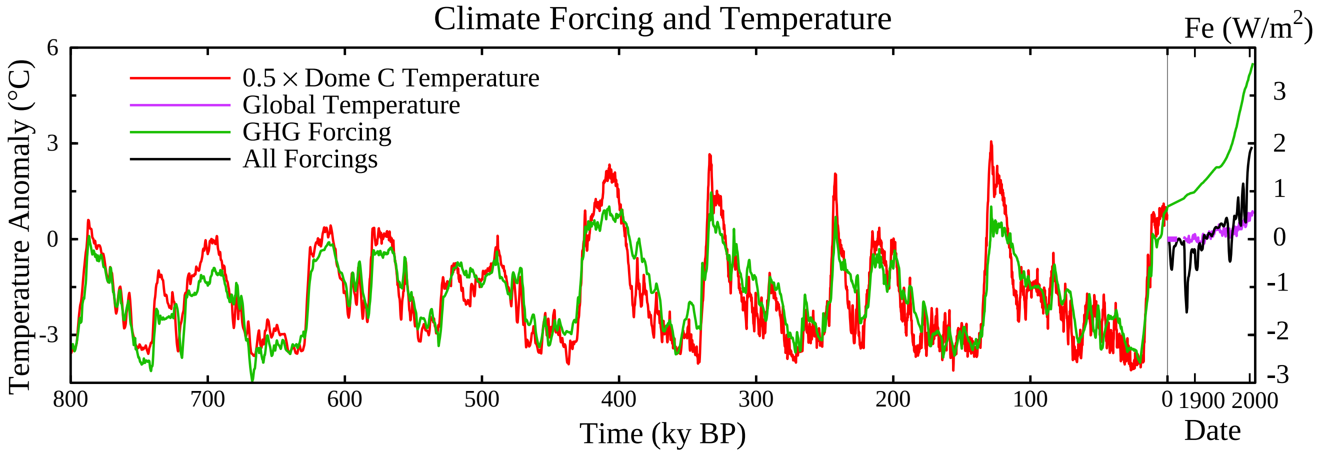


Fig. (S19). Global temperature change (left scale) estimated as half of temperature change from Dome C ice core [S8] and GHG forcing (right scale) due to CO_2, CH_4 and N_2O [S38, S39]. Ratio of temperature and forcing scales is 1.5°C per W/m^2. Time scale is expanded in the extension to recent years. Modern forcings include human-made aerosols, volcanic aerosols and solar irradiance [5]. GHG forcing zero point is the mean for 10-8 ky before present. Net climate forcing and modern temperature zero points are at 1850. The implicit presumption that the positive GHG forcing at 1850 is largely offset by negative human-made forcings [7] is supported by the lack of rapid global temperature change in the Holocene (Fig. **S6**).

17. COMPARISON OF ANTARCTIC DATA SETS

Fig. (**S20**) compares Antarctic data sets used in this supplementary section and in our parent paper. This comparison is also relevant to interpretations of the ice core data in prior papers using the original Vostok data.

The temperature records of Petit *et al.* [17] and Vimeux *et al.* [18] are from the same Vostok ice core, but Vimeux *et al.* [18] have adjusted the temperatures with a procedure designed to correct for climate variations in the water vapor source regions. The isotopic composition of the ice is affected by the climate conditions in the water vapor source region as well as by the temperature in the air above Vostok where the snowflakes formed; thus the adjustment is intended to yield a record that more accurately reflects the air temperature at Vostok. The green temperature curve in Fig. (**S20c**), which includes the adjustment, reduces the amplitude of glacial-interglacial temperature swings from those in the original (red curve) Petit *et al.* [17] data. Thus it seems likely that there will be some reduction of the amplitude and spikiness of the Dome C temperature record when a similar adjustment is made to the Dome C data set.

The temporal shift of the Dome C temperature data [S8], relative to the Vostok records, is a result of the improved EDC3 [S40, S41] time scale. With this new time scale, which has a 1σ uncertainty of ~3 ky for times earlier than ~130 ky BP, the rapid temperature increases of Termination IV (~335 ky BP) and Termination III (~245 ky BP) are in close agreement with the contention [7] that rapid ice sheet disintegration and global temperature rise should be nearly simultaneous with late spring

(April-May-June) insolation maxima at 60N latitude, as was already the case for Terminations II and I, whose timings are not significantly affected by the improved time scale.

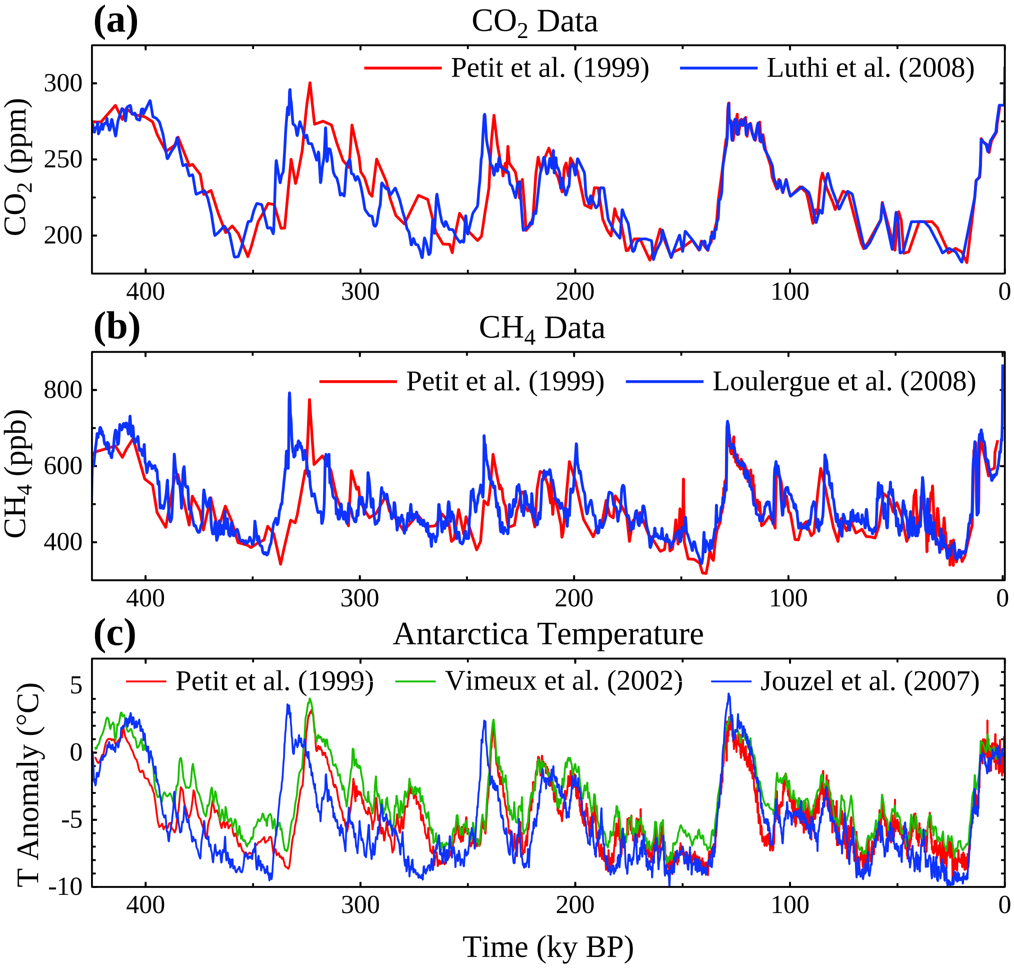


Fig. (S20). Comparison of Antarctic CO_2, CH_4, and temperature records in several analyses of Antarctic ice core data.

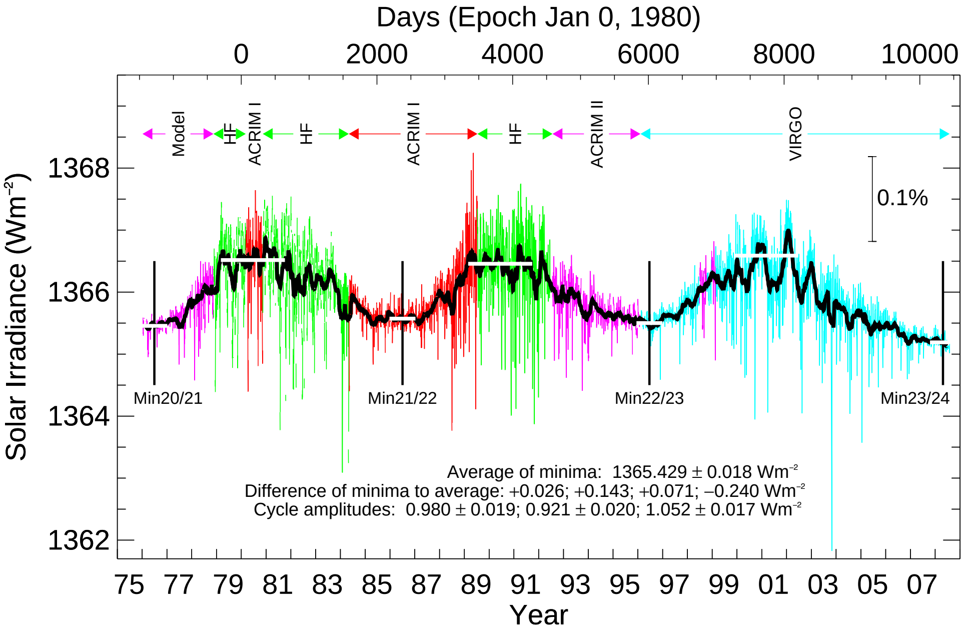


Fig. (S21). Solar irradiance from composite of several satellite-measured time series based on Frohlich and Lean [S44].

18. CLIMATE VARIABILITY, CLIMATE MODELS, AND UNCERTAINTIES

Climate exhibits great variability, forced and unforced, which increases with increasing time scale [2, 90, 91]. Increasing abilities to understand the nature of this natural variability and improving modeling abilities [S42] do not diminish the complications posed by chaotic variability for interpretation of ongoing global change.

Expectation that global temperature will continue to rise on decadal time scales is based on a combination of climate models and observations that support the inference that the planet has a positive energy imbalance [5, 8, 96]. If the planet is out of energy balance by +0.5-1 W/m^2, climate models show that global cooling on decadal time scales is unlikely [96], although one model forecast [95] suggests that the Atlantic overturning circulation could weaken in the next decade, causing a regional cooling that offsets global warming for about a decade.

The critical datum for determining the certainty of continued global warming on decadal time scales is the planet's energy imbalance. Improved evaluations of ocean heat storage in the upper 700 m of the ocean [97] yield ~0.5 x 10^{22} J/yr averaged over the past three decades, which is ~0.3 W/m^2 over the full globe. Our model has comparable heat storage in the ocean beneath 700 m, but limited observational analyses for the deep ocean [S43] report negligible heat storage.

If our modeled current planetary energy imbalance of 0.5-1 W/m^2 is larger than actual heat storage, the likely explanations are either: (1) the climate model sensitivity of 3°C for doubled CO_2 is too high, or (2) the assumed net climate forcing is too large. Our paleoclimate analyses strongly support the modeled climate sensitivity, although a sensitivity as small as 2.5 W/m^2 for doubled CO_2 could probably be reconciled with the paleoclimate data. The net climate forcing is more uncertain. Our model [8] assumes that recent increase of aerosol direct and indirect (cloud) forcings from developing country emissions are offset by decreases in developed countries.

These uncertainties emphasize the need for more complete and accurate measurements of ocean heat storage, as well as precise global observations of aerosols including their effects on clouds. The first satellite observations of aerosols and clouds with the needed accuracy are planned to begin in 2009 [98]. Until accurate observations of the planetary energy imbalance and global climate forcing are available, and found to be consistent with modeled climate sensitivity, uncertainties in decadal climate projections will remain substantial.

The sun is another source of uncertainty about climate forcings. At present the sun is inactive, at a minimum of the normal ~11 year solar cycle, with a measureable effect on the amount of solar energy received by Earth (Fig. **S21**). The amplitude of solar cycle variations is about 1 W/m^2 at the Earth's distance from the sun, a bit less than 0.1% of the ~1365 W/m^2 of energy passing through an area oriented perpendicular to the Earth-sun direction.

Climate forcing due to change from solar minimum to solar maximum is about ¼ W/m^2, because the Earth absorbs ~235 W/m^2 of solar energy, averaged over the Earth's surface. If equilibrium climate sensitivity is 3°C for doubled CO_2 (¾°C per W/m^2), the expected equilibrium response to this solar forcing is ~0.2°C. However, because of the ocean's thermal inertia less than half of the equilibrium response would be expected for a cyclic forcing with ~11 year period. Thus the expected global-mean transient response to the solar cycle is less than or approximately 0.1°C.

It is conceivable that the solar variability is somehow amplified, e.g., the large solar variability at ultraviolet wavelengths can affect ozone. Indeed, empirical data on ozone change with the solar cycle and climate model studies indicate that induced ozone changes amplify the direct solar forcing, but amplification of the solar effect is by one-third or less [S45, S46].

Other mechanisms amplifying the solar forcing have been hypothesized, such as induced changes of atmospheric condensation nuclei and thus changes of cloud cover. However, if such mechanisms were effective, then an 11-year signal should appear in temperature observations (Fig. **7**). In fact a very weak solar signal in global temperature has been found by many investigators, but only of the magnitude (~0.1°C or less) expected due to the direct solar forcing.

The possibility remains of solar variability on longer time scales. If the sun were to remain 'stuck' at the present solar minimum (Fig. **S21**) it would be a decrease from the mean irradiance of recent decades by ~0.1%, thus a climate forcing of about -0.2 W/m^2.

The current rate of atmospheric CO_2 increase is ~2 ppm/year, thus an annual increase of climate forcing of about +0.03 W/m^2 per year. Therefore, if solar irradiance stays at its recent minimum value, the climate forcing would be offset by just seven years of CO_2 increase. Human-made GHG climate forcing is now increasing at a rate that overwhelms variability of natural climate forcings.

Climate models are another source of uncertainty in climate projections. Our present paper and our estimated target CO_2 level do not rely on climate models, but rather are based on empirical evidence from past and ongoing climate change. However, the limited capability of models to simulate climate dynamics and interactions among climate system components makes it difficult to estimate the speed at which climate effects will occur and the degree to which human-induced effects will be masked by natural climate variability.

The recent rapid decline of Arctic ice [S47-S49] is a case in point, as it has been shown that model improvements of multiple physical processes will be needed for reliable simulation. The modeling task is made all the more difficult by likely connections of Arctic change with the stratosphere [S50] and with the global atmosphere and ocean [S51].

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ALLIANCE OF SMALL ISLAND STATES (AOSIS)
DECLARATION ON CLIMATE CHANGE 2009

We, the Member States of the Alliance of Small Island States (AOSIS), meeting in New York this 21st day of September,

Gravely concerned that climate change poses the most serious threat to our survival and viability, and, that it undermines our efforts to achieve sustainable development goals and threatens our very existence;

Alarmed that emerging scientific evidence shows that the effects of human-induced climate change are worse than previously projected and that the impacts of climate change which we are already experiencing including sea level rise, more frequent and extreme weather events, ocean acidification, coral bleaching, coastal erosion, and changing precipitation patterns, will further intensify;

Greatly disturbed that despite the mitigation commitments made by Parties to the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol, especially those of the developed countries, global emissions continue to increase, leading to rapidly accelerating impacts, accompanied by costs and burdens that are beyond the ability of many, but, especially the small island developing states (SIDS) and other particularly vulnerable countries, to control;

Profoundly disappointed by the lack of apparent ambition within the international climate change negotiations to protect SIDS and other particularly vulnerable countries, their peoples, culture, land and ecosystems from the impacts of climate change and our further concern at the slow pace of these negotiations;

1. *Now therefore,* we, call upon the international community, with the developed countries taking the lead, to undertake urgent, ambitious and decisive action to significantly reduce emissions of all green house gases, including fast action strategies, and to support SIDS, and other particularly vulnerable countries, in their efforts to adapt to the adverse impacts of climate change, including through the provision of increased levels of financial and technological resources.

2. We underscore that adaptation must be an urgent and immediate global priority.

3. We firmly maintain that the UNFCCC is the primary international, intergovernmental forum for negotiating the global response to climate change.

4. We reaffirm the principles enshrined in the Rio Declaration and the UNFCCC and its Kyoto Protocol, in particular, the principle of common but differentiated responsibilities and

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respective capabilities having regard to national circumstances, and, the precautionary principle.

5. We urge all Parties to work with an increased sense of urgency and purpose towards an ambitious, comprehensive and meaningful outcome that preserves the legal nature of the international climate change regime and the existing commitments under the UNFCCC and its Kyoto Protocol.

6. We assert thus that the outcome to be concluded at the fifteenth session of the Conference of the Parties to the United Nations Framework Convention on Climate Change in Copenhagen in 2009 should inter alia:

   a. Use the avoidance of adverse climate change impacts on SIDS as one of the key benchmarks for assessing its appropriateness, consistent with the precautionary principle and the principle of prevention;

   b. Adopt a package of mitigation activities, now, up to and beyond 2012 that provides for:

      i. long-term stabilization of atmospheric greenhouse gas concentrations at well below 350ppm CO2-equivalent levels;

      ii. global average surface temperature increases to be limited to well below 1.5° C above pre-industrial levels;

      iii. global greenhouse gas emissions to peak by 2015 and decline thereafter;

      iv. reductions in global greenhouse gas emissions by more than 85% below 1990 levels by 2050

      v. Annex I parties to the UNFCCC to reduce their collective GHG emissions by more than 45% below 1990 levels by 2020, and more than 95% below 1990 levels by 2050, given their historical responsibility;

      vi. A significant deviation from business as usual by developing countries through measurable, reportable and verifiable nationally appropriate mitigation actions in the context of sustainable development, supported and enabled by technology, financing and capacity-building, in a measurable, reportable and verifiable manner.

   c. Provide SIDS with new, additional, predictable, transparent and adequate sources of grant-based financing to fully meet the adaptation needs of these particularly vulnerable countries, and ensure for SIDS that access is timely, direct, prioritized and simplified.

   d. Call for an urgent and significant scaling up of the provision of financial resources and investment that is adequate, predictable and sustainable to support action on mitigation in developing country Parties for the enhanced implementation of national mitigation strategies; including positive incentives, the mobilization of public- and private-sector funding and investment and facilitation of carbon-friendly investment choices.

e. Ensure that renewable energy and energy efficiency form essential pillars of future mitigation actions by all countries, taking into account national circumstances.

f. Establish a mechanism to address loss and damage from climate change comprised of a disaster risk component, insurance, and compensation funds, to help SIDS manage the financial and economic risks arising from climate impacts; to assist in the rapid recovery and rehabilitation from climate related extreme weather events and to address unavoidable damage and loss associated with the adverse effects of climate change.

g. Provide support to SIDS to enhance their capacities to respond to the challenges brought on by climate change and to access the technologies that will be required to undertake needed mitigation actions and to adapt to the adverse impacts of climate change, noting the obligations of Annex 1 countries under the UNFCCC in this regard;

7. In our voluntary efforts to defeat deforestation and increase carbon sequestration, finance, technology and capacity development is necessary to underpin a step-wise process for reducing emissions and increasing carbon sequestration through the conservation and sustainable management of forest crops which are good carbon dioxide sequestrators. Based on national circumstances, a well designed REDD Plus instrument will require resource mobilization from a variety of sources, including public, private and market-based, as appropriate[1], that employ robust methodological standards for measurable, reportable and verifiable actions. Robust environmental integrity will need to be maintained if a REDD mechanism is linked to the international carbon markets.

8. Acknowledging the portfolio of technologies identified by the Intergovernmental Panel on Climate Change to achieve lower stabilization levels, including hydropower, solar, wind, geothermal and bioenergy and determined to avail ourselves of such technologies as appropriate and based on their feasibility and applicability, we encourage, where applicable, national, regional and international efforts for consideration of a process to overcome technical, economic and policy barriers with a view to facilitating the development and commercialization of appropriate and affordable low- and zero- emission technologies.

9. We further recognize that the inclusion of Carbon Capture and Storage (CCS) is potentially an important mitigation option for achieving the ambitious emission reduction targets being supported by AOSIS and urge the development of a program of work on Carbon Capture and Storage in order to resolve related issues.

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[1] Tuvalu expressed a reservation on the reference to market-based sources.

10. We also emphasize that there is an urgent need to consider and address the security implications and the human dimensions of climate change, including where necessary, initiatives for preparing communities for relocation.

11. We underscore that while SIDS contribute the least to global emissions, and have limited human, financial and technical resources, our nations continue to take significant actions towards the reduction of our own emissions including through regional and inter-regional energy initiatives.

12. We also recognize the need to reinforce the UNFCCC process by calling on the big emitters to agree to produce enough clean energy to attain the targets of limiting temperature rise to 1.5 degree Celsius and 350 parts per million of atmospheric greenhouse gas concentrations.

13. Finally, we express our support for the establishment of the Headquarters of the UNFCCC Adaptation Fund Board in Barbados.

14. We, the Member States of AOSIS, strongly emphasize the importance of urgent progress towards a fair and meaningful Copenhagen outcome which, through safeguarding the most vulnerable countries, ensures a truly shared and sustainable global vision for our present and future generations.

HOW MUCH WARMING ARE WE COMMITTED TO AND HOW MUCH CAN BE AVOIDED?

BILL HARE[1] and MALTE MEINSHAUSEN[2,3]

[1]*Visiting Scientist, Potsdam Institute for Climate Impact Research (PIK), P.O. Box 60 12 03,*
D-14412 Potsdam, Germany
E-mail: hare@pik-potsdam.de
[2]*Swiss Federal Institute of Technology (ETH Zurich), Environmental Physics, Department of Environmental Sciences, Rämistrasse 101, CH-8092 Zurich, Switzerland;* [3]*Currently at National Center for Atmospheric Research (NCAR), P.O. Box 3000, Boulder, CO 80307-3000, USA*
E-mail: malte.meinshausen@gmail.com

Abstract. This paper examines different concepts of a 'warming commitment' which is often used in various ways to describe or imply that a certain level of warming is irrevocably committed to over time frames such as the next 50 to 100 years, or longer. We review and quantify four different concepts, namely (1) a 'constant emission warming commitment', (2) a 'present forcing warming commitment', (3) a 'zero emission (geophysical) warming commitment' and (4) a 'feasible scenario warming commitment'. While a 'feasible scenario warming commitment' is probably the most relevant one for policy making, it depends centrally on key assumptions as to the technical, economic and political feasibility of future greenhouse gas emission reductions. This issue is of direct policy relevance when one considers that the 2002 global mean temperatures were 0.8 ± 0.2 °C above the pre-industrial (1861–1890) mean and the European Union has a stated goal of limiting warming to 2 °C above the pre-industrial mean: What is the risk that we are committed to overshoot 2 °C? Using a simple climate model (MAGICC) for probabilistic computations based on the conventional IPCC uncertainty range for climate sensitivity (1.5 to 4.5 °C), we found that (1) a constant emission scenario is virtually certain to overshoot 2 °C with a central estimate of 2.0 °C by 2100 (4.2 °C by 2400). (2) For the present radiative forcing levels it seems unlikely that 2 °C are overshoot. (central warming estimate 1.1 °C by 2100 and 1.2 °C by 2400 with ~10% probability of overshooting 2 °C). However, the risk of overshooting is increasing rapidly if radiative forcing is stabilized much above 400 ppm CO_2 equivalence (1.95 W/m^2) in the long-term. (3) From a geophysical point of view, if all human-induced emissions were ceased tomorrow, it seems 'exceptionally unlikely' that 2 °C will be overshoot (central estimate: 0.7 °C by 2100; 0.4 °C by 2400). (4) Assuming future emissions according to the lower end of published mitigation scenarios (350 ppm CO_2eq to 450 ppm CO_2eq) provides the central temperature projections are 1.5 to 2.1 °C by 2100 (1.5 to 2.0 °C by 2400) with a risk of overshooting 2 °C between 10 and 50% by 2100 and 1–32% in equilibrium. Furthermore, we quantify the 'avoidable warming' to be 0.16–0.26 °C for every 100 GtC of avoided CO_2 emissions – based on a range of published mitigation scenarios.

1. Introduction

In this article we attempt to address – not finally answer – a key question: What warming can be avoided by climate policy and what cannot?

What warming we are committed to, and what can be avoided, has a major bearing on issues such as the benefits of climate policy and to decisions relating to

Climatic Change (2006) 75: 111–149
DOI: 10.1007/s10584-005-9027-9

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Article 2 of the UNFCCC, which is the obligation to prevent dangerous interference with the climate system. For example, as a first step to operationalize Article 2 of the UNFCCC the Heads of Government of the European Union have confirmed a global goal of not exceeding a warming of 2 °C above pre-industrial levels.[1] With global mean temperatures in 2002 estimated to be $0.8 \pm 0.2\,^{\circ}\mathrm{C}$[2] above the pre-industrial mean (1861–1890) (Folland et al., 2001; Jones and Moberg, 2003)[3] the question arises of how much flexibility there is left in terms of greenhouse gas emissions in order to stay below the 2 °C target.

If the climate and socio-economic systems lacked significant inertia the question of what warming is committed by past activities, and what is avoidable through policy action would not be of great concern. The fact that both systems have substantial inertia means that this deceptively simple question has quite complex scientific dimensions and far reaching policy implications. Lack of scientific certainty in relation to key climate system properties adds a further layer of complexity to the issue.

In this paper, we provide quantifications of four conceptually different ‘warming commitments’ resulting from (1) constant emissions, (2) constant greenhouse gas concentrations, (3) an abrupt cessation of emissions (defined here as the ‘geophysical warming commitment’), and (4) from a range of feasible economic and technological emission scenarios. In addition to a systematic analysis of warming commitments, the question is addressed of how much warming is avoidable. Whilst it has been shown that global mean temperature response is insensitive to differences in SRES non-mitigation emission scenarios in the first several decades of this century (Stott and Kettleborough, 2002; Knutti et al., 2003), there has been little systematic examination of the differences between mitigation and non mitigation scenarios. Here we make a first examination of this issue on different decadal time frames across a range of mitigation and non-mitigation scenarios.

We start out by providing an overview of different concepts of a warming commitment and their respective limitations. Furthermore, a brief definition of the term “avoidable warming” is given (Section 2). For most of our analysis, we rely on a simple upwelling-diffusion energy balance climate model. Special attention is paid to dealing with the uncertainty in the climate sensitivity (Section 3). In the results section, we present the estimated ‘warming commitments’. In addition, we estimate the potential for avoidable warming, and attempt to generalise the results in terms of avoided cumulative emission over decadal timeframes (Section 4). In the penultimate section we discuss the results in terms of scientific uncertainties and their implications for long-term climate targets (Section 5). Section 6 concludes.

2. Definitions: Different Warming Commitment Concepts

The idea of a warming commitment is often used in climate policy and scientific discussions to convey the magnitude and time scales of inertia in the climate system with respect to human induced increases in greenhouse gas concentrations. At least two concepts of a warming commitment can be identified in the literature. Firstly, a scenario with constant emissions from some reference point, usually the present (IPCC, 2001a, p. 90; Wigley, 2005). Secondly, a warming commitment estimate is sometimes derived from a constant radiative forcing scenario, usually also from present levels (see e.g. Wetherald et al., 2001; Meehl et al., 2005; Wigley, 2005). The latter concept is often used to illustrate a more general property of the climate systems caused by its inertia: the substantial time lag between the forcing and the full realization of the global mean temperature change resulting from that forcing.

In addition to these concepts we analyse two others. The first we term the 'geophysical warming commitment', which is the warming commitment resulting after an abrupt and complete cessation of anthropogenic emissions. This captures the change in temperatures that results solely from the operation of geophysical and chemical processes on the burden of greenhouses gas and other forcing agents in the atmosphere without consideration of inertia in human, social and economic systems. Due to the inertia in these latter systems it is assumed that an abrupt and complete cessation is infeasible from any economic, human and social point of view, hence this is an idealized geophysical thought experiment. The second concept we term the 'feasible scenario' commitment, which is an attempt to describe the interaction between the inertia of the climate system and socio-economic systems, as will be discussed below. Figure 1 shows schematically the relationship between these four concepts.

2.1. CONSTANT EMISSIONS COMMITMENT

This is defined as the warming that would result at some determined time if present emissions continued indefinitely. Whilst sometimes used to illustrate a warming commitment, there are several difficulties and inconsistencies with applying this concept beyond a thought experiment. The time horizon over which the emissions are held constant more or less determines the warming commitment, which would continue to rise with emissions. Whilst even over very long time horizons (millennia) maintaining constant emissions would appear feasible as fossil fuel resources are potentially quite large when account is taken of conventional and unconventional reserves, including methane hydrates, these sources of CO_2 would ultimately run out. A further problem with this concept is that humanity is not committed to keeping emissions at presently high levels. Whilst emissions are likely to rise in the near future there is every likelihood that at some point emissions would decline below present levels. In other words, constant emission scenarios do not indicate a warming commitment – unless today's emissions levels were considered as a lower bound for the coming decades and centuries.

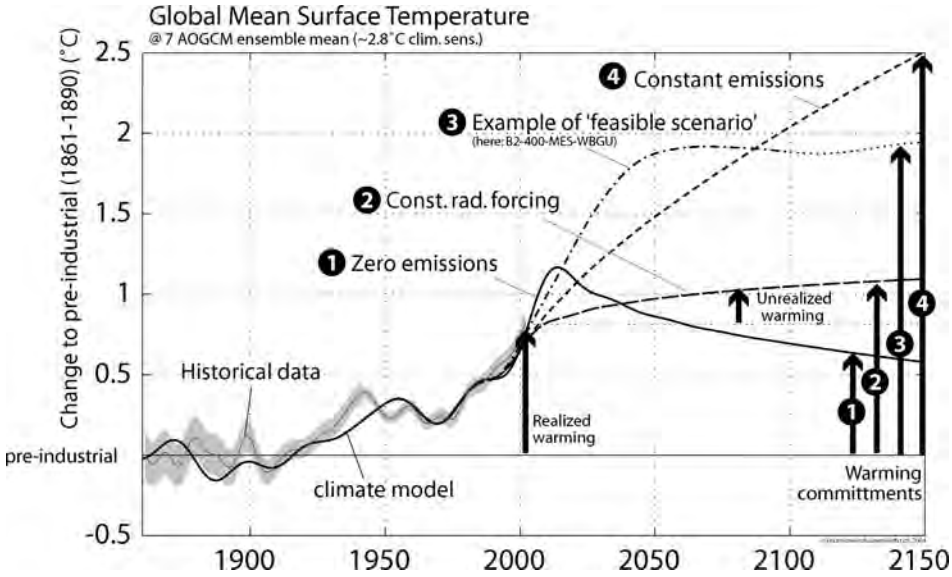

Figure 1. Four different types of warming commitments. (1) The 'geophysical' warming commitment in case that emissions are abruptly reduced to zero after 2005 ('Zero Emissions'); Note that emissions initially rise due to ceased cooling by aerosols. (2) The 'present forcing' warming commitment corresponds to constant radiative forcing at present (2005) levels and comprises the 'realized' and 'unrealized' warming; (3) the 'feasible scenario' warming commitment is the temperature rise that corresponds to the lowest emission scenario judged feasible. Note that the mitigation scenario B2-400-MES-WBGU is shown for illustrative purposes only (dash-dotted line: original scenario up to 2100; dotted part: the extended scenario as described in text). Lastly, (4) the 'constant emissions' warming commitment that corresponds to highest warming levels in the long term. The historical temperature record and its uncertainty (grey shaded area) is taken from Folland et al. (2001).

2.2. PRESENT FORCING COMMITMENT

This is defined here as the warming that would result if the present level of forcing were maintained indefinitely (or over defined time periods). In other words, the 'present forcing' warming commitment is considered to be the sum of the 'realized' and 'unrealized' warming (Hansen et al., 1985) that corresponds to present day composition of the atmosphere and its radiative forcing levels. Hence, this commitment can as well be termed the "constant-composition" commitment (Wigley, 2005).[4]

The actual present day radiative forcing is rather uncertain mainly due to uncertain contribution of aerosols. Central estimates range between 1.7 W/m^2 (Wigley, 2005), or 1.55 and 1.1 W/m^2, if individual radiative forcing estimates given by Hansen et al. (2000) or IPCC TAR are convoluted to a net forcing estimate. If today's net radiative forcing is constrained by consistency tests with historic temperature observations a central estimate between 1.25 to 2.5 W/m^2 seems likely

(Knutti et al., 2002). This study uses a net radiative forcing (human-induced & natural) of 1.93 W/m^2 for 2005 relative to the 1861–1890 period, of which 0.67 W/m^2 is due to natural forcing increases since 1861–1890.[5]

The concept of a present forcing commitment is often used to convey a sense of inertia to policy makers. For example, the IPCC WGI TAR report states that "Since the climate system requires many years to come into equilibrium with a change in forcing, there remains a 'commitment' to further climate change even if the forcing itself ceases to change." (Cubasch et al., 2001).

In terms of assessing a warming commitment that results from the inertia in both the climate and socio-economic system, the 'present forcing' commitment concept suffers from two problems, one obvious and the second perhaps less so. First, the greenhouse gas emission reductions required within a year or so to abruptly stabilize radiative forcing are unrealistically large. At the same time, emission from cooling aerosols would have to be kept at present (high) levels.[6] Secondly, in the longer term (22nd century and beyond) it is by no means clear that radiative forcing would not drop below present levels. As a consequence it is not obvious that estimates of a 'warming commitment' based on constant radiative forcing is a lower bound on warming in general, although it is sometimes interpreted that way. A scenario that has low emissions in the 21st century and beyond could produce warming levels that approach or drop below the levels implied in a constant radiative forcing scenario (see Figure 6c).

2.3. GEOPHYSICAL COMMITMENT

A warming commitment can be defined from a purely geophysical perspective, as the warming that would result after a complete cessation of anthropogenic emissions. Such a thought experiment has value in terms of showing the timescales of the climate system without implicit entanglements with socio-economic assumptions. The term geophysical is used here in the sense that following the cessation of emissions, the time path of warming is determined solely by the operation of the biogeophysical components of the climate system assimilating the effects anthropogenic perturbations to atmosphere without further human intervention. The time path of warming is influenced to a small degree by the assumed natural forcings (solar irradiance and volcanic eruptions) relative the preindustrial period, but this does not fundamentally affect the estimates.

An abrupt cessation of anthropogenic emissions is not at all likely, absent a global catastrophe. Hence, a geophysical warming commitment is primarily of interest when compared to 'feasible scenario' commitments. In this way, one can distinguish between the geophysical and socio-economic inertia components of a long-term future warming commitment. Note that an abrupt cessation of SO_2 emissions will cause an initial increase in forcing and temperature levels, thereby overshooting a 'feasible scenario' commitment in the short-term (see Figure 1).

2.4. FEASIBLE SCENARIO COMMITMENT

A ‘feasible scenario’ warming commitment can be defined based on emission scenarios that are considered to be plausible in the sense that they are viewed as technologically, economically and politically feasible. Deriving such a ‘feasible scenario’ warming commitment requires specific assumptions to be taken about what are feasible rates of future emission reductions, not just in the short term but also over many decades. Such commitment estimates could be used to define the outer bounds of climate policy, beyond which policy tools and technology that are presently judged to be feasible cannot reach. Put another way, energy-economic models could be used to define the region of climate change space (warming and sea level rise) still accessible to policy and technology choices.

The estimates of warming commitments with respect to feasible scenarios rely on published examples of scenarios that stabilize CO_2 at or below 450 ppm by 2100 by reputable modeling groups. Specifically, we used the post SRES A1F1-450 MiniCam, A1B-450 AIM, B1-450 IMAGE scenarios, the A1T–450 MESSAGE, and its WBGU variant (Nakicenovic and Riahi, 2003) as 450 ppm CO_2 stabilization scenarios.[7] In addition, we use recent scenarios for a CO_2 stabilization at 400 ppm that were created by one of the modelling groups (MESSAGE) involved in the SRES and post-SRES scenarios and carried out for the German Global Change Advisory Council (WBGU) (Graßl et al., 2003), namely the WBGU B1-400 MESSAGE and the WBGU B2-400 MESSAGE scenarios (Nakicenovic and Riahi, 2003). Finally, we explore the implications of biomass scenarios, which also incorporate variants of carbon capture and storage. These latter CO_2-only scenarios aim to stabilize CO_2 at 350 ppm (Azar et al., in press) and were here complemented by the WBGU B2-400 non-CO_2 and landuse CO_2 emissions.

‘Feasible scenario’ warming commitments are perhaps the most realistic of definitions in the sense that socio-economic inertia is taken into account. However, the presented illustrative ‘feasible scenario’ commitments do not provide a definitive answer to what is the lower bound of future warming for several reasons, as discussed in Section 5.1.

2.5. WHAT IS AVOIDABLE WARMING?

When assessing climate policy options, policy makers often want to know what the avoidable warming is when comparing different mitigation and reference scenarios in the future. Whereas a ‘warming commitment’ is defined with respect to some fixed base climate state (here we have used the pre-industrial mean temperature from 1861 to 1890), avoidable warming is defined with respect to an assumed future evolution of emissions and the climate system under a non-intervention scenario. Thus, we provide estimates of avoidable warming by computing warming differences of paired mitigation and non-mitigation scenarios of the same SRES scenario family (see Section 4.6).

3. Method

This section entails a brief description of the simple climate model MAGICC employed in this work (3.1). In the non probabilistic components of this work we use a standard '7 AOGCM ensemble mean' (7AEM) procedure to average over model runs tuned to different AOGCMs (3.2). In addition, a probabilistic procedure allows us to give special attention to uncertainties in the climate's sensitivity based on a range of literature estimates (3.3). For additional equilibrium calculations standard formulas were applied (3.4). Finally, we describe the assumptions made in regard to natural forcings (3.5).

3.1. SIMPLE CLIMATE MODEL

For the computation of global mean climate indicators, the simple climate model MAGICC 4.1 has been used.[8] The description in the following paragraph is largely based on Wigley (2003). MAGICC is the primary simple climate model that has been used by the IPCC to produce projections of future sea level rise and global-mean temperatures. Information on earlier versions of MAGICC has been published in Wigley and Raper (1992) and Raper et al. (1996). The carbon cycle model is the model of Wigley (1993), with further details given in Wigley (2000) and Wigley and Raper (2001). Modifications to MAGICC made for its use in the IPCC TAR (IPCC, 2001b) are described in Wigley and Raper (2001, 2002), Wigley et al. (2002) and (Wigley, 2005). Additional details are given in the IPCC TAR climate projections chapter 9 (Cubasch et al., 2001). Gas cycle models other than the carbon cycle model are described in the IPCC TAR atmospheric chemistry chapter 4 (Ehhalt et al., 2001) and in Wigley et al. (2002). The representation of temperature related carbon cycle feedbacks has been slightly improved in comparison to the MAGICC version used in the IPCC TAR, so that the magnitude of MAGICC's climate feedbacks are comparable to the carbon cycle feedbacks of the Bern-CC and the ISAM model (see Box 3.7 in Prentice et al., 2001).[9]

The gases that are modeled for each scenario are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorinated gases (HFCs, PFCs, SF_6), and sulphur emissions (SOx) as well as carbon monoxide (CO), volatile organic compounds (VOC), and nitrogen oxide (NOx). If not otherwise stated, all indicated temperatures are annual and global mean surface temperature levels above pre-industrial levels (1861–1890).

3.2. AOGCM ENSEMBLE MEAN

Ensemble mean outputs of this simple climate model are the basis for the non-probabilistic results presented in this study. The ensemble outputs are computed as means of seven model runs. In each run, 13 model parameters of MAGICC are adjusted to optimal tuning values for seven atmospheric-ocean global circulation models (AOGCMs) (see Raper et al., 2001). This '7 AOGCM ensemble mean' (7AEM) procedure, which we will hereafter refer to as 7AEM, is widely used in the IPCC Third Assessment Report and described in Appendix 9.1 (Cubasch et al., 2001). By using this 7AEM procedure, the implicit assumptions in regard to climate sensitivity is based on the seven AOGCMs. The mean climate sensitivity for those 7 AOGCMs models is 2.8 °C for doubled CO_2 concentration levels (median is 2.6 °C). Clearly, different climate projections would be obtained, if single model tunings or different climate sensitivities were used, reflecting the underlying uncertainty in the science.

3.3. HANDLING UNCERTAINTIES: CLIMATE SENSITIVITY

In addition to these 7AEM runs, another approach had to be chosen to deal with the main climate system uncertainty, the climate sensitivity. The climate sensitivity is simultaneously one of the most fundamental and uncertain properties of the climate system in relation to policy. Following the convention in the literature it is defined as the equilibrium increase in global mean surface temperature following a doubling of CO_2 concentrations, e.g. doubling of pre-industrial levels ($2 \times 278 = 556$ ppm). Thus, estimates of the climate sensitivity approximately reflect the equilibrium warming that can be expected under a 550 CO_2 equivalent stabilization scenario.

There is no single universally agreed estimate of climate sensitivity or even of a probability density function for it. We have attempted to deal with this uncertainty by making probabilistic calculations for temperature projected for different probability density functions of climate sensitivity. Whilst varying the climate sensitivity parameter we have maintained the default set of climate parameters for MAGICC consistent with the IPCC Third Assessment Report findings (Wigley, 2003). Specifically, we sampled climate sensitivity at the quantiles of interest, namely 1, 5, 10, 33, 50, 66, 90, 95 and 99% of the PDFs (cf. Figures 4 and 7).

Clearly, this procedure does not take into account interdependencies between climate sensitivity and other climate parameters, such as ocean heat diffusion. Ideally, the simple climate model should be run for parameter sets from a joint probability density distribution for the key uncertainties. We choose to focus only on climate sensitivity and neglect interdependencies as well as uncertainties in other key climate parameters. This should be kept in mind when reviewing the results. Neglecting uncertainties in ocean mixing, specifically the likely lower ocean

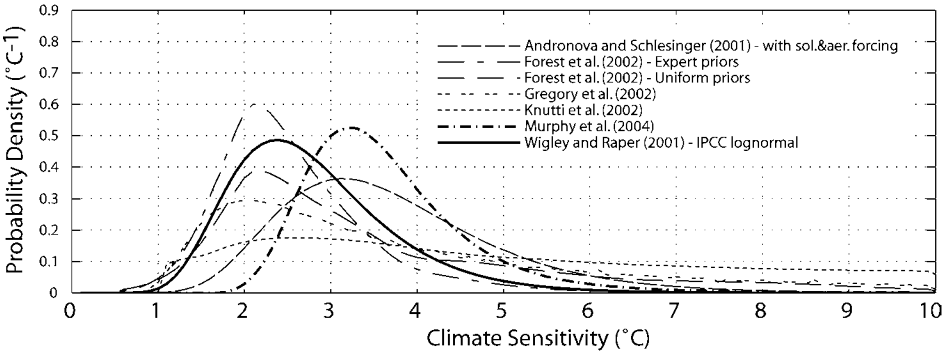

Figure 2. Different estimates of the probability density functions for climate sensitivity.

mixing rates for lower climate sensitivities, might have relatively limited effects though.[10]

Since its First Assessment Report in 1990, the IPCC has indicated that the climate sensitivity is most likely to lie in the range 1.5–4.5 °C. Prior to the IPCC TAR the IPCC had given a best estimate of 2.5 °C. However, in the TAR no reference was made to a best estimate and instead to an average model range. Hence there is no real quantitative guidance at this stage arising from the IPCC assessments other than by the "likelihood" of the climate sensitivity lying in range 1.5 to 4.5 °C.

After the completion of the IPCC TAR, a number of estimates of the climate sensitivity have been published each with its own strengths and weaknesses (see e.g. IPCC, 2004). Seven of these estimates are used in the subsequent analysis and shown in Figure 2[11]: Six studies have attempted objective estimation of a probability density function (PDFs) for climate sensitivity based on contemporary forcing history and the recent evolution of the climate system: (1) the combined PDF by Andronova and Schlesinger (2001) that takes into account both solar forcing and sulphate aerosols;[12] (2–3) estimates by Forest et al. (2002) with expert and uniform a priori distributions; (4) another observationally based estimate by Gregory et al. (2002); (5) the uniform prior estimate by Knutti et al. (2003); (6) a recent estimate based on a 53-member ensemble of an atmosphere GCM, HadAM3, coupled to a mixed layer ocean model to enable integrations to equilibrium (Murphy et al., 2004). (7) The seventh estimate is drawn from the conventional 1.5 to 4.5 °C IPCC uncertainty range with a pdf constructed by Wigley and Raper (2001). This estimate assumes that the distribution is log-normal with the IPCC range being taken as the 90% confidence range. This can be seen as an attempt to codify the expert judgement character of the IPCC assessments, but, as is emphasized by Wigley and Raper (2001) does not represent either the full range of uncertainty or some "best estimate" based on all other estimates.

In the following work we have used all of the pdfs described above and to illustrate some of our results we have chosen to focus on the PDFs (5) to (7) as they span the range of available climate sensitivity PDF estimates in terms of their shape and methods by which they have been derived (see Figure 2). PDFs (5) and (6) are based on the recent period but have very different shapes, PDF (7) is roughly similar to the Forest et al. (2002) expert prior estimate but has the virtue for the discussion of results here that it codifies the expert assessment of the IPCC.

3.4. TIME HORIZON, EQUILIBRIUM CONSIDERATIONS AND CO_2 EQUIVALENCE

The time horizon used to explicitly evaluate warming commitments based on defined scenarios here is to the year 2400. This is arbitrary given that the climate system will continue to respond well beyond this time. As has been shown the warming following greenhouse gas concentration stabilization will continue for a few thousand years and only slowly approach equilibrium (Watterson, 2003).

As in the MAGICC climate model, the following formula is used for the presented equilibrium calculations (see as well Ramaswamy et al., 2001, Table 6.2, page 358). The conversion between CO_2 (equivalence) concentrations and radiative forcing (ΔQ) (W/m^2) follows the logarithmic equation:

$$\Delta Q = \alpha \ln\left(\frac{C}{C_0}\right) \tag{1}$$

where α is 5.35 W/m^2 and C_0 the unperturbed pre-industrial CO_2 concentration level (278 ppm), based on Myhre et al. (1998). The equilibrium temperature is then assumed to scale linearly with radiative forcing:

$$\Delta T = \Delta Q \frac{\Delta T_{2\times CO_2}}{\alpha \ln(2)} \tag{2}$$

where $\Delta T_{2\times CO_2}$ (K) is the climate sensitivity and $\alpha \times \ln(2)$ is the radiative forcing for twice the pre-industrial CO_2 levels.

CO_2 equivalent concentrations are here derived from the net forcing of all anthropogenic radiative forcing agents. Thus, CO_2 equivalence comprises greenhouse gases, tropospheric ozone, and aerosols but not natural forcings.

3.5. NATURAL FORCINGS

Historic solar and volcanic forcings estimates have been assumed, according to Lean et al. (1995) and Sato et al. (1993) respectively, as presented in the IPCC TAR (see Figures 6–8 in Ramaswamy et al., 2001). Recent studies suggested that an up-scaling of solar forcing might lead to a better agreement of historic temperature records (e.g. Hill et al., 2001; North and Wu, 2001; Stott et al., 2003). In accordance with the best fit results by Stott et al. (2003, Table 2), a solar forcing scaling factor of

2.64 has been assumed for this study. Accordingly, volcanic forcings from Sato et al. (1993) have been scaled down by a factor 0.39 (Stott et al., 2003, Table 2). Future solar and volcanic forcings over the future time periods examined here have been assumed constant at levels equivalent to the scaled mean forcings over the past 22 and 100 years respectively. In other words, we have assumed a scaled solar forcing of $+0.44$ and $-0.14\,\mathrm{W/m^2}$ for volcanic forcing, which is together $0.67\,\mathrm{W/m^2}$ above the natural forcing of the 1861–1890 period.[13]

It should be noted that mechanisms for the amplification of solar forcing are not yet well established (Ramaswamy et al., 2001, section 6.11.2; Stott et al., 2003). As well, the evidence for the conventionally assumed long-term solar irradiance changes has recently been challenged (Foukal et al., 2004).

An exception to the above solar and volcanic forcing assumptions has been made for the calculations on the risk of overshooting certain temperature levels in equilibrium (Section 4.5). There, equilibrium temperatures have been directly derived from anthropogenic radiative forcings. Thus, natural forcings have implicitly been assumed constant at pre-industrial levels. This approach allows separating risks that solely accrue from human interference and those that accrue from changes in natural forcings. Assuming no change of natural forcings since pre-industrial times will lower the presented temperature increase by 0.35 °C in equilibrium for the 7AEM runs (see Tables I–III). Thus, it should be noted that the presented overshooting risks (Figure 8) are lower than if the above standard assumptions on natural forcings were applied.

4. Results: The Warming Commitments and Avoidable Warming

Below we first outline the results of the analysis for the warming commitments based on the four concepts outlined at the beginning of the paper (Sections 4.1 to 4.4). We then provide a compilation of results by deriving the probability that we are already ‘committed’ to overshoot certain warming levels (4.5). Finally, we present estimates of the scale of avoidable warming by analysing paired mitigation and non-mitigation scenarios (4.6).

4.1. CONSTANT EMISSIONS

If greenhouse gas and aerosol emissions were held constant at present day (2005) levels, the associated radiative forcing would rise markedly in the future. By inverting Equation (1) the total radiative forcing can be expressed in equivalent CO_2 concentrations – the CO_2 concentration which would produce that level of radiative forcing if acting alone. In CO_2 equivalent terms the radiative forcing would rise to 527 ppm CO_2eq by 2100 and 899 ppm CO_2eq by 2400 (excl. natural forcing). For comparison the actual CO_2 concentration would rise up to 531 ppm by 2100 and

929 ppm by 2400. The relatively small difference between CO_2 and CO_2eq is due to the offsetting effects of aerosol. A central estimate is that at the global mean level the direct and indirect aerosol cooling effects are sufficient to approximately counteract the warming effects of the non-CO_2 well mixed greenhouse gases. Temperature would increase monotonically up to 4.2 °C in 2400 (2.0 °C in 2100) – according to the 7AEM results. Assuming lower (1.5 °C) and higher (4.5 °C) climate sensitivities, the temperature range in 2400 spans from 2.5 to 6.1 °C, respectively (2100: 1.4 to 2.7 °C).[14] The 90% confidence ranges for global mean temperatures based on climate sensitivity estimates by Murphy et al. (2004) is 1.9 to 3.0 °C in 2100 and 3.7 to 7.0 °C by 2400. See Table I for further estimates for different climate sensitivity PDFs.

Figure 4 presents an example of a probabilistic assessment of warming resulting from constant emissions. In this figure the 1, 10, 33, 66, 90 and 99% percentiles for warming estimates are shown based on the IPCC range of climate sensitivity as codified by Wigley and Raper (2001).

TABLE I

'Constant emission' warming commitment: temperature implications in the case where emissions are held constant at today's (2005) levels

	Temperature above pre-industrial (°C above pre-industrial)							
Climate sensitivity	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF
7 AOGCM ensemble mean								
∼2.8	0.7	0.8	1.5	2.0	2.9	4.2	5.2	4.9
Wigley								
5%: 1.50	0.5	0.6	1.0	1.4	1.8	2.5	2.7	2.6
50%: 2.60	0.6	0.8	1.4	2.0	2.8	4.0	4.8	4.5
95%: 4.50	0.7	0.9	1.9	2.7	4.1	6.1	8.5	7.9
Murphy								
5%: 2.40	0.6	0.7	1.4	1.9	2.6	3.7	4.4	4.1
50%: 3.42	0.7	0.8	1.7	2.3	3.4	5.0	6.4	6.0
95%: 5.37	0.8	0.9	2.0	3.0	4.6	7.0	10.2	9.5
Knutti								
5%: 1.47	0.5	0.6	1.0	1.3	1.8	2.5	2.7	2.5
50%: 4.33	0.7	0.9	1.9	2.7	4.0	6.0	8.1	7.6
95%: 9.28	0.9	1.1	2.5	3.9	6.2	>8	18.1	17.0

Note. Results are given for the 7AEM as well as the probabilistic calculations based on different estimates of climate sensitivity PDFs by Wigley and Raper (2001), Murphy et al. (2004) and Knutti et al. (2003). In addition, equilibrium temperatures for 2400 forcing levels are given with applying the standard natural forcing assumptions (EQUI w NF) and without assuming any natural forcing changes from pre-industrial levels (EQUI w/o NF).

TABLE II

'Present forcing' warming commitment: temperature implications in case that radiative forcing is held constant at today's (2005) levels. Otherwise as Table I

	Temperature above pre-industrial (°C above pre-industrial)							
Climate Sensitivity	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF
7 AOGCM ensemble mean								
∼2.8	0.7	0.8	1.0	1.1	1.1	1.2	1.5	1.2
Wigley								
5%: 1.50	0.5	0.6	0.7	0.7	0.8	0.8	0.8	0.6
50%: 2.60	0.6	0.7	0.9	1.0	1.1	1.1	1.4	1.1
95%: 4.50	0.7	0.9	1.2	1.4	1.5	1.7	2.4	1.9
Murphy								
5%: 2.40	0.6	0.7	0.9	1.0	1.0	1.1	1.3	1.0
50%: 3.42	0.7	0.8	1.1	1.2	1.3	1.4	1.8	1.4
95%: 5.37	0.8	0.9	1.3	1.5	1.7	1.9	2.9	2.2
Knutti								
5%: 1.47	0.5	0.6	0.7	0.7	0.8	0.8	0.8	0.6
50%: 4.33	0.7	0.9	1.2	1.3	1.5	1.7	2.3	1.8
95%: 9.28	0.9	1.1	1.7	2.0	2.3	2.8	5.0	3.9

TABLE III

'Geophysical' warming commitment: temperature implications in case that all emissions are ceased from 2005. Otherwise as Table I

	Temperature above pre-industrial (°C above pre-industrial)							
Climate Sensitivity	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF
7 AOGCM ensemble mean								
∼2.8	0.7	0.8	0.9	0.7	0.6	0.4	0.4	0.1
Wigley								
5%: 1.50	0.5	0.7	0.6	0.5	0.4	0.3	0.2	0.0
50%: 2.60	0.6	0.8	0.8	0.7	0.5	0.3	0.4	0.1
95%: 4.50	0.7	1.0	1.2	1.0	0.7	0.5	0.7	0.1
Murphy								
5%: 2.40	0.6	0.8	0.8	0.7	0.5	0.3	0.3	0.1
50%: 3.42	0.7	0.9	1.0	0.8	0.6	0.4	0.5	0.1
95%: 5.37	0.8	1.0	1.3	1.1	0.8	0.6	0.8	0.2
Knutti								
5%: 1.47	0.5	0.7	0.6	0.5	0.4	0.3	0.2	0.0
50%: 4.33	0.7	1.0	1.1	0.9	0.7	0.5	0.6	0.1
95%: 9.28	0.9	1.2	1.6	1.5	1.2	0.9	1.5	0.4

4.2. THE ‘PRESENT FORCING’ WARMING COMMITMENT

One of the scenarios often used to convey a sense of inertia and of committed warming to policy makers is that of holding radiative forcing constant from a certain point in time.

The Hadley Centre, for example, recently estimated the additional warming that would follow from stabilization of greenhouse gas concentrations at present levels (see thick dotted line in panel c of Figure 3). The total warming above

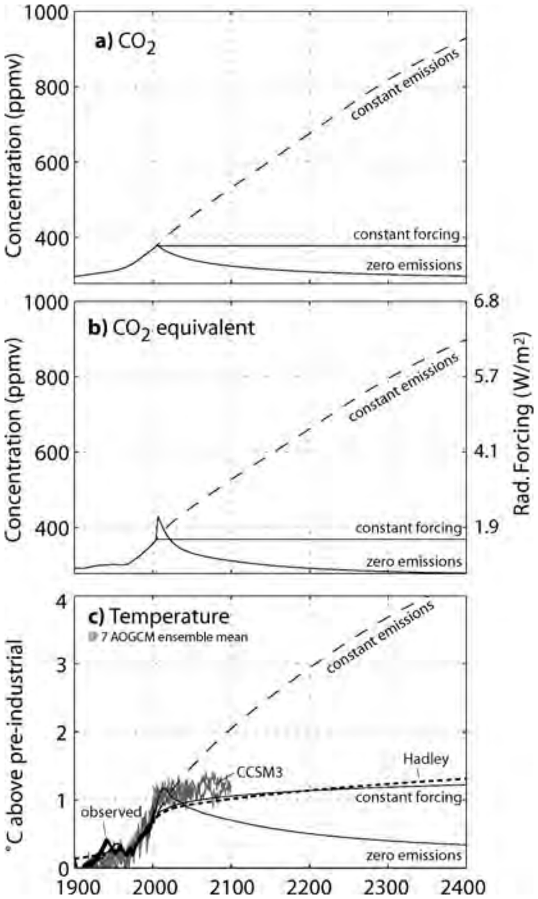

Figure 3. Effects of abrupt cessation of emissions, constant radiative forcing, and constant emissions from 2005 onwards (a) CO_2 concentrations, (b) CO_2 equivalent concentrations and radiative forcing, (c) global mean surface temperature. Shown are results of the ‘7 AOGCMs ensemble mean’ runs with an approximate climate sensitivity of 2.8 °C. In addition, the 20th warming commitment results are plotted for the CCSM3 model runs (Meehl et al., 2005) (grey solid lines). The Hadley centre’s estimate of the warming commitment related to a constant radiative forcing (dotted grey line in panel c) (Hadley Centre, 2002) is approximately equivalent to the 7AEM one derived here. All temperature model runs are calibrated towards the 1961–1990 observational record data from (Folland et al., 2001), shown with uncertainties (grey band with black solid line).

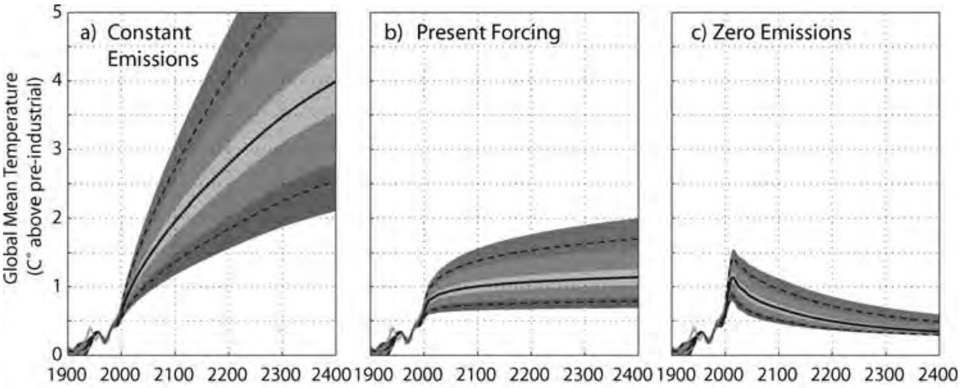

Figure 4. Global mean temperature increase in case that emissions are held constant at 2005 levels (left a), that radiative forcing is held constant (middle b) or that emissions are abruptly reduced to zero (right c). Likelihood ranges are given for the lognormal fit to the conventional 1.5–4.5 °C IPCC range (Wigley and Raper, 2001): the 90% confidence range (dashed lines), the median projection (solid line), as well as the 1, 10, 33, 66, 90 and 99% percentiles (borders of shaded areas).

pre-industrial by 2100 was estimated by about 1.1 °C with an ultimate warming of 1.6 °C over many centuries (Hadley Centre, 2002, p. 3, 2003, p. 12). Other models yield similar estimates when holding radiative forcing constant (Meehl et al., 2005; Wigley, 2005). Using a climate model with higher sensitivity (3.7 °C) than in the Hadley Centre analysis, the results of Wetherald et al. (2001)[15] indicate a total warming at equilibrium of around 2.1 °C above 1861–1890 would occur with forcing held constant at year 2000 levels.[16]

In this study, results suggest an increase of global mean surface temperatures by about 0.4 °C up to 2400 over the observed 2002 levels (1.2 °C above pre-industrial), if radiative forcing were held fixed at present levels (estimated to be 1.93 W/m^2 including natural forcings in 2005) (7AEM). In equilibrium, temperatures are estimated to rise up to 1.5 °C above pre-industrial values if assumptions on current natural forcing continue to apply. If no change of natural forcing since pre-industrial times were assumed, the equilibrium warming would be about 0.35 °C lower, namely 1.2 °C.

Running the simple climate model with default IPCC TAR parameter settings, but the IPCC bounds of climate sensitivity (1.5 and 4.5 °C), the 2400 total warming lies between 0.8 and 1.7 °C. At equilibrium the warming range would be 0.8 to 2.4 °C (cf. Table II).

It should be kept in mind that the present forcing is dampened greatly by the cooling effect of aerosols that counteracts the warming effect of greenhouse gases, although the magnitude is uncertain. Thus, the present forcing warming commitment might be up to 1.9 (2.1) °C by 2100 (2400) for the 7AEM, if it is assumed that SO_2 aerosol emissions were to cease, but greenhouse gas concentrations remain at the current level (452 ppm CO_2 equivalence).[17]

4.3. THE 'GEOPHYSICAL' WARMING COMMITMENT AND ITS INCREASE OVER TIME

A complete and abrupt cessation of human emissions would soon reverse the increase in radiative forcing and result in a halt to global mean temperature. However, in the beginning, the cessation of sulphur emissions causes a short, but pronounced, increase in net radiative forcing and temperatures (Wigley, 1991). Within a decade, temperatures would be begin to fall, though (Figure 3c). Until 2100 it seems likely that temperature levels at least as high as year 2000 levels would prevail, even if all human-induced emissions were to be halted today. However, beyond 2100, there is no geophysical commitment to a further increase in warming, but there is a floor to how fast temperatures can drop (in the absence of negative emissions).[18] The indicated lower bound of approximately 0.3 to 0.4 °C results largely from the increase in solar forcing since pre-industrial times and assumed continuation of current levels (see Section 3.5). CO_2 concentrations would fall slowly and approach levels that were found at the beginning of the 20th century towards the end of the 22nd century, namely 300 ppm (see Figure 3a). The slow take up of the airborne fraction of anthropogenic carbon emissions by the oceans determines the rates of temperature reduction in the 22nd century and beyond and also ultimately determines the rise in sea level.

In order to see how the geophysical warming commitment increases with time, we show the effects of emissions being switched off at six ten-year intervals from 2001 to 2051 for the SRES A1B scenario on global mean temperature. This may help place lower bounds on the costs of delaying policy action (see Section 5.2). The additional 'warming commitment' by 2100 increases by about 0.2–0.3 °C for each 10-year delay and over the period to 2400 by 0.1–0.2 °C (see Table IV and Figure 5). This estimate is similar to that made by Ramanathan (1988) of

TABLE IV

The geophysical warming commitment over time (columns) is depending on the year, when emissions are reduced to zero (rows)

	Temperature above pre-industrial (°C above pre-industrial)							
Ceasing emissions	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF
2001	0.7	1.1	0.8	0.7	0.5	0.3	0.4	0.0
2011	0.7	0.7	1.0	0.8	0.6	0.4	0.5	0.1
2021	0.7	0.7	1.3	1.0	0.8	0.6	0.6	0.3
2031	0.7	0.7	1.7	1.3	1.0	0.7	0.8	0.4
2041	0.7	0.7	2.1	1.6	1.2	0.9	0.9	0.6
2051	0.7	0.7	2.2	1.9	1.4	1.1	1.1	0.8

Note. Before being ceased, emissions were assumed to follow the SRES A1B-AIM baseline scenario (cp. Figure 5). Results are shown for the '7 AOGCM ensemble mean' and equilibrium values with and without natural forcing ('EQUI w NF' and 'EQUI w/o NF', respectively).

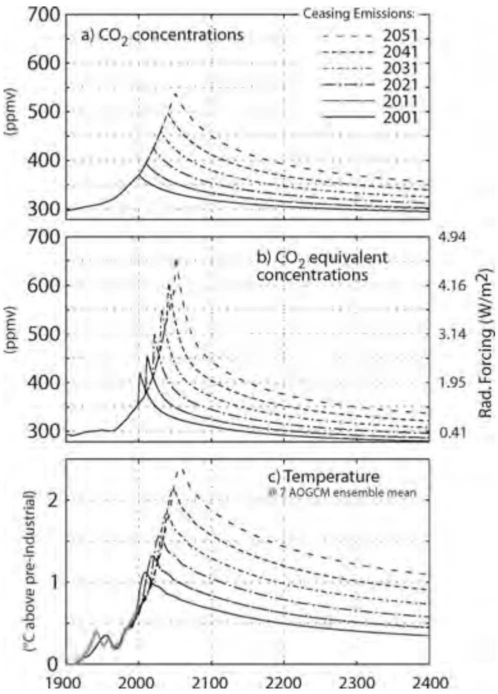

Figure 5. Effects of 10 year lags in reducing emissions to zero on (a) CO_2 concentrations, (b) CO_2 equivalent concentrations and radiative forcing, (c) global mean temperature. Emissions are reduced to zero in 2001, 2011,. . ., 2051 after following the SRES A1B-AIM scenario.

0.15–0.5 °C warming commitment for each decade of continued growth in greenhouse gas emissions.

4.4. THE ‘FEASIBLE SCENARIO’ WARMING COMMITMENT

We now turn to an examination of what the warming commitment might be for a range of feasible emissions scenarios. We use explicit scenarios from the literature that produce a range of different radiative forcing pathways (see Section 2.4). If not otherwise indicated, all results below refer to the 7AEM results (see Section 3.2). Furthermore, we examine the equilibrium warming when forcing is stabilized at a range of CO_2 equivalent levels (see method’s Section 3.4).

For the period up to 2100, the 450 ppm CO_2 scenarios result in a warming in the range of 2.2–2.4 °C above pre-industrial levels (7AEM). An exception is the A1FI-450 MiniCam scenario that results in higher warming (3.0 °C) due to very high unabated N_2O emissions. For the two 400 ppm scenarios the range is 1.9–2.1 °C in 2100. The 350 ppm CO_2 stabilization scenarios of Azar et al. (in press) yield a warming of about 1.5–1.7 °C by 2100.[19] In contrast, temperatures in 2100 will increase to levels that are between 2.5 to 4.8 °C above pre-industrial ones, if

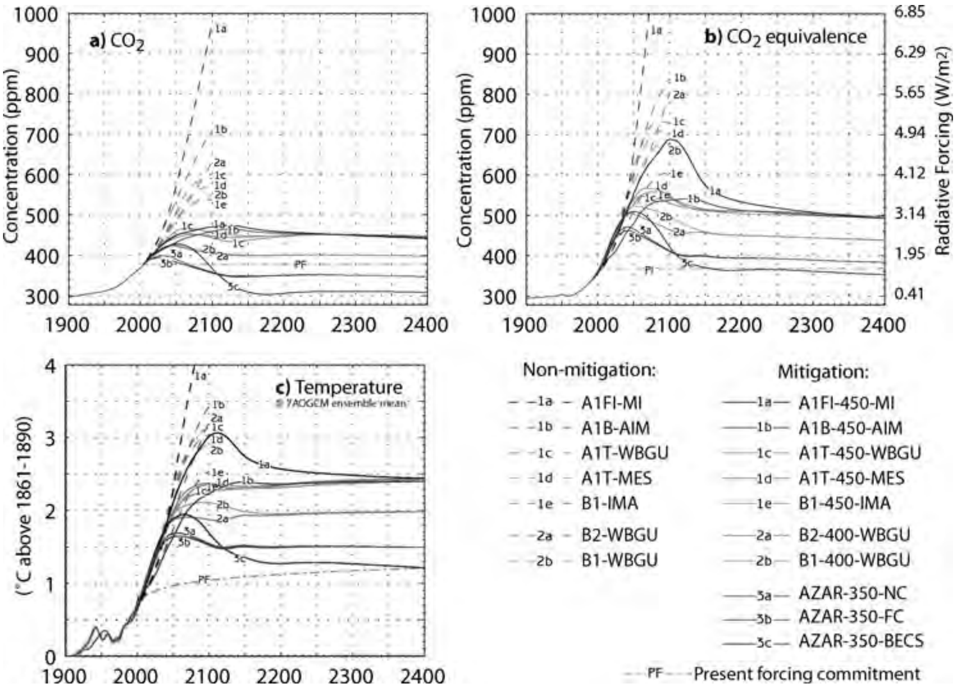

Figure 6. The climatic effects of a range of SRES non-mitigation scenarios (dotted line) and 350–450 ppm CO_2 stabilization scenarios (solid lines) on (a) CO_2 concentrations, (b) CO_2 equivalent concentration and radiative forcing, (c) global mean. For comparison, the 'constant present forcing' run is plotted as in Figure 3.

emissions were to follow one of the non-mitigation scenarios analysed here (see Figure 6).

In summary, if the 350 and 400 ppm CO_2 scenarios were considered to represent the outer limit of where climate policies can reach, we would be committed to an additional warming of 0.7 to 1.3 °C above the warming of 0.8 °C in 2002 (Folland et al., 2001; Jones and Moberg, 2003).

The period beyond 2100 is critical to warming commitment assessments. However, published mitigation scenarios are generally limited to 2100. Therefore, we have extended these scenarios so that they stabilize CO_2 concentrations at the indicated levels. For example, the WBGU B2-400 MESSAGE scenario is extended so that CO_2 concentrations stabilize at 400 ppm. The emissions of other greenhouse gases and aerosols beyond 2100 are assumed to correlate with the extended fossil CO_2 emissions in a specific way, namely by making use of the 2100 emission characteristics of 54 SRES and post-SRES scenarios via the 'Equal Quantile Walk' method (Meinshausen et al., in press).[20] A special case is the AZAR-350-BECS scenario, where the fossil CO_2 emissions are negative (−3.6 GtC/yr) in 2100 and assumed to smoothly return to zero by 2200. As a consequence, CO_2 concentrations

TABLE V

Risk of overshooting different global mean temperatures in equilibrium for the analyzed warming commitments (rows). In the first two rows, the CO_2, and CO_2 equivalent concentrations are given for 2400. The risk of overshooting a certain temperature limit in equilibrium (excluding natural forcings) is given for three climate sensitivity PDF estimates by 'Wigley' et al., 'Murphy' et al., and 'Knutti' et al. (see Section 3.3). Values in bold indicate risks of less then 33%, termed by IPCC as 'unlikely'. For example, only if future CO_2 equivalent concentrations are stabilized below 400 ppm, overshooting 2 °C in equilibrium is 'unlikely' (risk below 33%) for two out of the three climate sensitivity PDFs

Warming commitment		1. Constant emissions	2. Present forcing	3. Zero emissions	4. Feasible scenarios			
					a	b	c	d
CO_2 in 2400 (ppm)		929	377	298	450	400	350	310
CO_2eq in 2400 (ppm)		899	368	282	500	440	385	350
		Risk of overshooting warming level (%)						
>1.5 (°C)	Wigley	100	**14**	**0**	87	65	**26**	**6**
	Murphy	100	37	**0**	100	97	60	**17**
	Knutti	100	59	**0**	91	82	66	50
>2 (°C)	Wigley	99	**3**	**0**	60	**32**	**7**	**1**
	Murphy	100	**8**	**0**	95	69	**18**	**3**
	Knutti	98	43	**0**	81	69	50	**33**
>2.5 (°C)	Wigley	96	**0**	**0**	34	**12**	**1**	**0**
	Murphy	100	**2**	**0**	73	**33**	**5**	**1**
	Knutti	95	**30**	**0**	70	57	38	**20**
>3 (°C)	Wigley	87	**0**	**0**	**17**	**4**	**0**	**0**
	Murphy	100	**1**	**0**	43	**13**	**2**	**0**
	Knutti	91	**19**	**0**	61	47	**27**	**9**
>3.5 (°C)	Wigley	75	**0**	**0**	**8**	**2**	**0**	**0**
	Murphy	99	**0**	**0**	**21**	**5**	**1**	**0**
	Knutti	86	**10**	**0**	52	38	**18**	**0**

will stabilize at about 310 ppm and CO_2 equivalent concentrations at about 350 ppm by 2150 (see Table V).

By 2400, temperatures would have risen to 1.5, 2.0 and 2.4 °C for the 350, 400 and 450 ppm CO_2 stabilization scenarios, respectively, according to the '7AEM'. Temperatures for the AZAR-350-BECS scenario, which is assumed to stabilize at the lowest CO_2 level of 310 ppm, would have returned to about 1.2 °C by 2400 (see Figure 6).

The risk of overshooting 2 °C is about 66% for the 450 CO_2 scenarios ($\approx$500 CO_2eq) (Figure 7a), approximately 33% for the 400 ppm CO_2 scenarios ($\approx$440 ppm CO_2eq) (Figure 7b), and 33% around the peak and 2% in the long-term for the analysed 310 ppm CO_2 scenario AZAR-350-BECS ($\approx$350 ppm CO_2eq) (Figure 7c; cf. Table V for risks in equilibrium without natural forcing).

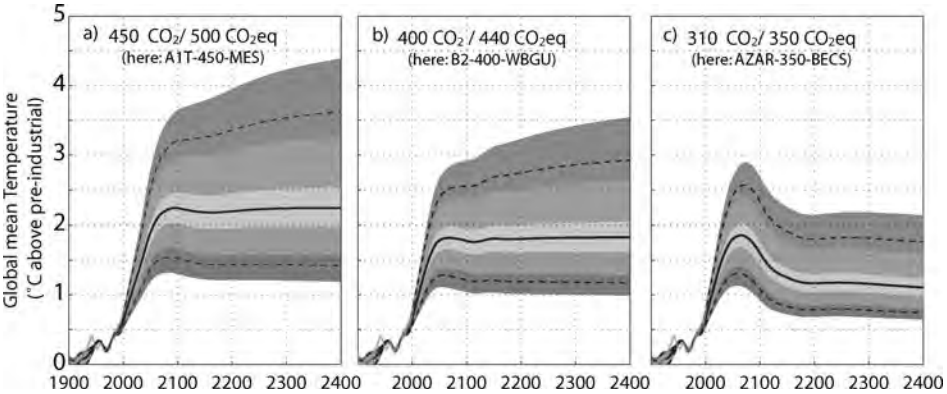

Figure 7. Temperature increase for mitigation scenarios stabilizing CO_2 at 450 ppm (left a), 400 ppm (middle b) and 310 ppm CO_2 (right c). The CO_2 equivalent concentrations in 2400 are about 500, 440 and 350 ppm, respectively (cf. Figure 6). Otherwise as Figure 4: The underlying climate sensitivity PDF is based on the conventional 1.5 to 4.5 °C range (Wigley and Raper, 2001).

4.5. RISK OF OVERSHOOTING CERTAIN WARMING LEVELS IN EQUILIBRIUM

The warming commitments shown for the scenarios extend to 2400 and are not the final warming of the system if these concentration levels are maintained (Watterson, 2003). It is instructive therefore to examine the final committed warming in equilibrium. Taking into account the uncertainty in the climate sensitivity, we present probabilistic results in terms of the risks that certain temperature thresholds (1.5 to 3.5 °C) are overshot (see Table V). The estimates we present here constitute a lower bound estimate, if stabilization levels are approached ‘from above’, i.e. after concentration peaked at higher levels before returning to the ultimate stabilization level (cf. Figure 6c). For the higher stabilization scenarios, risk might be lower in practice, if concentration levels were not stabilized, but continuously decreased after 2100. This would prevent the full equilibrium warming from being realized. It should be kept in mind that natural forcings are not taken into account for these equilibrium calculations (see Section 3.5).

Given contemporary policy discussions around warming limits of 2 °C (European Community, 1996; Caldeira et al., 2003)[1] we focus here on the probability that committed warming will lie above 2 °C for different long term stabilization levels. From Figure 8, it can be seen that the choice of PDF for climate sensitivity uncertainty is quite fundamental in determining the probability of whether or not 2 °C is already committed to for stabilization scenarios. The Knutti et al. (2002) and Gregory et al. (2002) PDFs with their long high tails imply the lowest probability to stay within the 2 °C limit for the lower concentration levels. In contrast, the Forest et al. (2002) estimate that is based on a confined expert a priori PDF suggests a narrower distribution and a lower mean estimate of climate sensitivity. Thus, according to the Forest et al. “expert prior” PDF, the risk of overshooting 2 °C enters

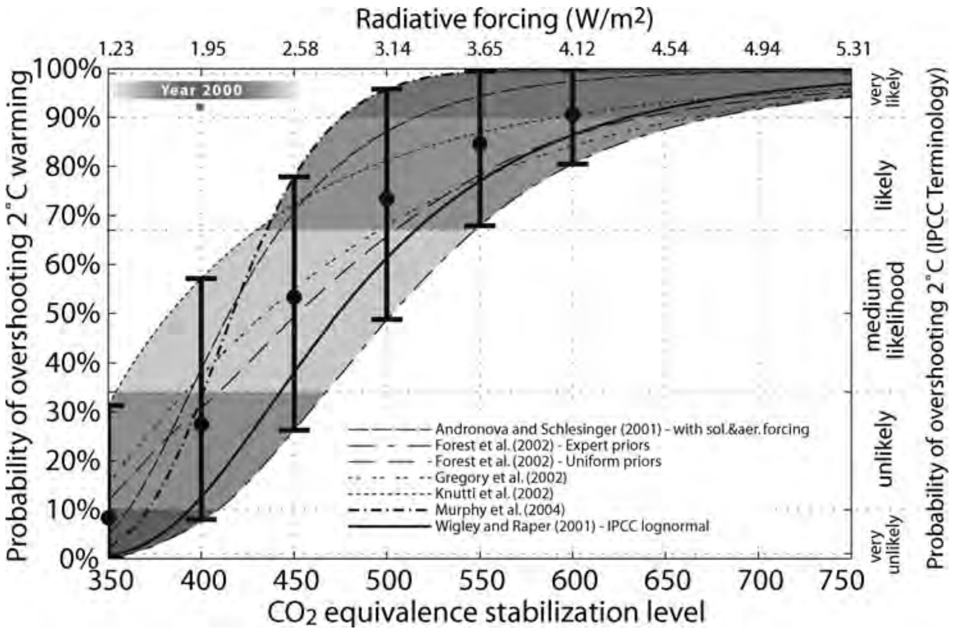

Figure 8. Risk of overshooting a 2 °C target. Current estimates of the climate sensitivity suggest that only by stabilizing anthropogenic radiative forcing at levels below 400 or 450 ppm CO_2 equivalent concentrations, the risk of overshooting the 2 °C target can be termed "unlikely". The actual 2000 forcing range and its uncertainty (upper left bar) is taken from Knutti et al. (2002), with the grey square indicating this study's present (2005) forcing assumption.

the "unlikely" range around 475 ppm CO_2 equivalent stabilization level and is further reduced to "very unlikely" below the 410 ppm CO_2 equivalent stabilization level.[21]

For stabilization of greenhouse gas concentrations at 550 ppm CO_2 equivalent, (corresponding approximately to a 475 ppm CO_2 stabilization), the risk of overshooting 2 °C is very high, namely between 68–99%, with a mean of 85% across the different climate sensitivity PDFs.[22] In other words, the probability that warming will exceed 2 °C could be categorized as 'likely' using the IPCC WGI Terminology. If greenhouse gas concentrations were to be stabilized at 450 ppm CO_2 equivalent then the risk of exceeding 2 °C would be lower, but still significant, in the range of 26 to 78% (mean 47%). This could roughly be categorized as having a "medium likelihood". The 450 ppm CO_2eq stabilization level would correspond roughly to the 400 ppm CO_2 scenarios discussed above. Only for stabilization levels of 400 ppm CO_2 equivalent and below, the possibility that warming of more than 2 °C will occur, could be classified as "unlikely" (range 2 to 57% with mean 27%). The risk of exceeding 2 °C in equilibrium is further reduced, namely to 0 to 31% (mean 8%), if greenhouse gases were stabilized at a 350 ppm CO_2 equivalent level (see Figure 8).

Again, the question of how much risk of overshooting 2 °C we are committed to primarily depends on the applied definition of a 'warming commitment'. Firstly, under a 'constant emission' scenario there is basically no chance (at best 2%, cf. Table V) to stay below 2 °C in the long-term. Secondly, the 'present forcing warming commitment' implies a 3 to 43% risk of overshooting 2 °C – depending on the assumed climate sensitivity probability distribution function. When assuming the Murphy et al. (2004) climate sensitivity, the risk is about 8%. Thirdly, the 'geophysical warming commitment' with zero emissions does not entail any risks to overshoot 2 °C in equilibrium, since it implies that radiative forcing levels will return to near pre-industrial levels in the long term. Fourthly, quantification of the 'feasible scenario warming commitment' again greatly depends on whether a 500 ppm CO_2 equivalent or rather a 350 ppm CO_2 equivalence scenario are considered the lowest feasible mitigation options. For the climate sensitivity PDF that is based on the conventional IPCC range (Wigley and Raper, 2001), the probability that we are committed to 2 °C in equilibrium range from a medium likelihood (60%) to exceptionally unlikely (1%) (see Table V).

4.6. AVOIDABLE WARMING

Avoidable warming is computed here on the basis of paired comparisons of mitigation and non-mitigation scenarios drawn from the range used in evaluating 'feasible scenario' warming commitments. We have compared the computed effects on global mean temperature between the SRES non-mitigation scenarios and the post SRES and/or WBGU 450 and 400 ppm CO_2 mitigation scenarios. We compute the global mean temperature differences between the non-mitigation and mitigation scenario of the same scenario family until the year 2100. As a lower bound of the expected climate benefits, the 'current avoidable warming' indicates the warming difference in a specific year. The 'equilibrium avoidable warming' refers to the equilibrium warming difference that corresponds to forcing differences in a specific year (see Figure 10).

4.6.1. *Current Avoidable Warming*

The climate benefits of mitigation scenarios can be correlated to the mitigation effort, here indexed by the avoided cumulative fossil CO_2 emissions in any given year (see Equation (3)). The analysis shows that there is a significant temperature benefit (0.12–0.50 °C) in most cases by 2050 based on the 7AEM climate simulations (see Figure 9). The benefits increase to a range of 0.13–0.60 °C for higher climate sensitivity (4.5 °C) and decrease to a range of 0.10–0.33 °C for lower sensitivity (1.5 °C). Note that for the B1 IMAGE scenarios the 450 ppm CO_2 scenario is *warmer* than the reference case by about 0.2 °C in 2050, which is due to the reductions of sulphur emissions in the 450 ppm CO_2 scenario (see Figure 9).

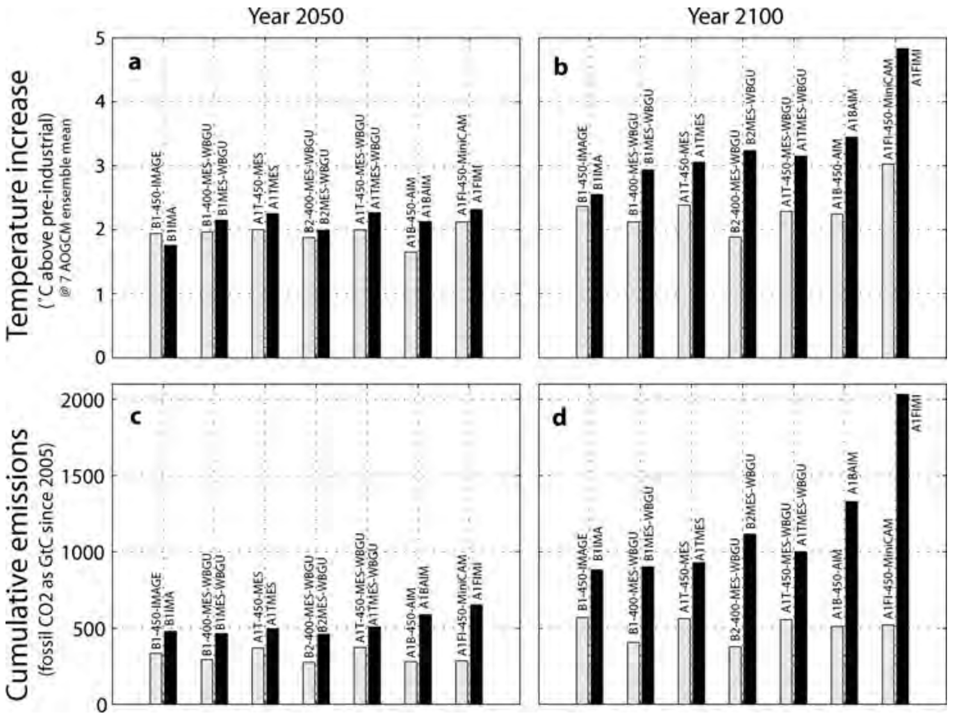

Figure 9. Comparison of cumulative emissions and temperature increase for 2050 and 2100. The non-mitigation scenarios (black bars) have higher cumulative emissions (c,d) than the mitigation scenarios (grey bars). Consequently, the ‘current’ temperature increase up to year 2050 and 2100 is lower for almost all mitigation scenarios (cf. Figure 10). The 7AEM procedure has been applied here (cf. Section 3.2).

It can be seen that the further one goes into the future the larger is the benefit of climate policy – with the benefit strongly associated with the scale of the mitigated emissions. In the 7AEM computations presented here, the avoided warming at any year is about 0.16 °C for each 100 GtC avoided cumulative fossil CO_2 emissions until that year (see Equation (3)). Statistical analysis of existing multi-gas mitigation and non-mitigation scenarios suggests the following regression relationship for a climate sensitivity of about 2.8 °C (‘7AEM’):

$$\Delta T_{\mathrm{current},t} = \frac{0.16\,^{\circ}\mathrm{C}}{100\,\mathrm{GtC}} * \sum_{i=2000}^{t} \Delta E_i \tag{3}$$

with ΔE_i: Difference in fossil CO_2 emissions in year i between the unmitigated and mitigated cases as index of the (multi-gas) mitigation effort.

$\Delta T_{\mathrm{current},t}$: Difference in temperature in year t. between the unmitigated and mitigated cases.

As in the case of Equation (4), the regression coefficients are estimated from warming and cumulative emission differences between the non-intervention and

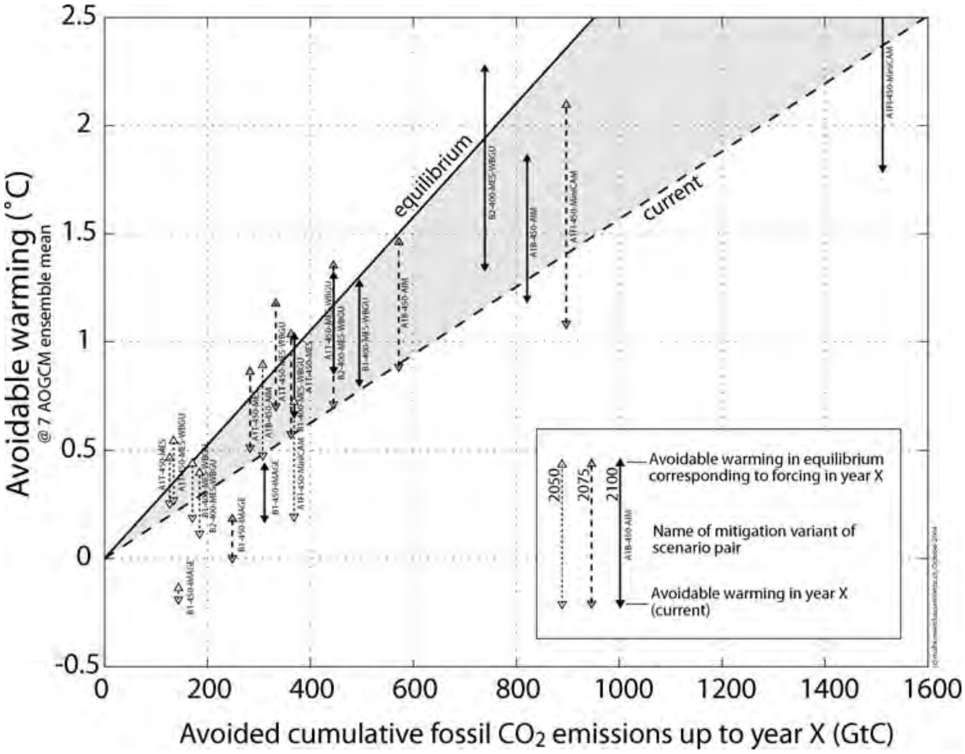

Figure 10. Benefits of mitigation. Here paired comparisons between mitigation and non-mitigation scenarios of the same SRES scenario families are shown. The horizontal axis displays the mitigation effort in terms of the difference in cumulative fossil CO_2 emissions of a mitigation and non-mitigation scenario up to the year 2050, 2075 and 2100, respectively. The vertical axis displays the avoidable warming up to the year 2050, 2075 and 2100. See text for more details.

intervention scenario variants in 2050, 2075, and 2100 (see Figure 10). A higher or lower climate sensitivity would produce a higher or lower temperature scaling factor in Equations (3) and (4).[23]

4.6.2. *Avoidable Warming in the Longer Term*

Note that the ‘current’ avoidable warming relation is a conservative lower bound estimate of the climate benefits of mitigation. The avoided warming due to fossil CO_2 emissions avoided up to specific year t, e.g. 2050, 2075 or 2100, will grow beyond that year due to the inertia of the climate system. This effect is not fully captured by comparing avoided warming and avoided emissions for the same year, as presented in the previous section. Therefore, we present as well the equilibrium benefits of mitigation. The equilibrium benefits are computed as the difference of equilibrium warming that correspond to the forcing of the mitigation and non-mitigation scenario in a specific year. The avoided emission are the integral of the difference between the unmitigated and mitigated emissions scenarios from the base year until a specific year t of interest. A linear least squares regression across the scenario pairs for the years 2050, 2075 and 2100 suggests that 0.26 °C warming can be avoided in equilibrium for every 100 GtC of avoided fossil CO_2 emissions ('7AEM'):

$$\Delta T_{\text{equilibrium},t} = \frac{0.26\,^{\circ}\text{C}}{100\,\text{GtC}} * \sum_{i=2000}^{t} \Delta E_i \tag{4}$$

with ΔE_i: Difference in fossil CO_2 emissions in year *i* as index of the (multi-gas) mitigation effort.

$\Delta T_{\text{equilibrium},t}$: Difference of equilibrium temperatures that correspond to radiative forcing levels in year *t*.

5. Discussion

In this section we turn to a discussion of the results and their implications for climate policy debates.

5.1. 'FEASIBLE SCENARIO' WARMING COMMITMENTS MIGHT UNDERESTIMATE AVOIDABLE WARMING

Several caveats indicate that the 'feasible scenario' warming commitments are probably an upper estimate on the warming that we are committed to – taking into account climate system as well as socio-economic inertia.

The feasible scenario range we deploy here does not necessarily cover the full range of plausible possibilities for future emissions. The biomass energy carbon capture and storage technologies used in one of the 350 ppm CO_2 scenarios (AZAR-350-BECS) could in principle draw down CO_2 in the atmosphere. This class of technologies appears feasible and the introduction rates could potentially be accelerated compared to the rates deployed in the 350 ppmv CO_2 scenarios if there were sufficient political interest in doing so.

There is substantial uncertainty in regard to the costs of mitigation scenarios, which influence judgements as to their plausibility. Costs are highly dependent on the assumed reference (non mitigation) case and the level to which technological learning is included. The scenarios generally do not include the full range of mitigation options known for agricultural and other sectors, particularly for non-CO_2 gases, and hence the temperatures calculated here are a bit higher (a few tenths of a degree) than might otherwise be the case.[24]

Furthermore, increased mitigation efforts and hence lower concentrations than analysed here might become more plausible if scientific developments raise and broaden the perceived risk of large scale climate system alterations. Examples for potential thresholds are manifold, such as the potential decay of the Greenland ice sheet or the collapse of the West Antarctic, either of which have the capacity to raise sea level by some 5–6 m on half millennial to millennial time scales in response to warming this century (Oppenheimer, 1998; O'Neill and Oppenheimer, 2002; Gregory et al., 2004; Oppenheimer and Alley, 2004; Thomas et al., 2004b). Other examples for potentially critical thresholds include a significant slow-down of the thermohaline circulation (Stocker and Wright, 1991; Rahmstorf, 1995, 1996), ecosystem risks, such as collapse of coral reefs (Hoegh-Guldberg, 1999), loss of biological hot spots or ecosystems with very high biodiversity values (Hannah et al., 2002; Midgley et al., 2002; Williams et al., 2003), or a threat of climate induced collapse of the Amazon rainforest (Cox et al., 2003; Cowling et al., 2004). In short, new scientific evidence and awareness of such potential thresholds is likely to change assessment of what is plausible policy action.

5.2. EXTRA WARMING DUE TO DELAYED MITIGATION IS LIKELY TO EXCEED THE ADDITIONAL GEOPHYSICAL WARMING COMMITMENT

One of the issues that arises in climate policy is the climatic consequence of delay in taking action to limit emissions. The results presented here for the geophysical commitment calculations provide a way of quantifying a lower bound for the effect of delay on long term warming. These show that the effect of a 10 year delay in emission action commits to at least a further 0.2–0.3 °C warming over 100 year time horizons. This is essentially a lower bound as emission reductions are very unlikely to exceed the complete cessation assumptions in these experiments. Also the geophysical warming commitment estimates neglect any technological or lock-in effects, if global emissions continue to rise unabated. Political, social, technical and infrastructural inertia is likely to multiply climatic costs that correspond to delays in mitigation action.

5.3. TIME IS RUNNING OUT FOR LIMITING WARMING BELOW 2 °C

The results can begin to provide an answer to the question "Under which emission scenarios is it still likely that we can achieve certain climate targets?".

The results suggest (see Figure 8) that a stabilization of radiative forcing at around 400 ppm CO_2 ($\sim 2\,W/m^2$) equivalence is needed, if global long-term temperature change is to be limited to at or below 2 °C with reasonable certainty. In 2000, the radiative forcing due to the well mixed greenhouse gases was already equivalent to 440 ± 20 ppm CO_2 ($2.43 \pm 0.24\,W/m^2$) (Ramaswamy et al., 2001, Table 6.11). The 2000 net radiative forcing was likely to be lower, equivalent to 350 to 450 ppm CO_2 (1.25–2.5 W/m^2 – cf. Knutti et al. (2002)), with positive contributions due to changes in tropospheric ozone and solar forcing, and (dominant) negative contributions due to (uncertain) aerosol cooling, among others. Thus, radiative forcing levels are likely to (or might have already) temporarily overshoot the levels that would be required to limit the temperature increase above preindustrial to below 2 °C in the long-term (see Figure 8). This does however not mean, that 2 °C warming is inevitable. Continued emission reductions might reduce the radiative forcing levels again in the long-term, so that the equilibrium warming levels might not be felt thanks to the inertia of the climate system.

The lower mitigation scenarios used here overshoot their ultimate CO_2 equivalent stabilization levels in the 21st century. The results suggest that if the ultimate stabilization level is below 450 ppm CO_2eq, the initial peaking level around 2100 seems to be the decisive characteristic for determining the maximum temperature increase (cf. Figure 7). The peaking concentration in turn will be the main determinant behind emission reduction needs in the coming years and decades (see Table VI), in the sense that the lower the peak level, the faster would need to be the emission reductions.

In any case, it becomes clear that rapid emission reductions are needed within the next few decades globally in order to substantially limit the risk of overshooting the European Union's 2 °C goal[1]. Only scenarios that aim at stabilization levels at or below 400 ppm CO_2 equivalence ($\sim$350 ppm CO_2) can limit the probability of exceeding 2 °C to reasonable levels (see Table V).

TABLE VI

Global emissions relative to 1990 for the analyzed mitigation scenarios. The 'all GHGs' columns comprise CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. Values are bracketed for the CO_2-only AZAR scenarios that have been complemented by non-CO_2 emissions from B2-400-WBGU. In addition, the first two columns indicate the risk of overshooting 2 °C in equilibrium and at peaking temperature values based on transient runs (roughly around 2100 for the lower 6 scenarios – cf. Figure 7). Only the lower stabilization scenarios have a "unlikely" risk of overshooting, although their overall risk from transient runs might be higher than the risks in equilibrium. The lognormal climate sensitivity PDF base on the conventional 1.5 to 4.5 °C IPCC uncertainty range has been applied here (Wigley and Raper, 2002) (cf. Table V)

Mitigation scenario	Risk $> 2\,^\circ$C in equilibrium (Wigley)	Risk $> 2\,^\circ$C $\sim$2100 (Wigley)	Global emissions relative to 1990 (%)					
			All GHGs			Fossil CO_2 only		
			2020	2050	2100	2020	2050	2100
B1-450-IMA	60%	$\sim$60%	127%	100%	46%	138%	102%	53%
A1T-450-MES	60%	$\sim$60%	122%	102%	54%	149%	107%	45%
A1B-450-AIM	60%	$\sim$60%	101%	102%	75%	103%	96%	65%
A1T-450-WBGU	60%	$\sim$60%	115%	107%	49%	125%	113%	31%
A1FI-450-MI	60%	93%	126%	120%	102%	119%	84%	94%
B2-400-WBGU	**32%**	**33%**	111%	66%	42%	121%	42%	26%
B1-400-WBGU	**32%**	50%	110%	69%	41%	120%	56%	27%
AZAR-350-FC	**7%**	**10%**	(80%)	(51%)	(28%)	67%	16%	1%
AZAR-350-NC	**7%**	**10%**	(87%)	(49%)	(28%)	80%	13%	1%
AZAR-350-BECS	**1%**	**33%**	(107%)	(78%)	($-$5%)	115%	64%	$-$57%

For moderate levels of risk and for scenarios using a conventional technological mix including renewables and some carbon capture and storage global fossil CO_2 emissions need to be limited to around a 20% increase by 2020 relative to 1990 and then decrease to around 40–60% below 1990 levels by 2050 (see Table VI).

5.4. INTERACTION BETWEEN AEROSOL AND WARMING COMMITMENT TIMESCALE

The committed warming, or level of warming that is avoidable, also depends on the residence times of the atmospheric radiative forcing agents. Tropospheric Aerosols have a short atmospheric residence time (days to weeks). Reductions in aerosols (which overall are estimated to have a negative radiative forcing) and other air pollutants, such as those leading to tropospheric ozone formation (with a substantial positive radiative forcing) can lead to large net changes in forcing on shorter times scales than apply to the well mixed greenhouse gases. Changes in CO_2 forcing, which are partly shaded by the aerosol effect, will happen much more slowly and the effects of past emissions will survive much longer in the atmosphere. The net effect is that policies that reduce both air pollution (aerosols) and CO_2 may result in more warming in the short term (decades), whilst reducing warming in the longer term (see Figures 3 and 10 and cf. Wigley, 1991). Hence the avoidable warming in the short term may not be as great as sometimes assumed. The robustness of these results outlined here need to be further examined to take into account actual sulphur emissions and other air pollutants that affect tropospheric ozone levels, for example. Sulphur emissions might already be lower than assumed in the post-SRES and SRES scenarios (Streets et al., 2001). This means that some of the additional temperature increases in the first decades of the 20th century resulting from the mitigation scenarios used in this work arising from the sulphur emission reductions in these scenarios would not occur. This may have the effect of enhancing the benefits of climate policy on a 2020s or 2030s time scale. On the other hand, actual reactive gas emissions, which lead to tropospheric ozone formation that adds positively to radiative forcing may as well be less than assumed under the post-SRES and SRES scenarios, reducing the apparent benefit of mitigation (Wigley et al., 2002). By the time of the 2050s, there is however a clear difference between mitigation and non-mitigation scenarios, up to 0.5 °C for the A1B scenarios (see Figure 9).

5.5. UNCERTAINTY IN CLIMATE SENSITIVITY

The climate sensitivity strongly affects estimates of the warming to which we are committed. Firstly, the higher the sensitivity, the higher is the equilibrium warming commitment for a given emissions pathway. Secondly, the range of warming implied by a fixed range of climate sensitivity can grow or shrink over time, depending on whether radiative forcing increases or decreases, respectively (see Figure 4). This illustrates the simple fact that the more we move away from pre-industrial greenhouse gas levels, the more uncertain we are about the absolute climate system response.

As can be seen from the range of climate sensitivity estimates in Figure 2 there is a large uncertainty in this key parameter, which is of quite fundamental significance for policy in general and specifically in relation to the question of long term warming commitments. This would be substantially reduced if there were some fundamental narrowing of the uncertainty range such as the the ruling out of climate sensitivities higher than 4 °C and lower than 1.5 °C, as has been argued by Schneider von Deimling et al. (2004) on the basis of assessment of constraints on climate system feedbacks that applied during the last the Last Glacial Maximum (about 21 000 years ago) and projected to a doubled CO_2 climate. However, several factors weigh against a strong conclusion based in this or earlier paleoestimates of climate sensitivity (Lorius et al., 1990; Hoffert and Covey, 1992; Covey et al., 1996; Alley, 2003). It cannot be assumed that the scale of climate system feedbacks during glacial times will be limited in the same way in a warmer world in the future. Much remains to be explained in relation to the operation of the hydrological cycle and oceans for example during warmer period of earth system history such as the Paleo Eocene Thermal Maximum (Schmidt and Shindell, 2003; Renssen et al., 2004) which may be relevant to the future.

Whilst research will assist in narrowing uncertainties, policy action based on current scientific knowledge may need to rely on a precautionary approach as recognised in Article 3.3 of the UNFCCC.

5.6. CARBON CYCLE FEEDBACKS AND THE WARMING COMMITMENT FOR A PARTICULAR EMISSION SCENARIO

Positive terrestrial carbon cycle feedbacks (Jones et al., 2003a,b) or releases of methane hydrates (Archer and Buffett, 2005) would add to the warming arising from any particular emission scenario as they would increase CO_2 and methane levels in the atmosphere substantially above the levels assumed in the current work. This would result in larger long term warming for any given emission scenario used here.

5.7. POSSIBLE UNDERESTIMATION OF THE COOLING RATE FOR SCENARIOS WITH REDUCING RADIATIVE FORCING

A limitation of the applied climate model and hence the presented results is its symmetric response to positive and negative radiative forcing. The climate system is likely to respond faster to a reduction in forcing than to an increase, due to the physics of the ocean response to forcing changes (Stouffer, 2004). In other words, the climate system at the global level is likely to cool faster than it warms. For a warming climate the ocean becomes more thermally stratified and hence deeper mixing slows relatively, and for a cooling climate, with declining radiative forcing, this thermal stratification is reduced and hence the response is faster. These processes are likely to be important in the latter parts of the 21st century and beyond in relation to climate policy aimed at preventing dangerous changes in the climate system. Thus, the rate of cooling for the geophysical warming commitment and the lower mitigation scenarios might actually be faster than presented here (see Figures 3, 5 and 6).

5.8. ULTIMATE WARMING COMMITMENT BOUND FROM BELOW BY SLOW PERMANENT CO_2 SINK AT OCEAN FLOOR

The long atmospheric residence time of CO_2 and long-lived halogenated compounds has a significant impact on the committed long-term warming and sea level rise. Anthropogenic carbon dioxide emissions are taken up by the terrestrial biosphere and the oceans at first relatively rapidly. Mid range carbon cycle model such as that used in MAGICC indicate that after a century about 30% of unit emissions made at present would remain in the atmospheres and after about 500 years 15% would remain. In the longer term however the uptake is governed by slow processes at the ocean floor and reactions with igneous rocks on land so that after 100 000 years about 7% of present emissions would still remain in the atmosphere (Archer et al., 1997, 1998; Archer, 2005). This implies a significant future commitment arising from contemporary emissions patterns over millennial time scales even if all emission ceased, unless there is substantial use of technologies such as the combined biomass burning and CO_2 capture and storage option – assuming the containment efficiency of the captured CO_2 is high for very long periods (Haugan and Joos, 2004) For example, in the absence of the latter option, even if emissions were to cease in the next few years, CO_2 levels would remain above the highest levels that have prevailed over the last 420 000 years before the present historical period for the next 10 000 years.[25]

6. Conclusions

There is no single scientific assessment that can be made of a ‘warming commitment’. If global human-induced greenhouse gas and aerosol emissions were to cease immediately temperature would continue to increase, but then begin dropping rapidly after a decade before slowly returning to temperature characteristic of the mid 20th century by the end of the 22nd century, namely to 0.3–0.5 °C above pre-industrial levels. The main insights that one can derive from the zero emissions scenario is that there is a floor to how fast temperatures can drop in the long term (in the absence of negative emissions).

It is clear from the analysis here that the ‘feasible scenario warming commitment’ for the period to 2100 depends significantly upon the assumed emission mitigation scenarios. Therefore, transparency is warranted in regard to the token socio-economic assumptions in each mitigation scenario. If one believes that the most rapid feasible CO_2 reduction scenario in the literature cited above is plausible (Azar et al., in press) then the peak temperature during the 21st century is around 1.6–1.7 °C and this declines to around 1.5–1.6 °C warming above pre-industrial by 2100, for the ‘7AEM’. On the other hand, if one believes that the maximum plausible policy effort corresponds to the B2 WBGU 400 ppm CO_2 stabilization scenarios then warming at the end of the 21st century would be around 1.9 °C or a bit lower when additional policies and options to reduce non-CO_2 gases were accounted for. If 450 ppm CO_2 scenarios correspond to one’s assessment of the maximum plausible climate policy then the warming by 2100 is limited to about 2.2–2.4 °C.

Uncertainties in knowledge of the climate sensitivity warrant probabilistic assessments of warming commitments for specific scenarios. The conventional uncertainty range of climate sensitivity (1.5 to 4.5 °C) suggests that only by stabilizing anthropogenic radiative forcings at levels below CO_2 equivalent concentrations of 440 ppm (CO_2 only below 400 ppm) is there more than a 66% chance of limiting the global mean temperature increase to below 2 °C. Five out of the 6 more recent climate sensitivity PDF estimates suggest that CO_2eq concentrations have to be even lower in order to have a “likely” chance of achieving a 2 °C target, namely below 400 ppm CO_2eq in equilibrium (see Figure 8).

The scenario range above does not necessarily cover the full range of possibilities. For example the introduction of biomass fuel with carbon capture and storage technology used in the Azar et al. (in press) scenarios, which essentially would draw down CO_2 in the atmosphere, could be accelerated if it were deemed necessary. Such a necessity might arise if critical climate damages were identified for warming levels whose avoidance or prevention, pursuant to international legal obligations under Article 2 of the UNFCCC, required that greenhouse gas concentrations be reduced after peaking. Whilst there is no global agreement at present on such thresholds, scientific progress points in the direction of the existence of these, which – if confirmed – could sooner or later yield to political agreement given the scale of the physical dangers. Examples of potential thresholds in this area include the risk of substantial ecosystem damage which has led to a finding that “returning to near pre-industrial global temperatures as quickly as possible could prevent much of the projected, but slower acting, climate-related extinction from being realized” (Thomas et al., 2004a) and the risk of West Antarctic Ice Sheet disintegration or collapse triggered by either atmospheric or ocean warming (Oppenheimer and Alley, 2004). The results of this work suggest that if operationalization of Article 2 of the UNFCCC required that global mean surface warming be limited below 2 °C with a high (90% or greater probability) then in the 22nd century CO_2 levels would need to be drawn down to below 350 ppmv CO_2 equivalent.

In relation to warming commitments in the period to the 2050s it is clear from the analysis here that there are significant benefits in terms of reduction in global mean warming available from mitigation scenarios. The benefits depend on the reference scenario – the higher the reference scenario the greater is the benefit of the mitigation scenarios examined here. For the '7AEM' computations, the avoidable warming in a given year is found to be about 0.16 °C for every 100 GtC avoided cumulative fossil CO_2 emissions up to that year. The ultimate benefit of mitigation efforts will be higher, though, about 0.26 °C for every avoided 100 GtC fossil CO_2 emissions in equilibrium.

Acknowledgments

The authors would like to thank Ursula Fuentes and Stefan Rahmstorf for most constructive suggestions which led to substantial improvements in this work. We would also like to thank Michael Oppenheimer, Michael Mastrandrea and two other anonymous reviewers as well as Marcel Berk, Paul Baer, Michèle Bättig for helpful comments, Vera Tekken for editing support and Reto Knutti for data analysis of the CCSM3 data. Furthermore, we are thankful to Tom Wigley for providing the MAGICC climate model. As usual, the authors are to be blamed for any errors of fact and judgement.

Notes

[1] The Presidency Conclusion of the European Council of 22 and 23 March 2005 state in paragraph 43 "The European Council acknowledges that climate change is likely to have major negative global environmental, economic and social implications. It confirms that, with a view to achieving the ultimate objective of the UN Framework Convention on Climate Change, the global annual mean surface temperature increase should not exceed 2 °C above pre-industrial levels." This decision adds weight to the position first adopted by the Council of Enviroment Ministers of the European Union in 1996.

[2] The temperature anomaly of 2002 compared to 1861–1890 is based on data by Folland et al. (2001) including updates with 2001–2002 data. The uncertainty band of ±0.2 °C is taken from IPCC's 19th century warming estimate. An uncertainty analysis based on error estimates by Folland et al. suggests a slightly lower uncertainty band (2σ) of ±0.15 °C.

[3] Own calculations based on data from (Folland et al., 2001; Jones and Moberg, 2003), available at: http://www.met-office.gov.uk/research/hadleycentre/CR__11_data/Annual/land+sst__11_web.txt, accessed 15. October 2004.

[4] Note that the Hadley centre uses the term 'current physical commitment' for what is termed 'present forcing warming commitment' in this study.

[5] There are different conventions in the literature in regard to wether volcanic forcing is adjusted to have (1) a zero mean or (2) left as absolute (negative) perturbation. Consequently, it is an issue whether net present radiative forcing, including natural forcing, is specified as (a) difference between present and the negative pre-industrial forcing (average) or (b) the 'zero line'. Thus, it is not straightforward to

compare all ‘present forcing’ data, if the applied convention is not specified, as is often the case. This study assumed volcanic forcing as being negative at all times (2) and we report net radiative forcing here as the difference between present and earlier period’s means (a): the net/human-induced/natural radiative forcing for 2005 relative to the periods 1861–1890 and 1770–1800 is 1.93/1.26/0.67 and 2.03/1.48/0.54 W/m^2, respectively. The human-induced forcing for 2005 above 1765 is 1.50 W/m^2. For natural forcing assumptions, see as well Section 3.5.

[6] Furthermore, it should be considered that from a health policy point of view, continued high aerosol emissions are not desirable. However, high aerosol emissions would be a temporary effect of a strict ‘constant radiative forcing’ scenario. Radiative forcing stabilization scenarios that return to present day levels of radiative forcing in the future can be constructed with much reduced aerosol emissions.

[7] The Post-SRES scenarios used here are presented in Swart et al. (2002). See as well (Morita et al., 2000; and Figure 2-1 in Nakicenovic and Swart, 2000). Selection is due to data availability.

[8] MAGICC 4.1 has been developed by T.M.L. Wigley, S. Raper, M. Salmon and M. Hulme and is available at http://www.cgd.ucar.edu/cas/wigley/magicc/index.html, accessed in May 2004.

[9] This improvement of MAGICC only affects the no-feedback results. When climate feedbacks on the carbon cycle are included, the differences from the IPCC TAR are negligible.

[10] The projection range for the ‘present forcing’ warming commitment due to the 1.5 to 4.5 °C uncertainty range in climate sensitivity narrows slightly, if a conventional uncertainty range for ocean mixing (1.3 to 4.1 cm^2/s, Wigley, 2005) is assumed to be dependent on climate sensitivity. The sensitivity of the simple climate model results to uncertainties in ocean mixing is highest for the near-term transient climate response and ceases in the long-term equilibrium. Specifically, the uncertainty range narrows in 2050 and 2400 by 18 and 1%, respectively, if the 1.3 (4.1) cm^2/s ocean mixing rate is assumed to go hand in hand with a 1.5 (4.5)°C climate sensitivity in comparison to computing future temperatures by using a medium range 2.3 cm^2/s ocean mixing ratio independent of climate sensitivity. This is generally in line with results by Wigley, who estimated that the effect of ocean mixing uncertainties being relatively small compared to uncertainties of climate sensitivity and present forcing (Wigley, 2005).

[11] Additional estimates of the climate sensitivity and their likely ranges have for example been performed by Harvey and Kaufmann (2002). However, adding more estimates to the analysis would not have added to the substance of the discussion below.

[12] Note, that the conventionally cited ‘combined pdf’ from Andronova & Schlesinger (Andronova and Schlesinger, 2001) has been combined from PDF estimates of which some do not take into account aerosol forcing or variations in solar radiation.

[13] The alternative, to leave natural forcings out in the future, is not really viable, since the model has been spun up with estimates of the historic solar and volcanic forcings. Assuming the solar forcing to be a non-stationary process with a cyclical component and assuming that the sum of volcanic forcing events can be represented as a Compound Poisson process, it seems more realistic to apply the recent and long-term means of solar and volcanic forcings, respectively, for the future. Note as well endnote 5.

[14] Note that there are corresponding slight variations in CO_2 concentrations across the different climate sensitivities due to climate feedbacks on the carbon cycle. For a climate sensitivity of 1.5 °C (4.5 °C), CO_2 concentration in 2400 will be 900 (960) ppm.

[15] The GFDL R15 model of (Manabe et al., 1991) was used and has a climate sensitivity in its mixed layer form of 3.7 °C and in the full coupled version 4.5 °C (Stouffer and Manabe, 1999). The committed warming has been calculated as the year 2000 difference of the mixed layer equilibrium model run and the transient AOGCM.

[16] This warming is the total reported from the equilibrium mixed layer (EML) model from 1760 and adjusted downwards by 0.2 °C in order to ensure consistency with the here used base period from 1861–1890 (cf. Figure 1 of Wetherald et al. (2001).

[17] Note that there is significant uncertainty in regard to the aerosols' cooling effect. This greenhouse gas only CO_2 equivalence level has been derived from the 2005 radiative forcing when running the SRES A1B emission scenario with zeroed SO_2 emissions under the 7AEM procedure.

[18] In regard to negative emissions: One potential technique for increasing the rate of CO_2 removal from the atmosphere beyond its natural limits could be biomass burning with subsequent capture and storage of CO_2 in the flue gas (Azar et al., in press).

[19] As aforementioned (Section 2.4), the non-CO_2 emissions for the Azar scenarios are here drawn from the WBGU B2-400 scenario. Thus, temperature levels in 2100 could be slightly lower by a few tenths of a degree, if additional non-CO_2 emission reductions were assumed below the ones of the WBGU B2-400 scenario.

[20] The 'Equal Quantile Walk' method allows designing new emission pathways on the basis of a large pool of existing scenarios. The basic premise of the method is to assume that each gases emissions' of the new mitigation pathways will lie on the same 'quantile' of the existing pool's emission distribution of the specific gases in any given year (see the method in detail described in Meinshausen et al., in press).

[21] If not otherwise noted, this study follows the terminology introduced by the IPCC TAR WGI for presenting likelihoods in its Summary for Policymakers: Virtually certain ($>$99%), very likely (90–99%), likely (66–90%), medium likelihood (33–66%), unlikely (10–33%), very unlikely (1–10%), exceptionally unlikely ($<$1%).

[22] Note that the reported probability *means* are presented for illustrative purposes only. Since the climate sensitivity estimates are not independent the presented means are of little statistical relevance. In other words, the choice to characterise these results by their means has been made subjectively.

[23] Note that the regression factor (0.16 °C/100 GtC) cannot be simply scaled by the climate sensitivity due to the generally higher climate system inertia for higher climate sensitivities. Approximately, the regression factor can be scaled by the square root of the climate sensitivity, though. The regression factor has been derived by linear least-squares. The A1FI-MiniCAM scenarios were exempted from the regression as they fall far outside the range of the other scenarios and would thereby overproportionally influence the regression. Including the A1FI-MiniCAM scenario in the regression leads to factors of 0.14 °C/100 GtC and 0.23 °C/100 GtC for current and equilibrium avoided warming, respectively.

[24] In the post SRES scenarios, including the WBGU variants, the non-CO_2 gases were not explicitly calculated except in so far as reductions occurred linked to change in fossil fuel emissions. Reductions in other sectors were usually not computed.

[25] Estimated using the following assumptions: (a) emissions from fossil fuels and deforestation in the historical period to the present are 450 GtC and (b) the time scales of removal are those reported by Archer et al. (1997, 1998) and (c) CO_2 did not exceed 280–290 ppm throughout the last 420 000 years.

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(Accepted 1 August 2005)