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Review

Risks to forest carbon offset projects in a changing climate

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ABSTRACT

When included as part of a larger greenhouse gas (GHG) emissions reduction program, forest offsets may provide low-cost opportunities for GHG mitigation. One barrier to including forest offsets in climate policy is the risk of reversal, the intentional or unintentional release of carbon back to the atmosphere due to storms, fire, pests, land use decisions, and many other factors. To address this shortcoming, a variety of different strategies have emerged to minimize either the risk or the financial and environmental implications of reversal. These strategies range from management decisions made at the individual stand level to buffers and set-asides that function across entire trading programs. For such strategies to work, the actual risk and magnitude of potential reversals need to be clearly understood. In this paper we examine three factors that are likely to influence reversal risk: natural disturbances (such as storms, fire, and insect outbreaks), climate change, and landowner behavior. Although increases in atmospheric CO_2 and to a lesser extent warming will likely bring benefits to some forest ecosystems, temperature stress may result in others. Furthermore, optimism based on experimental results of physiology and growth must be tempered with knowledge that future large-scale disturbances and extreme weather events are also likely to increase. At the individual project level, management strategies such as manipulation of forest structure, age, and composition can be used to influence carbon sequestration and reversal risk. Because some management strategies have the potential to maximize risk or carbon objectives at the expense of the other, policymakers should ensure that forest offset policies and programs do not provide the singular incentive to maximize carbon storage. Given the scale and magnitude of potential disturbance events in the future, however, management decisions at the individual project level may be insufficient to adequately address reversal risk; other, non-silvicultural strategies and policy mechanisms may be necessary. We conclude with a brief review of policy mechanisms that have been developed or proposed to help manage or mitigate reversal risk at both individual project and policy-wide scales.

Contents

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1. Introduction

Attention to climate change is increasing across domestic and international policy arenas. Beginning in the latter half of 2007 and extending well into 2008, multiple bills and legislative discussion drafts were introduced in the U.S. Congress (e.g., S.3036, Lieberman-Warner Climate Security Act of 2008; S.1766, the Low Carbon Economy Act of 2007; H.R. 6186, Investing in Climate Action and Protection Act; Boucher-Dingell Draft Climate Legislation [Discussion Draft—October 7, 2008]). International bodies also crafted a roadmap for future global action (UNFCCC, 2007).

One mitigation strategy receiving significant attention in policy discussions is carbon offsets, or the reduction in emissions or increase in sequestration of greenhouse gases (GHG) by one entity that is used to compensate for emissions produced by another entity. Within the category of carbon offsets, forest management is receiving particular attention as a way to reduce emissions or increase the uptake and storage of carbon dioxide (CO_2). When included as part of a larger cap-and-trade program, forest offsets have the potential to provide low-cost GHG mitigation, thus lowering the overall cost of climate policy implementation (Amano and Sedjo, 2006; Tavoni et al., 2007).

Forest offset projects, including afforestation, reforestation, and forest management activities, have the potential to contribute significant GHG mitigation benefits at prices as low as $5 per ton of CO_2 equivalent (U.S. Environmental Protection Agency, 2005). Despite this potential, forest offset projects are subjected to a number of hurdles that have limited their participation in early carbon markets and could hinder their role in future climate policy (see e.g., Tavoni et al., 2007). Quantification of the on-site and off-site GHG impacts of individual forest offset projects is a primary hurdle (Richards and Andersson, 2001). The impermanence of forest carbon sequestration is another hurdle, one that can negatively impact the market value of the offset (Kim et al., 2008).

Here we focus on one particular aspect of forest offset impermanence, the susceptibility of forest offset projects to reversal. Offset reversal, the intentional or unintentional release of stored carbon back to the atmosphere, is of particular interest in an environment characterized by a changing climate and shifting management objectives. Indeed, at least three factors will influence the risk of reversal faced by offset projects in the future: (1) the severity, duration, and frequency of natural disturbances, including fire, insect damage, and severe weather; (2) the response of trees to increasing atmospheric CO_2 concentrations and changes in climatic conditions; and (3) landowner behavior.

The exposure of offset projects to reversal risk may in turn influence the attractiveness of forest offsets as an investment strategy for both landowners and buyers and as a mitigation strategy for policymakers. A variety of different strategies have been developed or proposed to minimize the risk of reversal or the financial and emission implications of reversal should it occur. These strategies range from management decisions made at the individual stand level to buffers and set-asides that function across entire trading programs. For such strategies to be effective, however, the drivers and magnitude of potential reversals need to be clearly understood.

In this paper we examine each of the three reversal risk factors for forest offset projects identified above. We identify particular management strategies that could either minimize risk of reversal or increase stand susceptibility to loss. We then discuss policy mechanisms to help manage or mitigate reversal risk at both individual project and policy-wide scales. A focus throughout this review is the impact that shifting climate and management will have on individual landowners seeking to maximize carbon storage on their lands. Lands under different ownerships and landowners pursuing different project types will have different goals, motivations, and constraints (Malmsheimer et al., 2008). We emphasize private rather than public lands because private landowners are the focus of many of the existing registries and trading programs in use or under development today.

2. Natural disturbances in a changing climate

Forests are subject to a wide variety of disturbances, both unintentional, natural disturbances – insect, fire, or weather, for instance – and anthropogenic or intentional disturbances, such as harvest or conversion to another land use. Natural disturbances pose the greatest challenge to forest offset project accounting because of the inherent unpredictability and potential scale that characterize such disturbances. The intensity and frequency of forest disturbance can be influenced by short- and long-term shifts and cycles, such as the El Niño-Southern Oscillation (ENSO) (Swetnam and Betancourt, 1990; Kitzberger et al., 2001) and global climate change (IPCC, 2007). Here, we review the particular influence that climate change may have on disturbance frequency and intensity, and the potential impact on forests and forest systems.

Millions of hectares of forest and wildlands are subject to natural disturbance each year, including windthrow, ice storms, drought, pest and pathogen infestations, and fire (Table 1). Individual natural disturbance events can be comprised of single or multiple types of disturbance. For example, hurricanes bring both wind and heavy rain. Rain and other forms of heavy precipitation may accompany ice storms. The severity of individual disturbance events also varies, with impacts ranging from low-intensity modification of community structure to widespread mortality (Dale et al., 2001). At their most severe, disturbance events can have significant impacts on regional carbon balance (e.g., Chambers et al., 2007; Kurz et al., 2008; Lindroth et al., 2009).

Wind damage is an important disturbance in many forests. At high velocities (>100 mph or 45 m/s), wind is capable of destroying whole stands (Mason, 2002), and large individual windstorms can have significant impacts on regional carbon balance (Lindroth et al., 2009). Damage from hurricanes can also be significant. A recent analysis suggested that a single event – Hurricane Katrina in 2005 – converted an equivalent of 50–140% of the average annual U.S. forest carbon storage rate into downed or dead biomass (Chambers et al., 2007). Hurricane intensity and destructive potential are likely to increase this century (Emanuel, 1987, 2005). Recent studies link increased sea surface temperature with greater hurricane activity, as well (Saunders and Lea, 2008). Other studies suggest that climate change will influence hurricane intensity and associated rainfall,

Table 1
Examples of U.S. forest disturbance and approximate annual impact. Adapted from Dale et al. (2001).

Disturbance	Approximate annual impact (ha)
Fire	1,330,000[a]
Wind (hurricane + tornado)	1,650,000 (1,200,000 + 450,000)[b]
Ice	>180,000[c]
Insect/pathogen	20,400,000[d]
Drought	Nationwide[e]

[a] Flannigan et al. (2000), citing 10-year wildland fire average.
[b] Dale et al. (2001), citing Hebert et al. (1996) (hurricane) and Fujita (1971) (tornado). Forests can also be affected by downburst and other localized wind events; while difficult to attribute forest-specific impacts of this latter type of wind disturbance, the area affected may be significant (e.g., Brooks and Doswell, 1993).
[c] Dale et al. (2001), citing Michaels and Cherpack (1998).
[d] U.S. Department of Agriculture (1997). Recent insect outbreak activity has been significant, however (see e.g., Kurz et al., 2008), and may exceed the values reported here.
[e] Dale et al. (2001); site-specific impacts will be affected by drought intensity, frequency, and duration.

but that the data are insufficient to link climate change with increased storm frequency or changes in particular locations (Trenberth, 2005).

In other forests, ice storms are the primary cause of tree mortality (Lafon, 2006), with substantial ice damage historically occurring at least once a decade along a belt from Texas to New England (Irland, 2000). Single ice storms can inflict damage equivalent to approximately 10% of total U.S. annual forest carbon sequestration (McCarthy et al., 2006). In addition to direct mortality, ice storm damage can increase susceptibility to disease (Bragg et al., 2003). In a changing climate, the Mid-Atlantic is likely to experience less snow and ice but increased rainfall and wind (McKenney-Easterling et al., 2000).

Drought can directly reduce tree productivity and increase mortality, and interacts with other disturbances, as seen in recent fire and pest infestations for pine and juniper forests in the southwestern U.S. (Shaw et al., 2005). In the U.S., wildland fire totals have exceeded 3.5 million hectares in recent years (NIFC, 2008). Occurrence of natural-caused wildfire in the continental U.S. is expected to rise with increasing temperatures (Gan, 2005). In areas such as the western United States, changes in temperature and the timing and amount of snowmelt are expected to contribute to seasonal water shortages, longer fire seasons, and conditions favorable to large wildfires (Barnett et al., 2005; Westerling et al., 2006).

Insect outbreaks, one of the major agents of natural disturbance in North American forests, affect individual tree fitness and mortality and can in turn influence fire occurrence and severity (Logan et al., 2003). The scale of impact from even a single insect outbreak can be significant. For instance, a recent mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreak in British Columbia caused an impact equal to approximately 75% of the 40-year-average annual forest fire emissions for all of Canada (Kurz et al., 2008). Forest pest ranges are expected to expand and the frequency and intensity of outbreaks will likely increase under a changing climate (Volney and Fleming, 2000; Logan et al., 2003). Increased bark beetle damage is expected to impact both timber production and carbon storage (Seidl et al., 2008). An increase in the range of species such as the mountain pine beetle and the southern pine beetle (*Dendroctonus frontalis* Zimmermann) may expose new tree species to attack (Logan and Powell, 2001; Williams and Liebhold, 2002). Increasing winter and spring temperatures may increase southern pine beetle infestation risk by up to 5 times over current levels, with damage attributable to infestation increasing by up to 7.5 times (Gan, 2004).

3. Tree physiology in a changing atmosphere and climate

Tree physiology and ecosystem function are expected to be directly impacted by changing temperature and precipitation regimes, as well as increasing atmospheric CO_2 concentrations. In particular, aspects of growth, water use, and respiration are likely to be affected. These factors have the potential to influence forest carbon balance and the rate and extent of forest carbon accumulation. This can in turn influence project feasibility, the type of management regime undertaken, and the rate at which lost carbon may be recovered should a disturbance occur.

Based on responses to increased CO_2 alone, some increases in forest productivity seem likely for the coming century. For instance, rates of light-saturated photosynthesis for forest species were 51% higher on average in elevated (~700 μmol mol^{-1}) than in ambient CO_2 (350 μmol mol^{-1}) across 15 elevated CO_2 experiments (Medlyn et al., 1999). Wood growth also increased by an average of 23% in four long-term forest experiments that included the species *Pinus taeda*, *Liquidambar styraciflua*, *Populus alba*, and *Populus tremuloides* (Finzi et al., 2007). Where nitrogen is relatively available in the soil, responses of trees to increased CO_2 (700 μmol mol^{-1} versus 350 μmol mol^{-1} CO_2) tend to be greater than if N strongly limits growth (Maroco et al., 2002).

Increased atmospheric CO_2 also affects forest water use. Most tree species use substantially less water per unit leaf area at high CO_2 concentrations, but water savings at the canopy scale are often substantially smaller (e.g., Field et al., 1995). Data from 13 field-based studies using 15 European forest species in the genera *Betula*, *Fagus*, *Fraxinus*, *Phillyrea*, *Picea*, *Pinus*, *Pistacia*, *Populus*, and *Quercus*, showed that stomatal conductance decreased by 21% on average in response to growth at 700 μmol mol^{-1} versus 350 μmol mol^{-1} CO_2 (Medlyn et al., 2001); younger trees (<10 years) responded more than older trees (>10 years), and deciduous trees reduced their stomatal conductance more than conifers did. No evidence of acclimation of stomatal conductance to elevated CO_2 concentrations was found (Medlyn et al., 2001). If canopy leaf area increases, however, as is often observed in elevated CO_2 experiments, then these leaf-level reductions in stomatal conductance and transpiration will not consistently result in less canopy water use overall and greater soil moisture availability.

In addition to atmospheric CO_2, trees also respond physiologically to warmer temperatures (Cannell et al., 1998). Temperate and boreal forests tend to increase their net carbon uptake and growth in years where warmer temperatures extend the length of the growing season (e.g., White et al., 1999). Direct warming experiments with trees have also shown that rates of photosynthesis increase for many forest species (e.g., Kellomäki and Wang, 1996). Unlike increases in CO_2, however, warming has the potential to reduce photosynthesis and growth if temperature stress occurs. In the colder part of a tree's range, a tree may benefit from modest increases in temperature; in the warmer part of its range, it may be harmed (e.g., Hyvönen et al., 2007).

While warmer temperatures tend to increase carbon fluxes into forests, they also typically increase carbon fluxes back out. Rates of soil respiration at 32 research sites increased 20% on average for manipulative experiments that increased temperatures from 1 to 3.5 °C (Rustad et al., 2001). Furthermore, rates of plant respiration typically doubled with a 10 °C increase in temperature, often referred to as a Q_{10} response (e.g., Atkin and Tjoelker, 2003). A major scientific uncertainty is the extent to which warming will increase respiration, particularly of soil organic matter, and offset the potential increases in carbon uptake observed for photosynthesis (e.g., Melillo et al., 2002). This uncertainty could amount to hundreds of gigatonnes (10^{15} g) of carbon globally in the 21st century (e.g., Jackson and Schlesinger, 2004; Field et al., 2007).

Forest response to increased CO_2 and temperature are affected by many additional factors. For example, a recent meta-analysis of insect herbivory in 75 elevated CO_2 experiments (550–1000 μmol mol^{-1} CO_2) concluded that herbivore abundance decreased by about one-fifth at high CO_2 levels but that each insect ate ~17% more (Stiling and Cornelissen, 2007). While there is no consensus that increased atmospheric CO_2 will lead to more insect herbivory on trees, results do suggest that herbivore abundance will be greater as temperatures warm and insects are able to complete their lifecycles more quickly and overwinter more readily; this phenomenon has been observed in the paleo record during periods of warmer temperatures (Currano et al., 2008).

The few studies that have examined the interaction between increased atmospheric CO_2 and disturbance have yielded disparate results. McCarthy et al. (2006) found that ~20-year-old loblolly pine trees growing in elevated (ambient + 200 μmol mol^{-1}) CO_2 were slightly more resistant to ice damage and recovered more quickly than trees in ambient CO_2. In contrast, Li et al. (2007) found that wind damage from Hurricane Frances was just as great on 8-year-old oak trees growing in elevated (ambient + 350 μmol mol^{-1}) CO_2 as in ambient CO_2. Uncertainties in how disturbance and physiology interact reduce the confidence investigators might have for predictions of forest productivity based solely on the physiology of trees and other co-occurring species.

4. Forest management in a changing climate

Forest management usually has multiple objectives. Traditionally, these objectives include timber output and generation of non-timber goods and services (e.g., Jackson et al., 2005). Apart from the influences of disturbance, climate, and atmosphere, forest management also plays a key role in determining both potential for carbon sequestration and susceptibility to reversal. The importance of disturbance in forest management is well known (e.g., Routledge, 1980; Bodin and Wiman, 2007). The impact of climate change on forest ecosystems and markets has likewise been discussed in the literature (e.g., Dale et al., 2001; Irland et al., 2001), as has the role of forest management in mitigation and adaptation (e.g., Helms, 1996; Millar et al., 2007). With notable exceptions (Seidl et al., 2008), the collective impact of specific management strategies on simultaneously achieving risk reduction and carbon storage objectives under a changing climate has received considerably less attention.

4.1. Management techniques to minimize disturbance

Forest management has the potential to significantly influence the risk of damage from disturbance, especially at sites subject to moderate risk (Gardiner and Quine, 2000). Forest structure, age, and composition can all be manipulated to reduce exposure to or damage from disturbances. Relevant tools or techniques available to forest managers include the timing and intensity of thinning, stand spacing, rotation length, and site preparation.

Trees are generally more vulnerable to wind and ice disturbances immediately after thinnings until they can adjust to new stand conditions (Bragg et al., 2003; Irland, 2000). This vulnerability implies that treatments should be targeted to less-vulnerable areas or reduced in intensity and increased in frequency (Achim et al., 2005). Greater wind loading of dominant trees throughout the course of development may lend to greater stability, but thinning in older stands may decrease overall stand stability by exposing remaining trees to increased turbulence and wind loads (Cameron, 2002; Mason, 2002). Earlier and heavier removal of suppressed trees may also help to optimize the management of stands faced with increasing risk of fire (González et al., 2005). When wood quality is not a primary concern, no-thin regimes emerge as another potential strategy to minimize wind risks (Moore and Quine, 2000).

Wider spacing can also reduce susceptibility to wind damage (Moore and Quine, 2000) and minimize impacts of drought (Hanson and Weltzin, 2000). Stand density is directly correlated with susceptibility to southern pine beetle infestation as well (Fettig et al., 2007). Bragg et al. (2003), however, find inconsistent agreement between stand density and ice storm damage. Apart from stand density, the spatial arrangement of the stand is itself important, as is the structure of surrounding forest landscape (Meilby et al., 2001).

Research indicates that a higher risk of damage generally leads to shortened rotation times (e.g., Brumelle et al., 1990). In particular, short rotations may be particularly preferred in stands exposed to fire (Caulfield, 1988; González et al., 2005) and large ice storms (Irland, 2000). Older stands can also be disproportionately affected by wind and are sometimes more susceptible to drought, but complex interactions exist between various site-specific factors (Evans et al., 2007; Richardson et al., 2000).

Site preparation, including the use of container-grown seedlings, plowing to allow for deeper rooting, and draining to reduce soil saturation, can be used to minimize vulnerability to wind (Peterson, 2000). In some situations, combining fertilization with other management techniques like thinning can enhance stand development and reduce fire hazard (Zhang et al., 2005). Fertilization may also lead to increased flows of protective resins, thus decreasing susceptibility to beetle attack, especially when growth response is constrained by water stress or other factors (Knebel et al., 2008). Alternatively, fertilization can increase susceptibility to wind and snow damage by inducing upper crown growth (Mitchell, 2000).

Management for mixed forest communities is another potential strategy to maintain resilient systems and minimize impacts of disturbance. For example, stands with increased age or species heterogeneity may be more resistant to large outbreaks of insects or pathogens (Bodin and Wiman, 2007). Simply managing for diversity may not in itself guarantee resistance or resilience to disturbance. Species differ in their response to drought (Hanson and Weltzin, 2000), wind (Foster and Boose, 1992), ice storms (Lafon, 2006), hurricane, fire, and insect infestation (McNulty, 2002); the most diverse stand may not necessarily be the most resistant to disturbance (see e.g., Tanner and Bellingham, 2006).

These individual tools and techniques can all affect a stand's susceptibility to or recovery from disturbance. However, individual management tools or techniques can exacerbate or mitigate multiple threats. Managers must therefore assess the full suite of risks facing a stand so as not to mitigate one threat at the expense of others (Gardiner and Quine, 2000).

4.2. Management techniques to maximize carbon storage

As with management for risk, a variety of treatment options exist to maximize forest carbon storage. To some extent, however, the specific management tools available to landowners wishing to participate in an offsets market will be influenced by the rules and regulations established by the offset program (i.e., whether harvested wood products are included). Owing to the sensitivity of carbon management to the structure of the offset program, generalizing an optimal management strategy for all carbon sequestration is difficult. The literature on management for carbon is also not as developed as that for disturbance risk or for timber management. However, several basic management strategies and trends to maximize the sequestration of forest carbon do emerge.

In even-aged management systems, longer rotations generally lead to greater amounts of carbon sequestration in aboveground biomass. The optimal rotation length for a particular stand, however, depends on discount rate, timber price, carbon price, and treatment of wood products under an offset program. With full credit given for harvested wood products, rotation ages increase with increasing carbon prices and alternative rates of return (ARR) (Huang and Kronrad, 2006). van Kooten et al. (1995) show that, at timber prices of \$15 per cubic meter, carbon prices of \$20 per metric ton carbon, and allowing for 50% of harvested wood to be credited, boreal forest rotation age is extended by over 26% compared to a timber-only management regime. At higher carbon prices (\$200 per metric ton carbon), low wood prices ($<$\$25 m^{-3}), and less than 100% credit given for harvested wood, rotation ages become indefinite as any harvest is uneconomical (van Kooten et al., 1995). At low ARRs (2.5–5.0%), however, rotation length may actually decrease to avoid the repayment of carbon lost in older, higher-mortality stands (Huang and Kronrad, 2006). In forests subject to fire, the consequences of losing carbon stored in sawlogs can lead to earlier planned harvest ages as carbon prices increase (Spring et al., 2005).

The choice of thinning regime also influences carbon sequestration. Altering thinning regimes to allow for higher stocking can result in increased levels of carbon sequestration in a stand, achieving a maximum under no-thin management (Garcia-Gonzalo et al., 2007). In an even-aged stand, thinning to a specified relative density from below can result in greater sequestration than thinning from above, even when accounting for wood products, dead wood, and debris (Hoover and Stout, 2007).

By minimizing the amount of time that a site is not forested, rapid replanting after harvest may be one potential site preparation strategy to maximize carbon sequestration (Malmsheimer et al., 2008). Fertilization can also play a role in the management of forests for carbon sequestration, especially under changing atmospheric conditions. Research shows that fertilization may improve tree biomass accumulation under elevated CO_2 levels (Oren et al., 2001; Maroco et al., 2002). Under some trading programs, however, the emissions tied to the use of synthetic fertilizer are also factored into some projects, potentially lowering the net GHG benefit of an offsets project (Voluntary Carbon Standard, 2007).

In addition to the management techniques outlined above, the choice of species will influence the rate and amount of carbon sequestered on a site. Liski et al. (2004) find that the maximum combined carbon sequestration of Scots pine and Norway spruce soil, vegetation, and forest product pools are generated under different rotation lengths; of 60, 90, or 120 year rotations, Scots pine is found to sequester the greatest amounts in 120 year rotations and Norway spruce in 60 year rotations. Regardless of the rotation length, total per-hectare carbon stocks were also considerably greater in Norway spruce stands than in Scots pine. Gutrich and Howarth (2007) likewise calculate widely ranging shifts in optimal rotation age across five different forest types at carbon prices of $25–$75 per metric ton carbon, finding that rotations are extended in white-red-jack-pine forests by 16 years while spruce-fir forest rotations are extended 133 years. The management strategy with the largest impact on carbon sequestration (e.g., modifying thinning regime versus lengthening rotation age) may also vary by species (Pohjola and Valsta, 2007).

Finally, the use of mixed species or mixed age stands has the potential to increase rates of sequestration. Kelty (2006) documents that stand productivity can be increased through the use of species mixes that either more fully utilize limited site resources (complementary) or that physically benefit the growth of another (facilitative). For instance, management for stratified, multistoried canopies may achieve greater sequestration through maximization of leaf area (Helms, 1996; Malmsheimer et al., 2008). Total growth of *Eucalyptus* stands may be increased with the addition of N-fixing species (Binkley and Luis Stape, 2004).

5. Disturbance, physiology, and management interactions

The management of forests, regardless of the objective, will be further complicated by a changing climate. Increased temperatures and concentrations of atmospheric CO_2 may influence the rates of carbon sequestration, soil respiration, and water use efficiency, and will likely bring increases in productivity to some forest systems. Absolute gains in sequestration may be limited, however, by increases in disturbance frequency and intensity. Further uncertainty arises from the influence of increased atmospheric concentrations of CO_2 on tree responses to disturbance, a topic about which little is known. In light of these potential changes and uncertainties, an obvious question is how best to simultaneously manage for risk, carbon, and any other product or amenity that a forest may produce.

Stand composition, especially the management for mixed species or mixed age classes, and the choice of species may help to simultaneously address multiple objectives, including the maximization of carbon sequestration and minimization of reversal risk. Other management treatments can improve forest resistance to or resilience from numerous types of disturbance. In particular, shorter rotations and increased spacing are potential management options to address disturbance risk. In contrast, longer rotations and increased stocking levels can help optimize carbon sequestration. While the exact impact of any management treatment on risk or carbon objectives will obviously depend on individual stand conditions, such as pre-existing health and stocking levels, these generalized examples do point to an important issue—strategies maximizing carbon storage may at times be directly at odds with strategies that minimize disturbance risk.

Given the potential conflicts between risk and carbon management, policymakers should ensure that forest offset protocols do not provide singular incentives to maximize stocking levels at the expense of risk management. Instead of providing credit only for the amount of carbon stored on-site, an alternative approach could also award credits for activities that reduce reversal risk, such as fuel reduction activities to address wildfire risk in fire prone areas (Hurteau et al., 2008). Even if credits are not directly awarded for risk reduction activities, policymakers should strive to provide incentives that promote the integration of risk management and carbon management objectives.

6. Role of risk management mechanisms and strategies

Mitigation or management of reversal risk need not be limited to silvicultural practices and other aspects of forest management (Table 2). Other tools exist and vary in scope and objective. Some are targeted to the individual project, whereas others operate at the regional or full trading program level. Some serve to minimize the exposure to disturbance while others compensate for lost carbon should a disturbance occur (Ellis, 2001).

At the individual project level, maintaining the integrity of carbon markets requires that carbon sold to the market but subsequently lost to reversal be bought back from the market or replaced with in-kind sequestration. Assuming that liability rests with the seller of the forest offset, there is an incentive at the project level to minimize exposure to reversal risk (see Murray and Olander, 2008 for an expanded discussion of assignment of liability). As explored above, one potential mechanism to minimize exposure at the project level is appropriate forest management.

Other mechanisms or strategies, such as third-party insurance or the inclusion of harvested wood products and down, dead wood, can reduce the impact of disturbance should it occur. While presently rare, insurance products targeted specifically to carbon offset investments have been considered (e.g., AIG Inc., 2007). Alternatively, including wood products in a carbon offsets program allows for some of the carbon contained in downed or damaged trees to be recaptured through salvage operations. If dead wood is included in the program, some percentage of carbon may simply be transferred from live tree to dead wood pools. Even though carbon in these pools will be reemitted back to the atmosphere over time, the amount of carbon deemed to be "lost" immediately following the disturbance event (and therefore required to be replaced) will be lessened considerably.

Another mechanism to assist in the replacement of carbon lost to disturbance is the use of a buffer or reserve pool. Buffers can range in scale from project-specific to trading program-wide (Murray and Olander, 2008). Under some existing programs, such as the Voluntary Carbon Standard, the amount of buffer withheld is tied to the risk rating of the project, providing a direct link between risk management activities and the amount of carbon a landowner can claim and sell to market. Other programs (Chicago Climate Exchange) require a flat contribution to a pooled buffer regardless of project-specific risk.

Beyond the individual project level, diversification can be an effective strategy for reducing risk (Laurikka and Springer, 2003).

Table 2
Mechanisms and strategies to address reversal risk in forest offset projects. The scope at which a mechanism addresses risk is indicated, and ranges from the individual project to a collection of projects across an individual region to the entire registry or trading program. Examples of existing offset trading programs that utilize or consider a particular approach are noted, as are relevant readings.

Mechanism/strategy	Overview	Scope of coverage	Implementation examples
Forest Management	Management of forests to promote resistance to or resilience from disturbance.	Project	California Climate Action Registry (2007) and Voluntary Carbon Standard (2007)
Inclusion of Salvage/ Wood Products	Minimizes impact of disturbance on project by providing credit for carbon in dead/downed wood or storage in wood products.	Project	California Climate Action Registry (2007), Chicago Climate Exchange (2007), Voluntary Carbon Standard (2007) and recommendation to Regional Greenhouse Gas Initiative (Maine Forest Service, 2008)
Assignment of liability	Influence of behavior by identifying the party responsible for repaying lost carbon storage.	Project	California Climate Action Registry (2007), Chicago Climate Exchange (2007) and Voluntary Carbon Standard (2007)
Insurance	Allows for the replacement of lost carbon in the event of reversal.	Project	AIG Inc. (2007); Recommendation to Regional Greenhouse Gas Initiative (Maine Forest Service, 2008)
Buffer	Requires set-aside of some portion of storage in project-specific or program-wide pool.	Project to Program	Chicago Climate Exchange (2007) and Voluntary Carbon Standard (2007)
Portfolio Diversification	Minimizes impact of disturbances by pooling diverse project types or projects in geographically diverse areas.	Region to Program	Laurikka and Springer (2003) and Hultman (2006)
Program re-evaluation	Periodic evaluation of expected sequestration versus realized, allowing for additional credits to be released or withheld.	Program	Murray and Olander (2008)

The role of diversification as an effective risk reduction strategy may be limited by risks that are systemic or that are of low probability but high impact (Brumelle et al., 1990). Program re-evaluation could also be used to ensure that levels of expected sequestration and actual realized carbon storage match. If discrepancies arise as a result of reversal or other reasons, future buffer withholding rates can be adjusted or additional credits can be obtained from elsewhere under the cap (Murray and Olander, 2008). Despite the numerous forest management techniques and risk management mechanisms available at the project level, such high-level, integrated approaches may ultimately be necessary to successfully address forest offset project reversal risk in a changing climate.

7. Conclusion

The addition of carbon sequestration to the list of potential forest management objectives will place additional demands on forests and provide additional opportunities for landowners. Furthermore, increases in atmospheric CO_2 and to a lesser extent warming will likely bring benefits to some forest ecosystems, with temperature stress resulting in others. Optimism based on experimental results of physiology and growth must be tempered with the knowledge that future large-scale disturbances and extreme weather events are likely to increase. Importantly, climate change may also create novel disturbances or interactions between disturbance events for which current understanding and management strategies may not apply (Dale et al., 2001; Millar et al., 2007).

Uncertainties over the response of forest systems to changing temperature and precipitation regimes, increased atmospheric CO_2 concentrations, and the magnitude of shifts in disturbance frequency and intensity will likely require integrated approaches to address forest offset project reversal risk for forest offset projects to be included in comprehensive climate policy. At the scale of the individual project, the literature suggests that stand composition, especially the choice of species and management for mixed stands, can simultaneously address carbon sequestration and reversal risk management objectives. Other management strategies, such as contraction or extension of rotation ages in even-aged stands, may singularly maximize risk or carbon objectives at the expense of the other. Accordingly, policymakers should ensure that forest offset policies and programs do not provide an incentive to maximize carbon storage at the expense of risk management.

Given the potential scale and magnitude of natural disturbance events, management decisions at the individual project level will likely be insufficient to adequately address reversal risk. Other, non-silvicultural strategies and mechanisms may be necessary. Existing carbon markets and trading programs already make use of a number of these strategies and mechanisms. For a majority of these mechanisms to function correctly, however, a firm understanding of the magnitude of reversal risk is needed. If risk is underestimated, the scale of reversal is likely to outweigh a particular mechanism's ability to mitigate it. If risk is overestimated, participating landowners may be penalized with excessive premiums or set-asides. Projected changes in disturbance regimes, climate, atmospheric concentrations of CO_2, and likely shifts in landowner management to maximize carbon sequestration necessitate further work to better understand the full implications of pursuing specific risk management strategies and policies.

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References

Achim, A., Ruel, J.-C., Gardner, B.A., Laflamme, G., Meunier, S., 2005. Modeling the vulnerability of balsam fir forests to wind damage. Forest Ecology and Management 204, 35–50.

AIG, Inc. 2007. Conceptual for carbon credit delivery insurance. <http://www.aig.com/aigweb/internet/en/files/mkt_RF_AIG_CarbonTradingFlyer_US_062007_tcm20-7183.pdf> (retrieved 16.07.08).

Amano, M., Sedjo, R.A., 2006. Forest Sequestration: Performance in Selected Countries in the Kyoto Period and the Potential Role of Sequestration in Post-Kyoto Agreements. Resources for the Future, Washington, DC, p. 65.

Atkin, O.K., Tjoelker, M.G., 2003. Thermal acclimation and the dynamic response of plant respiration to temperature. Trends in Plant Science 8, 343–351.

Barnett, T.P., Adam, J.C., Lettenmaier, D.P., 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438, 303–309.

Binkley, D., Luis Stape, J., 2004. Sustainable management of Eucalyptus plantations in a changing world. In: Borralho, N.M.G., Periera, J.S., Marques, C., Coutinho, J., Madeira, M., Tomé, M. (Eds.), Eucalyptus in a Changing World. Proceedings of IUFRO Conference, Aveiro, October 11–15, 2004.

Bodin, P., Wiman, B.L.B., 2007. The usefulness of stability concepts in forest management when coping with increasing climate uncertainties. Forest Ecology and Management 242, 541–552.

Bragg, D.C., Shelton, M.G., Zeide, B., 2003. Impacts and management implications of ice storms on forests in the southern United States. Forest Ecology and Management 186, 99–123.

Brooks, H.E., Doswell III, C.A., 1993. Extreme winds in high-precipitation supercells. In: Preprints, Proceedings of the 17th Conference on Severe Local Storms, Saint Louis, Missouri, 4–8 October, 173–177..

Brumelle, S., Stanbury, W.T., Thompson, W.A., Vertinsky, I., Wehrung, D., 1990. Framework for the analysis of risks in forest management and silvicultural investments. Forest Ecology and Management 35, 279–299.

California Climate Action Registry, 2007. Forest Project Protocol, Version 2.1. Los Angeles, CA.

Cameron, A.D., 2002. Importance of early selective thinning in the development of long-term stand stability and improved log quality: a review. Forestry 75, 25–35.

Cannell, M.G.R., Thornley, J.H.M., Mobbs, D.C., Friend, A.D., 1998. UK conifer forests may be growing faster in response to increased N deposition, atmospheric CO_2 and temperature. Forestry 71, 277–296.

Caulfield, J.P., 1988. A stochastic efficiency approach for determining the economic rotation of a forest stand. Forest Science 34, 441–457.

Chambers, J.Q., Fisher, J.I., Zeng, H., Chapman, E.L., Baker, D.B., Hurtt, G.C., 2007. Hurricane Katrina's carbon footprint on U.S. Gulf Coast forests. Science 318, 1107.

Chicago Climate Exchange, 2007. CCX Rulebook. 9.8.4. Managed Forest Projects. <http://www.chicagoclimatex.com/docs/offsets/CCX_Rulebook_Chapter09_OffsetsAndEarlyActionCredits.pdf> (retrieved 29.06.08).

Currano, E.D., Wilf, P., Wing, S.L., Labandeira, C.C., Lovelock, E.C., Royer, D.L., 2008. Sharply increased insect herbivory during the Paleocene–Eocene thermal maximum. Proceedings of the National Academy of Sciences USA 105, 1960–1964.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flanningan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., Wotton, B.M., 2001. Climate change and forest disturbances. Bioscience 51, 723–734.

Ellis, J., 2001. Forestry Projects: Permanence, Credit Accounting and Lifetime. OECD Environment Directorate and International Energy Agency, Paris, France, 36.

Emanuel, K.A., 1987. The dependence of hurricane intensity on climate. Nature 326, 483–485.

Emanuel, K.A., 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436, 686–688.

Evans, A.M., Camp, A.E., Tyrell, M.L., Riely, C.C., 2007. Biotic and abiotic influences on wind disturbance in forests of NW Pennsylvania, USA. Forest Ecology and Management 245, 44–53.

Fettig, C.J., Klepzig, K.D., Billings, R.F., Munson, A.S., Nebeker, T.E., Negrón, J.F., Nowak, J.T., 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the western and southern United States. Forest Ecology and Management 238, 24–53.

Field, C.B., Jackson, R.B., Mooney, H.A., 1995. Stomatal responses to increased CO_2: implications from the plant to the global scale. Plant, Cell and Environment 18, 1214–1225.

Field, C.B., Lobell, D.B., Peters, H.A., Chiariello, N.R., 2007. Feedbacks of terrestrial ecosystems to climate change. Annual Review of Environment and Resources 32, 1–29.

Finzi, A.C., Norby, R.J., Calfapietra, C., Gallet-Budynek, A., Gielen, B., Holmes, W.E., Hoosbeek, M.R., Iversen, C.M., Jackson, R.B., Kubiske, M.E., Ledford, J., Liberloo, M., Oren, R., Polle, A., Pritchard, S., Zak, D.R., Schlesinger, W.H., Ceulemans, R., 2007. Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO_2. Proceedings of the National Academy of Sciences USA 104, 14014–14019.

Flannigan, M.D., Stocks, B.J., Wotton, B.M., 2000. Climate change and forest fires. The Science of the Total Environment 262, 221–229.

Foster, D.R., Boose, E.R., 1992. Patterns of forest damage resulting from catastrophic wind in central New England, USA. Journal of Ecology 80, 79–98.

Fujita, T.T., 1971. Proposed characterization of tornadoes and hurricanes by area and intensity. Satellite and Mesometeorology Research Project Paper 91. Department of Geophysical Sciences, University of Chicago, Chicago, IL.

Gan, J., 2004. Risk and damage of pine beetle outbreaks under global climate change. Forest Ecology and Management 191, 61–71.

Gan, J., 2005. Incorporating human and natural adaptations in assessing climate change impacts on wildfire occurrence. p61–73. In: Burk, A.R. (Ed.), New Research on Forest Ecosystems, Nova Publishers, Hauppauge, NY, 186pp.

Garcia-Gonzalo, J., Peltola, H., Briceño-Elizondo, E., Kelomäki, S., 2007. Changed thinning regimes may increase carbon stock under climate change: a case study from a Finnish boreal forest. Climatic Change 81, 431–454.

Gardiner, B.A., Quine, C.P., 2000. Management of forests to reduce the risk of abiotic damage—a review with particular reference to the effects of strong winds. Forest Ecology and Management 135, 261–277.

González, J.R., Pukkala, T., Palahí, M., 2005. Optimising the management of *Pinus sylvestris* L. stand under risk of fire in Catalonia (north-east of Spain). Annals of Forest Science 62, 493–501.

Gutrich, J., Howarth, R.B., 2007. Carbon sequestration and the optimal management of New Hampshire timber stands. Ecological Economics 62, 441–450.

Hanson, P.J., Weltzin, J.F., 2000. Drought disturbance from climate change: response of United States forests. The Science of the Total Environment 262, 205–220.

Hebert, P.T., Jarrell, J.D., Mayfield, M., 1996. Deadliest, Costliest, and Most Intense United States Hurricanes of This Century (and Other Frequently Requested Hurricane Facts). NOAA Technical Memorandum MWS-TPC-1. National Oceanic and Atmospheric Administration, Tropical Prediction Center, Miami, FL.

Helms, J.A., 1996. Management strategies for sequestering and storing carbon in natural, managed, and highly disturbed coniferous ecosystems. p. 167–179. In: Sampson, R.N., Hair, D. (Eds.), Forests and Global Change, vol. 2, Forest Management Opportunities for Mitigating Carbon Emissions. American Forests, Washington, DC 379p.

Hoover, C., Stout, S., 2007. The carbon consequences of thinning techniques: stand structure makes a difference. Journal of Forestry 105, 266–270.

Huang, C.-H., Kronrad, G.D., 2006. The effect of carbon revenues on the rotation and profitability of loblolly pine plantations in East Texas. Southern Journal of Applied Forestry 30, 21–29.

Hultman, N.E., 2006. Geographic diversification of carbon risk—a methodology for assessing carbon investments using eddy correlation measurements. Global Environmental Change 16, 58–72.

Hurteau, M.D., Koch, G.W., Hungate, B.A., 2008. Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets. Frontiers in Ecology and the Environment 6, 493–498.

Hyvönen, R., Agren, G.I., Linder, S., Persson, T., Cotrufo, M.F., Ekblad, A., Freeman, M., Grelle, A., Janssens, I.A., Jarvis, P.G., Kellomaki, S., Lindroth, A., Loustau, D., Lundmark, T., Norby, R.J., Oren, R., Pilegaard, K., Ryan, M.G., Sigurdsson, B.D., Stromgren, M., van Oijen, M., Wallin, G., 2007. The likely impact of elevated [CO_2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. New Phytologist 173, 463–480.

IPCC, 2007. Fourth assessment report: synthesis report. Summary for policymakers. <http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf> (retrieved 12.02.08).

Irland, L.C., 2000. Ice storms and forest impacts. The Science of the Total Environment 262, 231–242.

Irland, L.C., Adams, D., Alig, R., Betz, C.J., Chen, C.-C., Hutchins, M., McCarl, B.A., Skog, K., Sohngen, B.L., 2001. Assessing socioeconomic impacts of climate change on U.S. forests, wood-product markets, and forest recreation. BioScience 51, 753–764.

Jackson, R.B., Jobbágy, E.G., Avissar, R., Baidya Roy, S., Barrett, D., Cook, C.W., Farley, K.S., le Maitre, D.C., McCarl, B.A., Murray, B., 2005. Trading water for carbon with biological carbon sequestration. Science 310, 1944–1947.

Jackson, R.B., Schlesinger, W.H., 2004. Curbing the U.S. carbon deficit. Proceedings of the National Academy of Sciences USA 101, 15827–15829.

Kellomäki, S., Wang, K.Y., 1996. Photosynthetic responses to needle water potentials in Scots pine after a four-year exposure to elevated CO_2 and temperature. Tree Physiology 16, 765–772.

Kelty, M.J., 2006. The role of species mixtures in plantation forestry. Forest Ecology and Management 233, 195–204.

Kim, M.-K., McCarl, B.A., Murray, B.C., 2008. Permanence discounting for land-based carbon sequestration. Ecological Economics 64, 763–769.

Kitzberger, T., Swetnam, T.W., Veblen, T.T., 2001. Inter-hemispheric synchrony of forest fires and the El Nino-Southern Oscillation. Global Ecology and Biogeography 10, 315–326.

Knebel, L., Robison, D.J., Wentworth, T.R., Klepzig, K.D., 2008. Resin flow responses to fertilization, wounding and fungal inoculation in loblolly pine (*Pinus taeda*) in North Carolina. Tree Physiology 28, 847–853.

Kurz, W.A., Dymond, C.C., Stinson, G., Rampley, G.J., Neilson, E.T., Carroll, A.L., Ebata, T., Safranyik, L., 2008. Mountain pine beetle and forest carbon feedback to climate change. Nature 452, 987–990.

Lafon, C.W., 2006. Forest disturbance by ice storms in *Quercus* forests of the southern Appalachian Mountains, USA. Ecoscience 13, 30–43.

Laurikka, H., Springer, U., 2003. Risk and return of project-based climate change mitigation: a portfolio approach. Global Environmental Change 13, 207–217.

Li, J., Powell, T.L., Seiler, T.J., Johnson, D.P., Anderson, H.P., Bracho, R., Hungate, B.A., Hinkle, C.R., Drake, B.G., 2007. Impacts of Hurricane Frances on Florida scrub-oak ecosystem processes: defoliation, net CO_2 exchange and interactions with elevated CO_2. Global Change Biology 13, 1101–1113.

Lindroth, A., Lagergren, F., Grelle, A., Klemedtsson, L., Langvall, O., Weslien, P., Tuulik, J., 2009. Storms can cause Europe-wide reduction in forest carbon sink. Global Change Biology 15, 346–355.

Liski, J., Pussinen, A., Pingoud, K., Mäkipää, R., Karjalainen, T., 2004. Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research 31, 2004–2013.

Logan, J.A., Powell, J.A., 2001. Ghost forests, global warming, and the mountain pine beetle. American Entomologist 47, 160–173.

Logan, J.A., Régnière, J., Powell, J.A., 2003. Assessing the impacts of global warming on forest pest dynamics. Frontiers in Ecology and Environment 1, 130–137.

Maine Forest Service, Environment Northeast, Manomet Center for Conservation Sciences, Maine Department of Environmental Protection, 2008. Recommendations to RGGI for including new forest offset categories: a summary.

Malmsheimer, R.W., Heffernan, P., Brink, S., Crandall, D., Deneke, F., Galik, C., Gee, E., Helms, J.A., McClure, N., Mortimer, M., Ruddell, S., Smith, M., Stewart, J., 2008. Forest management solutions for mitigating climate change in the U.S. Journal of Forestry 106, 115–171.

Maroco, J.P., Breia, E., Faria, T., Pereira, J.S., Chaves, M.M., 2002. Effects of long-term exposure to elevated CO_2 and N fertilization on the development of photosynthetic capacity and biomass accumulation in *Quercus suber* L. plant. Cell and Environment 25, 105–113.

Mason, W.L., 2002. Are irregular stands more windfirm? Forestry 75, 347–355.

McCarthy, H.R., Oren, R., Kim, H.-S., Johnsen, K.H., Maier, C., Pritchard, S.G., Davis, M.A., 2006. Interaction of ice storms and management practices on current carbon sequestration in forests with potential mitigation under future CO_2 atmosphere. Journal of Geophysical Research 111, D15103.

McKenney-Easterling, M., DeWalle, D.R., Iverson, L.R., Prasad, A.M., Buda, A.R., 2000. The potential impacts of climate change and variability on forests and forestry in the Mid-Atlantic region. Climate Research 14, 195–206.

McNulty, S.G., 2002. Hurricane impacts on U.S. forest carbon sequestration. Environmental Pollution 116, S17–S24.

Medlyn, B.E., Badeck, F.W., De Pury, D.D.G., Barton, C.V.M., Broadmeadow, M.S.J., Ceulemans, R., De Angelis, P., Forstreuter, M., Jach, M.E., Kellomäki, S., Laitat, E., Marek, M., Philippot, S., Rey, A., Strassemeyer, J., Laitinen, K., Liozon, R., Portier, B., Roberntz, P., Wang, K., Jarvis, P.G., 1999. Effects of elevated [CO_2] on photosynthesis in European forest species: a meta-analysis of model parameters. Plant, Cell and Environment 22, 1475–1495.

Medlyn, B.E., Barton, C.V.M., Broadmeadow, M.S.J., Ceulemans, R., De Angelis, P., Forstreuter, M., Freeman, M., Jackson, S.B., Kellomäki, S., Laitat, E., Rey, A., Roberntz, P., Sigurdsson, B.D., Strassemeyer, J., Wang, K., Curtis, P.S., Jarvis, P.G., 2001. Stomatal conductance of forest species after long-term exposure to elevated CO_2 concentration: a synthesis. New Phytologist 149, 247–264.

Meilby, H., Strange, N., Thorsen, B.J., 2001. Optimal spatial harvest planning under risk of windthrow. Forest Ecology and Management 149, 15–31.

Melillo, J.M., Steudler, P.A., Aber, J.D., Newkirk, K., Lux, H., Bowles, F.P., Catricala, C., Magill, A., Ahrens, T., Morrisseau, S., 2002. Soil warming and carbon-cycle feedbacks to the climate system. Science 298, 2173–2176.

Michaels, G., Cherpack, J., 1998. Ice storm ravages northern forests. Washington, DC: National Association of Conservation Districts. Forestry Notes 7.

Millar, C.I., Stephenson, N.L., Stephens, S.L., 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications 17, 2145–2151.

Mitchell, S.J., 2000. Stem growth responses in Douglas-fir and Sitka spruce following thinning: implications for assessing wind-firmness. Forest Ecology and Management 135, 105–114.

Moore, J., Quine, C.P., 2000. A comparison of the relative risk of wind damage to planted forests in Border Forest Park, Great Britain, and the Central North Island, New Zealand. Forest Ecology and Management 135, 345–353.

Murray, B.C., Olander, L.P., 2008. Addressing Impermanence Risk and Liability in Agriculture, Land Use Change, and Forest Carbon Projects. Paper prepared for Agriculture's Role in Mitigating Climate Change Workshop, hosted by American Farmland Trust, Farm Foundation, and USDA Economic Research Service, August 13–14, 2008, Washington, DC.

National Interagency Fire Center, 2008. Fire information—wildland fire statistics. <http://www.nifc.gov/fire_info/fires_acres.htm> (retrieved 19.09.08).

Oren, R., Ellsworth, D.S., Johnsen, K.H., Phillips, N., Ewers, B.E., Maier, C., Schafer, K.V.R., McCarthy, H., Hendrey, G., McNulty, S.G., Katul, G.G., 2001. Soil fertility limits carbon sequestration by forest ecosystems in a CO_2-enriched atmosphere. Nature 411, 469–472.

Peterson, C.J., 2000. Catastrophic wind damage to North American forests and the potential impact of climate change. The Science of the Total Environment 262, 287–311.

Pohjola, J., Valsta, L., 2007. Carbon credits and management of Scots pine and Norway spruce stands in Finland. Forest Policy and Economics 9, 789–798.

Richards, K., Andersson, K., 2001. The leaky sink: persistent obstacles to a forest carbon sequestration program based on individual projects. Climate Policy 1, 41–54.

Richardson, A.D., Berlyn, G.P., Ashton, P.M.S., Thadani, R., Cameron, I.R., 2000. Foliar plasticity of hybrid spruce in relation to crown position and stand age. Canadian Journal of Botany 78, 305–317.

Routledge, R.D., 1980. The effect of potential catastrophic mortality and other unpredictable events on optimal forest rotation policy. Forest Science 26, 389–399.

Rustad, L.E., Campbell, J.L., Marion, G.M., Norby, R.J., Mitchell, M.J., Hartley, A.E., Cornelissen, J.H.C., Gurevitch, J., 2001. A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. Oecologia 126, 543–562 GCTE-NEWS.

Saunders, M.A., Lea, A.S., 2008. Large contribution of sea surface warming to recent increase in Atlantic hurricane activity. Nature 451, 557–560.

Seidl, R., Rammer, W., Jaeger, D., Lexer, M.J., 2008. Impact of bark beetle (*Ips typographus* L.) disturbance on timber production and carbon sequestration in different management strategies under climate change. Forest Ecology and Management 256, 209–220.

Shaw, J.D., Steed, B.E., DeBlander, L.T., 2005. Forest inventory and analysis (FIA) annual inventory answers the questions: what is happening to pinyon-juniper woodlands. Journal of Forestry 103, 280–285.

Spring, D., Kennedy, J., MacNally, R., 2005. Optimal management of a flammable forest providing timber and carbon sequestration benefits: an Australian case study. Australian Journal of Agricultural and Resource Economics 49, 303–320.

Stiling, P., Cornelissen, T., 2007. How does elevated carbon dioxide (CO_2) affect plant-herbivore interactions? A field experiment and meta-analysis of CO_2-mediated changes on plant chemistry and herbivore performance. Global Change Biology 13, 1823–1842.

Swetnam, T.W., Betancourt, J.L., 1990. Fire-southern oscillation relations in the Southwestern United States. Science 249, 1017–1020.

Tanner, E.V.J., Bellingham, P.J., 2006. Less diverse forest is more resistant to hurricane disturbance: evidence from montane rain forests in Jamaica. Journal of Ecology 94, 1003–1010.

Tavoni, M., Sohngen, B., Bosetti, V., 2007. Forestry and the carbon market response to stabilize climate. Energy Policy 35, 5346–5353.

Trenberth, K., 2005. Uncertainty in hurricanes and global warming. Science 308, 1753–1754.

U.S. Department of Agriculture, 1997. Forest insect and disease conditions in the United States 1996. Washington, DC: USDA Forest Service, Forest Health Protection.

U.S. Environmental Protection Agency, 2005. Greenhouse Gas Mitigation Potential in U.S. Forestry and Agriculture. 430-R-05-006. Washington, DC.

UNFCCC, 2007. Bali Action Plan. Adopted at the United Nations Climate Change Conference in Bali, Indonesia, Thirteenth Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC). <http://unfccc.int/files/meetings/cop_13/application/pdf/cp_bali_action.pdf> (retrieved 22.02.08).

van Kooten, G.C., Binkley, C.S., Delcourt, G., 1995. Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. American Journal of Agricultural Economics 77, 365–374.

Volney, W.J.A., Fleming, R.A., 2000. Climate change and impacts of boreal forest insects. Agriculture, Ecosystems and Environment 82, 283–294.

Voluntary Carbon Standard, 2007. Voluntary Carbon Standard: Guidance for agriculture, forestry and other land use projects. <http://www.v-c-s.org/docs/AFOLU%20Guidance%20Document.pdf> (retrieved 10.06.08).

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313, 940–943.

White, M.A., Running, S.W., Thornton, P.E., 1999. The impact of growing-season length variability on carbon assimilation and evaprotranspiration over 88 years in the eastern US deciduous forest. International Journal of Biometeorology 42, 139–145.

Williams, D.W., Liebhold, A.M., 2002. Climate change and the outbreak ranges of two North American bark beetles. Agricultural and Forest Entomology 4, 87–99.

Zhang, J.W., Oliver, W., Powers, R., 2005. Long-term effects of thinning and fertilization on growth of red fir in northeastern California. Canadian Journal of Forest Research 35, 1285–1293.