Radiative forcing of natural forest disturbances

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Abstract

Forest disturbances are major sources of carbon dioxide to the atmosphere, and therefore impact global climate. Biogeophysical attributes, such as surface albedo (reflectivity), further control the climate-regulating properties of forests. Using both tower-based and remotely-sensed data sets, we show that natural disturbances from wildfire, beetle outbreaks, and hurricane wind throw can significantly alter surface albedo, and the associated radiative forcing either offsets or enhances the CO_2 forcing caused by reducing ecosystem carbon sequestration over multiple years. In the examined cases, the radiative forcing from albedo change is on the same order of magnitude as the CO_2 forcing. The net radiative forcing resulting from these two factors leads to a local heating effect in a hurricane-damaged mangrove forest in the sub-tropics, and a cooling effect following wildfire and mountain pine beetle attack in boreal forests with winter snow. Although natural forest disturbances currently represent less than half of gross forest cover loss, that area will likely increase in the future under climate change, making it imperative to represent these processes accurately in global climate models.

Introduction

Terrestrial disturbances are primary regulators of the global carbon cycle (Running, 2008), and can switch entire ecosystems from carbon sinks to sources (Luysseart *et al.*, 2008). Increasing evidence suggests major natural forest disturbances are increasing in frequency and/or intensity under climate change, including fire (Westerling *et al.*, 2006), insect outbreaks (Raffa *et al.*, 2008), and landfalling hurricanes (Bender *et al.*, 2010). Over the last decade, these three disturbances destroyed approximately 2-4 million hectares of forest annually in the U.S. alone (Forest Service, 2008, Schwind, 2008, Zeng *et al.*, 2009). In British Columbia the extent of forest mortality caused by mountain pine beetle has reached unprecedented levels. In 2007 the affected area surpassed 10 million hectares (Westfall & Ebata, 2009). A warming and drying in the region associated with climate change has allowed the beetle to expand its range to these exceptional limits (Carroll *et al.*, 2003). Warming climate has also contributed to increasing the size and frequency of wildfires (Kasischke & Turetsky, 2006). Over the last 50 years, an average 2 million hectares of boreal forest have burned each year in North America (Stocks *et al.*, 2002). A recent estimate indicates that over the last 150 years, landfalling hurricanes have released an average 25 Tg of carbon per year in the United State alone (Zeng *et al.*, 2009). This is enough carbon to offset 9-18% of the annual U.S. forest carbon sink. Hurricane Katrina destroyed an estimated 105 Tg of biomass when it made landfall on the U.S. Gulf coast in 2005 (Chambers *et al.*, 2007).

However, little is known about the impacts of these forest disturbances on albedo, and therefore it is unclear whether these disturbances will generate reinforcing climate feedbacks (Adams *et al.*, 2010, Dale *et al.*, 2001, Running, 2008). Disturbances that decrease surface albedo (reflectivity) have the potential to create a positive (heating) radiative forcing by

increasing the amount of solar radiation absorbed in the climate system. In the case of fire in boreal forests, the increase in surface albedo following fire can offset the heating associated with the carbon released to the atmosphere (Randerson *et al.*, 2006). This occurs under snowy conditions because open (i.e. burned) spaces, relative to forested space, create relatively homogenous snowy surfaces that have a very high albedo. Forests, in contrast, have structures such as foliage and braches that create and trap multiple reflections of incoming solar radiation and decrease albedo. The low albedo of boreal forests creates a relative radiative forcing equivalent to that provided by its sequestered carbon (Anderson *et al.*, 2011, Bala *et al.*, 2007, Betts, 2000, Bonan, 2008, Bonan *et al.*, 1992). Albedo effects can outweigh the climate benefits of carbon sequestration in boreal and semi-arid forests, depending on integration time or duration of disturbance recovery (Betts, 2000, Rotenberg & Yakir, 2010).

Here we quantify the radiative forcing associated with perturbations to atmospheric CO_2 (ΔF_{CO2}) and surface albedo (ΔF_α) to weigh the climate effects (e.g., Betts, 2000, Randerson *et al.*, 2006, Rotenberg & Yakir, 2010) of major natural disturbance mechanisms from hurricane, wildfire and beetle attack.

Methods

We apply the concept of radiative forcing (Hansen *et al.*, 1997) to quantify the per-unit area climate impacts of forest disturbance from perturbations to surface albedo and the concomitant efflux of CO_2 associated with such disturbances in subsequent years. We define the net radiative forcing (ΔF_{net}) as the sum of two quantities: First, the shortwave radiative forcing (ΔF_{α}) is the mean annual change in reflected shortwave radiation at the top of the atmosphere resulting from changes in surface albedo. Second, radiative forcing caused by perturbations to atmospheric CO_2 from disturbance (ΔF_{CO2}) was calculated from measured and modeled changes in net ecosystem carbon balance (NECB). For both quantities, the disturbed state is compared to the undisturbed state at an annual time step, and the net effect is determined over multiple years following several disturbance events. Instantaneous radiative forcings for albedo and CO_2 are evaluated in the absence of feedbacks, such as changes to cloudiness resulting from other potential biogeophysical impacts like perturbations to roughness or evapotranspiration. To define the impact of various types of disturbance on surface albedo, we analyzed both AmeriFlux micrometeorological tower observations (Law *et al.*, 2002) and MODIS broadband albedo (Schaaf *et al.*, 2002). Three case studies are presented, including 1) defoliation and mortality of a sub-tropical mangrove canopy by hurricane, 2) forest mortality from mountain pine beetle, and 3) stand replacing fire in boreal forests.

Albedo radiative forcing

Albedo perturbation from forest disturbance was evaluated by comparing measurements of albedo in disturbed and undisturbed forests using both tower-based and remotely-sensed datasets. Tower data were available for case studies of hurricane defoliation of a mangrove

forest and wildfire in boreal forest. For those sites, daily values of albedo were calculated from tower-measured daily sums of half-hourly incoming and outgoing (reflected) shortwave radiation. Half-hourly values were excluded when the solar elevation angle (θ) did not exceed a minimum threshold (θ_{min}), which was set to approximately the local midday winter solstice value for each site, and therefore varied by latitude. Values of θ_{min} were 40° and 10° for the mangrove and boreal sites, respectively. The radiometer manufacturer (model CNR1 or CM3, Kipp & Zonen, Delft, Netherlands) specifies an accuracy of 10% for daily sums of radiation. This corresponds to an uncertainty of approximately 0.015 in daily albedo measurements, and thus applies to all of our reported tower-measured albedo values.

Where tower data were not available, MODIS (MCD43A) broadband shortwave blue-sky albedo data (Schaaf *et al.*, 2002) were extracted using the MODIS subsetting tool (ORNL DAAC, 2011) for 6.25 km^2 areas (25 pixels) of interest for all available years (2000-2010). Only data that passed the quality control filters and were associated with the vegetation type of the center pixel were included. An aerosol optical depth of 0.2 was used in the calculation of blue sky albedo. The accuracy of the MODIS Collection 5 shortwave albedo has been reported as 0.05 but is generally less than 0.03 (Roman *et al.*, 2009, Wang *et al.*, 2010). For each site, gaps in the 8-day MODIS albedo time series were filled by averaging values linearly interpolated across gaps with values taken from the 10-year ensemble average for that site, which has the benefit of constraining the local information provided by the interpolation with phenological and climatological information included in the ensemble average. This helps reduce interpolation errors from the discontinuities caused at the edges of snowy periods, where the albedo changes abruptly. The error associated with this technique was calculated by randomly creating and then filling a set of artificial gaps of the same length as the actual gaps. The bias error (BE) and root

mean squared error (RMSE) were calculated by comparing the artificially filled and original time series. Results of 1000 simulations for each case (Table 1) show that the gap filling attributes negligible bias in all cases and only a significant RMSE in one case (boreal fire), where the large difference in summer and winter albedo make the gap filling more sensitive to error. Resulting potential errors in radiative forcing at the annual scale range from 0.05 to 0.59 W m^{-2} and are incorporated in reported ranges of uncertainty. For the radiative forcing calculations, the 8-day MODIS values were averaged to monthly resolution.

The top-of-the-atmosphere (TOA) radiative forcing caused by the measured perturbations to surface albedo was calculated using the radiative kernel technique (Shell *et al.*, 2008, Soden *et al.*, 2008). The radiative kernel represents changes to TOA fluxes caused by incremental changes in monthly average surface albedo from present-day values at 2.5° resolution. It essentially represents a climatology of the sensitivity of TOA net shortwave radiation to incremental changes in albedo at the surface, neglecting feedbacks. The kernel used here was produced using the offline radiative transfer model of the National Center for Atmospheric Research (NCAR) Community Atmospheric Model version 3 (Collins *et al.*, 2006) as described in (Shell *et al.*, 2008), but with an incremental albedo increase of 0.01 rather than 0.001. Relative to calculations of surface radiative forcing, using values of insolation measured at the surface, the TOA calculations with the kernel account for the attenuation of the upwelling beam by clouds and aerosols. It also accounts for spatial variability in incoming radiation. For example, annual average daily insolation measured at the surface was 18.4, 12.9, and 10.6 MJ m^{-2} day^{-1} for the Florida, Manitoba, and British Columbia sites, respectively, presented in this study. The radiative forcing is then calculated at a monthly time step from perturbations in forest albedo caused by the disturbance relative to an undisturbed control stand. We report ranges of

uncertainty in the radiative forcing that include 10% for accuracy in albedo measurements and an additional 10% associated with the radiative kernel technique.

CO₂ Radiative Forcing

To model the radiative forcing associated with the release of terrestrial carbon to the atmosphere due to disturbance, the concept of net ecosystem carbon balance (NECB) was employed . NECB has been defined as the net carbon balance of an ecosystem, and includes net ecosystem exchange with the atmosphere (NEE) as well as lateral transport of carbon from disturbances and anthropogenic activities (Chapin *et al.*, 2006). Integrating NECB over larger spatial and temporal domains produces estimates of net biome productivity (NBP; Schulze & Heimann, 1998). Here we are interested in the source of CO_2 to the atmosphere from changes to NECB (δNECB) resulting from a disturbance. δNECB represents the difference between the disturbed and undisturbed NECB, all else being equal, and is defined explicitly below for each of three case studies. The input of CO_2 to the global atmosphere in year t (δCO_{2t}) was calculated from annual $\delta NECB_t$ using Eqn (1), where M_c is the molecular mass of carbon, M_a is the molecular mass of dry air, and m_a is the mass of the atmosphere.

$$\delta CO_{2t} = \frac{M_a \, \delta NBP_t}{M_C \, m_a} \qquad\qquad (1)$$

The input of atmospheric CO_2 was drawn down in each year by terrestrial and ocean uptake by applying a response function developed with the Bern 2.5 Carbon Cycle model (Joos *et al.*, 2001) and used in the IPCC radiative forcing calculations for atmospheric CO_2 (Forster *et al.*, 2007). Following uptake by biota and the oceans, the radiative forcing (ΔF_{CO2}) associated with the resulting CO_2 perturbation (ΔCO_2) was calculated at an annual time step calculated using a

well known parameterization (Eqn 2.; Myhre *et al.*, 1998), where CO_2* is the reference CO_2 concentration.

$$RF = 5.35 \times \ln \frac{\partial CO_2}{CO_2^*}$$ (2)

The reported radiative forcing represents that associated with the CO_2 perturbation from 1 m^2 of disturbed forest, mixed in the global atmosphere and then attributed to that 1 m^2, after uptake by the oceans and terrestrial biota. Therefore to convert the radiative forcings (both CO_2 and albedo) for comparison with global radiative forcings, they should be divided by the area of the earth. Ranges of uncertainty in ΔF_{CO2} are calculated from the reported uncertainty in $\delta NECB$ and an additional 10 % associated with the radiative forcing parameterization (Myhre *et al.*, 1998). Where temporal trends are discussed, model statistics from least squares regression models are reported to indicate the statistical significance of those trends.

Hurricane defoliation of mangroves

Since 2004 an AmeriFlux micrometeorological tower (25°21'46"N, 81°4'40"W) has operated near Shark River at the eastern edge of the Florida Everglades. Using the eddy covariance technique, the tower measures meteorological variables and determines turbulent heat and CO_2 fluxes (Barr *et al.*, 2010). The tower site is only 30 km from where the eye of hurricane Wilma made landfall on October 24, 2005. After achieving the lowest recorded central pressure of any hurricane in history, Wilma landed as a category 3 hurricane with sustained winds of 190 km hr^{-1} (Pasch *et al.*, 2006). The mangrove tower data record contains a 442-day gap associated with the destruction and eventual redeployment of the tower and instrumentation. As such, MODIS albedo was used to provide a continuous record both before and after the hurricane. Data from a 6.25 km^2 area adjacent to the tower site were extracted for all available years (2000-2010)

and the change in albedo caused by the hurricane was defined relative to monthly albedo values averaged over the pre-hurricane period (2000-2005).

Strictly speaking, NECB in this tidally driven mangrove forest is composed of temporal summations of net ecosystem exchange ($-\Sigma NEE$) and lateral fluxes of dissolved inorganic (DIC), dissolved organic (DOC), and particulate (PC) carbon entering or exiting the ecosystem (Chapin et al., 2006). The $\delta NECB$ is then:

$$\delta NECB = -\Sigma NEE_{disturbed} + -\Sigma NEE_{undisturbed} + \delta F_{DIC} + \delta F_{DOC} + \delta F_{PC}$$

where F represents lateral fluxes of carbon constituents with a positive sign convention for carbon entering the ecosystem. Fluxes of DIC, DOC, and PC (F_{DIC}, F_{DOC}, and F_{PC}, respectively), exported to the estuary may represent between 25% and 70% of $-\Sigma NEE$ based on regional and global estimates for mangroves while the remainder of $-\Sigma NEE$ is stored in biomass or soil carbon (Barr et al., 2010). Though carbon leaves the flux footprint of the tower as DIC, DOC, and PC, some fraction is consumed or buried within the surrounding estuary and therefore remains sequestered. Without detailed estimates of lateral carbon fluxes, perturbations in these fluxes resulting from disturbance, and estimates of the amount of carbon remaining sequestered, our best estimate of $\delta NECB$ excludes δF_{DIC}, δF_{DOC}, and δF_{PC}. The quantity $-\Sigma NEE_{undisturbed}$ (1175 ± 141 gC m^2 year^{-1}) was determined as the average of annual gap-filled NEE during 2004-2005 before the hurricane disturbance (Barr et al., 2010). During the period following the hurricane in 2007-2010, $-\Sigma NEE_{disturbed}$ was the measured annual sum of -NEE (Barr *et al.*, 2011). During 2006, eddy covariance (EC) estimates of NEE were only available during November and December, after the tower was rebuilt. For 2006 only, $-\Sigma NEE$ was determined as the difference between modeled gross primary production (GPP) and ecosystem respiration (R_E) rates. GPP 8-day estimates were determined from a vegetation photosynthesis model (Xiao *et al.*, 2004),

which was trained using EC-derived GPP from the tower site from periods before (2004-05) and after (2007-09) hurricane disturbance. Drivers of modeled GPP (GPP_{mod}) included a green vegetation index derived from MODIS reflectance products as well as local climate data, including air temperature, photosynthetically active irradiance, and surface water salinity levels measured near the tower site. Monthly R_E was determined as the sum of expected respiration in an undisturbed mangrove forest ($R_{E\,undist}$) and respiration contributed by the decomposition of coarse woody debris (R_{CWD}) resulting from tree mortality. Monthly $R_{E\,undist}$ was modeled using Eqn. 2 with linear coefficients determined from least squares regression of monthly EC-derived GPP and R_E during 2004-05.

$$R_{E\,undist} = m\,GPP_{mod} + b$$

(2)

Monthly R_{CWD} equaled the carbon content from the decomposition of dead trees. Cumulative tree mortality was measured at quarterly intervals in three circular plots adjacent to the tower (Smith *et al.*, 2009) starting November 2005. Decomposition rates of the coarse woody debris pool were assumed to follow the exponential decay function of Romero et al., (2005). Their model includes rate constants for both labile and refractory biomass fractions of wood in three species of mangroves (*Rhizophora mangle L., Avicennia germinans, and Laguncularia racemosa*) on site. On an annual basis, modeled -ΣNEE was 7% to 32% higher than EC-derived -ΣNEE during 2007 to 2009. Modeled GPP was within 3% of EC-derived GPP estimates, suggesting an underestimate of R_E. Underestimates may have resulted from exclusion of root decomposition of the dead trees and increased soil respiration rates resulting from increased irradiance penetration to the surface and higher soil temperatures following hurricane disturbance (Barr *et al.*, 2011). To account for these and any other potential biases, the -ΣNEE estimate for 2006 was taken as the average of bias-corrected -ΣNEE estimates (average of -

$\Sigma NEE_{2006}/1.07$ and $-\Sigma NEE_{2006}/1.32$). Given that model uncertainties in $-\Sigma NEE$ for 2006 were

expected to be larger than those during years when $-\Sigma NEE$ was determined from EC data, an

additional constraint was applied to $-\Sigma NEE$ during the first full year of recovery in 2006. The $-$

ΣNEE (± uncertainty) during 2007 and subsequent years of recovery should equal or exceed the $-$

ΣNEE estimate for 2006.   This constraint was based on both higher R_E and lower or equal GPP

rates during the first full year of recovery compared to those rates in subsequent years. Mortality

rates of mature trees reached 20% before 2007 and reached a maximum of 30% by mid-year

2009 (Barr et al., 2011). Based on the exponential decay function of Romero et al. (2005),

R_{CWD}, and therefore its contribution to R_E, would have been highest during November 2005 to

December 2006 when the pool of labile biomass of dead wood was at a maximum. Model

estimates of GPP were also lower during the first half of 2006 as a result of reduced green

vegetation cover compared to later periods.

Mountain Pine Beetle

   Mountain pine beetle (MBP) has impacted millions of hectares of pine forests in western

North America in the last decade (Raffa *et al.*, 2008). In British Columbia (B.C.), the outbreak

has reached epidemic proportions (Kurz *et al.*, 2008), with significant infestations also extending

southward into the United States along the Cascade and Rocky Mountain ranges into

Washington, Oregon, Idaho, Montana, Wyoming, and Colorado. Here we develop two case

studies to quantify the impact of mortality in lodgepole pine stands from mountain pine beetle

infestation in British Columbia and Oregon. In British Columbia, some of the earliest beetle

infestations of the recent epidemic occurred in Northern Tweedsmuir and Entiako Provincial

Parks starting in 1994 (Garbutt, 1994). Aerial surveys in 1999 (Cichowski *et al.*, 2001) revealed

the attack in those areas was severe (30-100% infestation) with some areas already experiencing dead, or grey-attacked trees. Using a combination of those surveys and contemporary LANDSAT imagery we have identified four beetle attacked stands in that region that have not burned or been salvaged as of 2010 (Table 1). To isolate the beetle effect on albedo from interannual variability in snow pack, a nearby control stand was identified with little or no beetle attack. Due to the ubiquity of attack in mature lodgepole stands in the region, the unattacked stand necessarily contains a significant proportion of subalpine fir and spruce in addition to lodgepole pine, and occurs at slightly higher elevation (1300 vs 1000 meters). MODIS blue sky broadband albedo data were extracted for 6.25 km^2 areas for each of the four beetle-attacked sites and the control site. To improve statistics, the time series of albedo at the four attacked sites were averaged together and an average year of attack of 1996 was assumed.

As a replicate of the albedo analysis in British Columbia we also identified an MPB-attacked stand in Oregon, approximately 1,000 km south of the B.C. sites. U.S. Forest Service aerial survey data (Forest Service, 2010) were used to identify a beetle infested lodgepole pine stand in the central Oregon Cascades where red attack was first detected in 1996. MODIS blue sky albedo data were extracted for an attacked and adjacent control site (Table 1), from which the albedo perturbation from beetles was defined.

The effect of beetle mortality on productivity in lodgepole pine forests of British Columbia has been reported by Kurz et al., (2008). For the current outbreak, they report NBP from 2000-2006 based on forest inventory data, and develop model projections for 2007-2020. A baseline control NBP was reported that incorporated regional rates of harvest and fire in the absence of beetles, and a beetle case included the additional effect of beetle, but not additional harvest (Kurz *et al.*, 2008). Here we define the net effect of the beetles (δNECB) as the difference between the

reported NBP values for the beetle and control cases, to remove the effects of harvest and fire. Mean annual δNECB began at -0.7 ± 2 gC m^{-2} year^{-1} in the first year and increased to a max of -54 ± 22 gC m^{-2} year^{-1} at 10 years since attack. Mean annual δNECB over the first 14 years was -33 ± 16 gC m^{-2} year^{-1}.

Boreal fire

A mesonet of six tower sites in Manitoba, Canada, that represent a chronosequence of coniferous forest sites with mean stand ages ranging from 11 to 159 years since fire, provided measurements of radiation, heat, and carbon dioxide fluxes between 2001-2005 *(Amiro et al., 2006, Goulden et al., 2006, McMillan & Goulden, 2008).* The sites, which range in vegetation cover from early successional herbs to mid-aged jack pine and mature black spruce, experience similar climate and have similar soil types and drainages (Goulden *et al.*, 2006), providing an unprecedented opportunity to study carbon and energy cycling in the boreal forests, including patterns of albedo after fire *(Amiro et al., 2006, Goulden et al., 2006, McMillan & Goulden, 2008).* Here we extend beyond previous albedo analyses by averaging all the available data from 2001-2005 to produce monthly, seasonal, and annual site means of albedo. To fill the albedo record in the first 10 years following fire, we extracted MODIS albedo for a burn that occurred in 1998 and an adjacent control stand in the same ecoregion as the mesonet, 100 km to its northeast (Table 1). The fire was identified using the Canadian Large Fire Database (Stocks *et al.*, 2002). Seasonal and annual means of albedo from MODIS and the tower chronosequence were combined and fit with exponential functions to provide continuous estimates of boreal albedo for years 2-159 after fire. The agreement between the tower and MODIS data is excellent, which is consistent with a formal evaluation that included these sites (Wang *et al.*, 2010). The radiative

forcing was calculated from albedo perturbations relative to the MODIS control stand for the

MODIS data, and from the oldest site in the chronosequence (159 years) for the other tower sites.

To produce continuous values of ΔF_α, the combined time series of annual radiative forcing was

modeled with a two-term exponential function (R^2=0.90, p<0.001).

Biometric and eddy covariance measurements of carbon stocks and fluxes were also

measured at the tower mesonet (Goulden *et al.*, 2011). For those sites δNECB was defined as

δNECB = NECB$_{disturbed}$-NECB$_{undisturbed}$, where NECB$_{disturbed}$ was determined from NEP in the

first 100 years following fire, but includes the pyrogenic flux in year one. That is, in year one

NECB$_{disturbed}$ = NEP – Ld, where Ld is the pyrogenic flux due to the combustion of forest

biomass. NEP was measured using the eddy covariance technique (Goulden *et al.*, 2011).

Annual NEP data for the seven sites were fit with a 4-parameter lognormal function that was

used to model NEP at an annual time step (Figure 1). To be consistent with an average fire

return interval of approximately 80 years in this region (Harden *et al.*, 2000, Manies *et al.*, 2005),

pyrogenic carbon emissions were calculated for the 74-year stand by applying combustion

factors (Campbell *et al.*, 2007) to measurements of four carbon pools, including live vascular,

live moss, forest floor (dead moss, leaf litter, fine debris and partially decomposed organic

material above the mineral soil), and coarse woody debris (Goulden et al., 2010). The resulting

estimate is a pyrogenic flux of 1720 ± 370 gC m^{-2} from the fire at time zero, where the range is

based on the uncertainty in both the carbon stock measurements and the emission factors. This

falls within the range of 1235 ± 410 gC m^{-2} reported as the 1959-1999 average for this ecoregion

(Amiro *et al.*, 2001) and estimates from other northern coniferous forests of 1900 ± 250 gC m^{-2}

and 1246 gC m^{-2} (Campbell *et al.*, 2007, Randerson *et al.*, 2006), respectively. Given a mean

stand age of 74 years at the time of fire, $NECB_{undisturbed}$ was estimated as NEP from years 74-174 from the extrapolated model fit to measured NEP.

Results

Case Studies

Hurricane defoliation of mangroves

In the Florida Everglades, Hurricane Wilma partially defoliated at least 270,000 ha of coastal mangrove forest. MODIS imagery indicates a reduction in the enhanced vegetation index (EVI), an indicator of canopy light interception, of as much as 80% in some areas (Figure 2). Removal of the mangrove foliage and damage to the canopy exposed the dark, moist underlying surface (Figure 3), resulting in a reduction in mean annual albedo from 0.11 to 0.09 in the year after the hurricane (Figure 4). Due to high levels of insolation, this translates to $\Delta F_\alpha = 3.6 \pm 0.5$ W m^{-2} in the first year (Figure 5A). Albedo recovered towards pre-hurricane values in the first three years following Hurricane Wilma, and has remained unchanged during the last two years. The reduction in albedo remains statistically significant five years following the hurricane (Student's t-test, $p < 0.001$). At the same time, the damage to the canopy also caused a large reduction in gross photosynthesis (GPP) and an increase in ecosystem respiration (Barr *et al.*, 2011). In the first five years following the hurricane, the average $\delta NECB$ was -344 ± 54 gC m^{-2} year^{-1}. As CO_2 emission from the disturbance accumulates in the atmosphere, the radiative forcing associated with $\delta NECB$ (ΔF_{CO2}) increases. Over the five years following the hurricane the sum of the two positive (heating) forcings results in an average net radiative forcing of 5.3 ± 1.0 W m^{-2} that is still increasing with time (Figure 5A), where the albedo forcing accounted for 45% of the total forcing.

Mountain Pine Beetle

Mortality in forests attacked by insects was thought to have only a small effect on albedo (Running, 2008). Here we find that that defoliation caused by the beetles only marginally affects summer albedo, but significantly increases winter albedo. In both British Columbia and Oregon the winter albedo had already increased by 0.06 at four years following attack (Figure 6), suggesting that the dead trees had already shed their needles, exposing the underlying snow. Winter albedo in coniferous forests experiencing snow is particularly sensitive to the degree of canopy cover, because less foliage exposes underlying snow and increases albedo (Amiro *et al.*, 2006, McMillan & Goulden, 2008). In B.C., the winter albedo perturbation then decreased until nine years after attack, before increasing to another local maximum of 0.08 at eleven years. The albedo perturbation in Oregon followed the same general pattern, such that the winter values at both sites could be described by a periodic Fourier function (Figure 6; $R^2 = 0.76$, p<0.001). The resulting radiative forcing at the B.C. site (Fig. 5B) started at -1.9 ± 0.3 W m^{-2} at year 4 and then oscillated, reaching a local minimum at 8 years, with another local maximum of -2.4 ± 0.4 W m^{-2} at year 11. The radiative forcing in years 1-3 was assumed to decrease linearly to zero at time zero.

The average CO_2 radiative forcing associated with (δNECB) averaged over the 14-year study period was 0.49 ± 0.15 W m^{-2} for the MPB study (Figure 5B). Thus, the magnitude of ΔF_α exceeded ΔF_{CO2} and opposed it in sign over the 14 year period, and the resulting mean net forcing was -0.98 ± 0.3 W m^{-2} (cooling effect).

Boreal fire

For the wildfire cases, results of the MODIS analysis show that albedo was initially elevated (compared to mature stands) in all seasons two years after fire, and then further increased with time for the next ten years (Figure 7). Tower data from the mesonet agree well with MODIS data for the year of overlap (year 11) and then indicate an exponential decay of albedo in all seasons towards mature boreal values over the next 100 years (McMillan & Goulden, 2008). Model fits to the data shown in Figure 7 are provided in an appendix online. This results in an annual radiative forcing that increases until approximately 10-20 years following fire, and then decreases exponentially with time (Figure 5C). In the first twenty years following fire, NEP and δNECB were negative (Figure 1), creating a large relative source of CO_2 to the atmosphere. The resulting radiative forcing, ΔF_{CO2}, peaked at year 10 (Figure 5C) and then decreased to become negative following year 65. This occurs because δNECB remains positive while NEP in the mid-successional stage exceeds that of late successional undisturbed stands (Luysseart *et al.*, 2008). Subsequently, large opposing values of ΔF_{CO2} and ΔF_α mostly balanced in the first 50 years, with ΔF_{CO2} dominating in the first 10 years due to the initial large pyrogenic pulse of CO_2. The average ΔF_{net} over the first 50 years was 0.59 ± 3.8 W m^{-2} (warming effect) and -2.4 ± 1.0 W m^{-2} (cooling effect) in the next 50 years. The average net radiative forcing over 100 years was -0.9 ± 2.4 W m^{-2}.

Discussion

In each of our case studies, the albedo change associated with a stand-altering forest disturbance caused a radiative forcing on the same order of magnitude as the concomitant CO_2 forcing. The mangrove/hurricane case provided the only example in which the CO_2 and albedo forcings were both positive, resulting in a large net heating. With both beetle attack and fire, where snow is present, the removal of the canopy greatly increases albedo, creating a cooling radiative forcing relative to the CO_2 forcing. We hypothesize that the albedo radiative forcing (whether positive or negative) will be significant relative to the CO_2 radiative forcing in most stand-altering forest disturbances, as the albedo of underlying soil or early successional species (e.g. grasses) is rarely the same as the forest albedo. This is especially important in high latitude or elevation sites that experience snow because of the well-documented snow-masking effect of forests (Betts & Ball, 1997, Mcfadden & Ragotzki, 1967). Furthermore, in colder environments, where succession tends to proceed slower, the recovery to pre-disturbance albedo is slower, extending the longevity of the radiative forcing. In our boreal fire example, the albedo radiative forcing persisted for approximately 100 years, while in contrast, the subtropical mangrove forest recovered half of its albedo perturbation in only three years. At the time of writing, at five years since hurricane, both albedo and -ΣNEE are still suppressed in the mangroves, such that the radiative forcing is still non-zero. The duration of those forcings can only be determined by continuing to monitor these processes into the future.

The decrease in albedo in the mangroves may be relatively unique, as even in other tropical environments, albedo tends to increase following deforestation because of the quick establishment of grasses, which have a higher albedo than forest. Evidence from the tropics suggests that following clearing, pasture albedo, when left to return to forest, can return to pre-

disturbance tropical forest values in approximately 30 years (Giambelluca, 2002), well before the carbon stocks. These examples also highlight the complexity in determining the net climate effect of forest disturbances, as the albedo and carbon components can recover at different rates. This occurs because the radiative properties of the canopy (i.e., albedo) depend on canopy geometry, which may have controls in addition to the ecological controls governing succession and recovery of carbon stocks (e.g. competition for light, water, and nutrients). In mangroves, the quick, but partial recovery of albedo was not matched by recovery in -ΣNEE. This is likely related to the early recovery of foliage and growth of epicormic sprouts, which partially close the canopy and affect albedo. However, leaf area index and density of photosynthetically active vegetation has likely not been restored to pre-disturbance conditions as evidenced by reduced enhanced vegetation index (EVI) in the 2.5 km by 2.5 km grid centered on the tower site (Barr *et al.*, 2011). In addition, higher respiratory fluxes have persisted during the 5 years following the storm as the result of several factors including decomposition of storm-generated coarse woody debris, statically unstable conditions which characterized the canopy air mass, and higher post-storm soil temperatures, especially during dry seasons when water levels are seasonally low.

The beetle case illustrates another level of complexity, where the disturbance is not as discrete or as complete as other disturbances, such as severe fire. This results in a disturbance in albedo and carbon stocks that amplifies for some time before transitioning into recovery. The net effect to carbon stocks (and albedo, we hypothesize) depends on the death, decay, and fall of trees over several years, balanced with the release of understory and surviving trees made possible by the increasing availability of resources, such as light (Waring & Pitman, 1985). Estimates of NEP show that the loss of productivity from dead trees may be balanced by the release of surviving trees in the first few years following attack (Brown *et al.*, 2010). MPB-

killed trees lose nearly all their needles by 4 years after attack (Safranyik *et al.*, 2006). We find that this significantly increases winter (and annual) albedo. Following that, albedo actually decreased for a few years. We hypothesize that this may reflect the initial release of surviving and understory trees. After about 9 years, albedo began to increase again, perhaps as fine branches, and the smallest snags began to fall. This is again followed by a decrease in albedo. We hypothesize that this may be followed by one final increase in albedo that would be associated with the fall of the remaining larger snags, which could open the canopy to its barest state.   In Oregon, MPB-killed lodgepole pine trees in unthinned forests were found to begin to fall five years following death (Mitchell & Preisler, 1998), where 50% were down by 9 years, and 90% by 14 years. Significant blowdown has not yet been observed in our study areas around Eutsuk Lake, and is expected to occur soon, in years 15-20 following attack (Dave Coates, personal communication). Albedo radiative forcing will likely reach peak negative values at that time. MPB-killed lodgepole tend to break and fall from the base (Mitchell & Preisler, 1998), so that the process is partially controlled by the decay rate at the base, which will be a function of moisture and temperature, among other variables. The other major control of snag fall rate is the experienced wind speed, which for any given snag can be a function of local weather and climatology, elevation, aspect, stand density etc. This may lead to a large degree of variability in the timing of snag fall, and our case study should be viewed as one example. Continued measurements and monitoring will be required to determine the duration and net impact of the beetle epidemic. At the landscape scale, the most important control on the albedo perturbation is likely the severity of attack, which varies from just a few attacked trees, to near complete stand replacement. This is also the most important predictor of the impact to carbon stocks, where recovery relative to unattacked stands can take decades. Measurements and simulations from

MBP-attacked lodgepole stands from the current epidemic in Idaho indicate recovery of attacked carbon stocks can take anywhere from 56-185 years, depending mostly on the severity of attack (Pfeifer *et al.*, 2011).

Our post-boreal fire analysis supports previous findings that summer albedo tends to increase with time starting two years after fire as early successional herbs, shrubs, and deciduous seedlings begin to reestablish (Amiro *et al.*, 2006, Lyons *et al.*, 2008, McMillan & Goulden, 2008, Randerson *et al.*, 2006). The greatest increase in albedo occurs in winter (Amiro *et al.*, 2006, Liu & Randerson, 2008, Liu *et al.*, 2005, Randerson *et al.*, 2006), where the loss of canopy creates a much more reflective surface for lying snow (Betts & Ball, 1997). This mechanism also increases albedo in spring and fall (Liu *et al.*, 2005, Lyons *et al.*, 2008, Randerson *et al.*, 2006) which represent the transition period for snow cover, making albedo during these times especially sensitive to interannual variability in snowfall (Liu *et al.*, 2005). In our analysis, winter albedo increased with time in the first ten years following fire. As with the beetle case, we hypothesize that this increase in time may result from the fall of standing dead snags. The time it takes for half of dead snags to fall (i.e., half life) has been reported as 5-15 years after fire in smaller fire-killed coniferous trees in western North America (Russell *et al.*, 2006). Thus, the progression of seasonal albedo with time during recovery not only depends on the rate of reestablishment during succession, but also the loss of standing dead snags and branches following fire.

Addressing multiple disturbances across very different biomes necessitated employing a variety of measurement and modeling techniques within this work. We have attempted to quantify and highlight the uncertainties in these techniques throughout. To the best of our knowledge, no systematic biases have been imputed from the diversity of methodologies. The

greatest shortcoming of this work may be the duration of beetle and hurricane cases studies, which do not capture the full recovery of the ecosystems to pre-disturbance levels of albedo or NECB. Continued measurement and monitoring will be required of ongoing work to determine the duration and net climate impact of these disturbances.

Conclusions

This analysis shows that, in terms of radiative forcing, albedo perturbations from natural forest disturbances can impact climate as much as the associated relative source of CO_2 to the atmosphere. Depending on the disturbance, the net of these two forcings can be positive (heating) or negative (cooling) when averaged over the measurement period.   That is, the albedo effect can either enhance or reduce the positive radiative forcing from CO_2 efflux, depending on the albedo of the underlying soil and early successional vegetation type, as well as the climate zone. Defining the net impact of a disturbance requires integration of fluxes and albedo over long timeframes, on the order of 100 years. Generally, in places that experience snow, removal of forest canopy via disturbance will lead to an increase in albedo. The magnitude of that increase depends on the severity of disturbance, preexisting stand density, snow amount, and radiation environment (e.g., latitude). However, albedo can also decrease after a disturbance, as demonstrated by our hurricane-defoliated mangrove case. The rate of recovery of albedo depends on the complex controls governing the ecological processes of succession, which also determine the recovery of carbon stocks. However, albedo and carbon stocks are not exactly coupled during succession, highlighting the complexity of representing these processes in global climate models. These processes vary greatly across ecoregions, and representing them properly will require continued use of carbon flux measurements, biometry, and remote sensing.

Improving our understanding of these processes is particularly crucial with regard to global scale prognostic climate modeling, since natural disturbances are expected to increase under a changing climate. This study adds to a now considerable body of work suggesting that albedo needs to be incorporated into carbon/climate management decisions.

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Tables

		Gapfilling error analysis					
		N gaps	BE	RMSE	RF error (std) (W m^{-2})	elevation (m)	lat	lon
Florida	both	15	-9.73e-007 +/- 4.94e-005	0.0011 +/- 0.0002	0.05	0	25.39	-81.13
Manitoba	control	17	-6.14e-006 +/- 1.74e-004	0.0036 +/- 0.0012	0.1	250	56.37	-96.80
Manitoba	fire	64	-1.75e-005 +/- 9.59e-004	0.0191 +/- 0.0035	0.59	200	56.36	96.37
Oregon	control	86	-1.80e-005 +/- 3.29e-004	0.0064 +/- 0.0011	0.28	1600	44.00	-121.82
Oregon	beetles	84	-8.48e-006 +/- 4.64e-004	0.0093 +/- 0.0019	0.41	1500	43.93	-121.76
B.C.	control	16	-1.38e-005 +/- 3.08e-004	0.0061 +/- 0.0011	0.17	1300	53.08	-125.01
B.C.	beetles	6	-1.06e-006 +/- 2.42e-004	0.0053 +/- 0.0014	0.16	900	53.19	-126.37

Table 1. Location, elevation, and statistics describing the error associated with gapfilling the MODIS time series of 8-day shortwave broadband albedo. Statistics include bias error (BE), root mean squared error (RMSE), and the average error imputed to the annual calculation of radiative forcing as calculated from the error statistics and 1000 Monte Carlo simulations.

Figure Legends

Figure 1. Mean annual NEP as measured with eddy covariance across the boreal chronosequence (Goulden et al., 2010) with 25th and 75th percentile confidence intervals of a 4-parameter lognormal fit (R^2 = 0.88, p<0.07). The model fit is used to predict NEP at an annual time scale. The ecosystem is a carbon source for approximately the first 11 years following fire.

Figure 2. Difference in MODIS enhanced vegetation index (EVI) from before and after hurricane Wilma, expressed as percent change. Three 16-day EVI scenes from November and December were averaged before Wilma in 2004 and after in 2005 to produce the difference. The inset shows southern Florida with the area of EVI analysis indicated by a white box. Visible imagery used in fair use, ©2011 Google, imagery © 2011 TerraMetrics.

Figure 3. (A) View of the understory and boardwalk leading to the tower at the mangrove site before the hurricane shows a closed canopy. (B) After the hurricane the canopy was nearly completely removed, exposing the dark, damp soil.

Figure 4. Time series of MODIS 8-day shortwave broadband albedo (hollow circles) with annual moving average (solid line, left axis), and annual tower-measured and modeled -ΣNEE with uncertainty estimates (squares with error bars, right axis). The value of -ΣNEE in 2006 is shown as a hollow square to indicate that the value was modeled rather than measured, as in other years. The impact of defoliation from Hurricane Wilma is visible as a significant reduction in both albedo and -ΣNEE.

Figure 5. Top of the atmosphere radiative forcing resulting from changes to albedo (data as red symbols; model fit as red line) and net biome productivity (δNECB, green line) and the net of those two processes (dashed blue line) for (A) hurricane damage to a mangrove forest, (B) lodgepole pine mortality from mountain pine beetle, (C) stand replacing fire in coniferous forests in and Manitoba, Canada (squares=MODIS; circles=towers). Values of ΔF_{net} averaged over the period indicated in each panel are included. The radiative forcing from albedo changes and CO_2 release are on the same order of magnitude, and can either oppose in sign to reduce the net forcing (e.g., B,C), or combine constructively to enhance it (e.g., A).

Figure 6. Time series of the perturbation of MODIS albedo in summer (JJAS) and winter (NDJF), as a function of years since mountain pine beetle attack in lodgepole pine stands in British Columbia (B.C.) and Oregon (OR). Albedo is greatly enhanced in winter after the dead trees drop their needles. The albedo perturbation changes with time as the degree of canopy openness is controlled by the balance of the release of surviving trees and fall of standing dead branches and snags. Error bars are shown on the B.C. winter values to indicate the reported accuracy of MODIS albedo data.

Figure 7. Annual and seasonally-averaged albedo as a function of years since fire (stand age) for summer (JJAS), winter (JFMD), and spring/fall (AMON). Data from years 2-11 since fire are MODIS data, and years 11-159 are tower data from the boreal chronosequence. Model fits are two-term exponential functions (see supporting information online). Error bars on the annual albedo means indicate confidence intervals of 0.03 for MODIS data and 0.015 for tower data.

Change in MODIS EVI

A ΔFnet = +5.3 W m⁻²

B ΔFnet = -0.98 W m⁻²

C ΔFnet = -0.92 W m⁻²

Radiative forcing (W m⁻²)

Years since hurricane

Years since beetle attack

Years since fire

NECB
net
albedo