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Global estimates of boreal forest carbon stocks and flux

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ABSTRACT

The boreal ecosystem is an important global reservoir of stored carbon and a haven for diverse biological communities. The natural disturbance dynamics there have historically been driven by fire and insects, with human-mediated disturbances increasing faster than in other biomes globally. Previous research on the total boreal carbon stock and predictions of its future flux reveal high uncertainty in regional patterns. We reviewed and standardised this extensive body of quantitative literature to provide the most up-to-date and comprehensive estimates of the global carbon balance in the boreal forest. We also compiled century-scale predictions of the carbon budget flux. Our review and standardisation confirmed high uncertainty in the available data, but there is evidence that the region's total carbon stock has been underestimated. We found a total carbon store of 367.3 to 1715.8 Pg (10^{15} g), the mid-point of which (1095 Pg) is between 1.3 and 3.8 times larger than any previous mean estimates. Most boreal carbon resides in its soils and peatlands, although estimates are highly uncertain. We found evidence that the region might become a net carbon source following a reduction in carbon uptake rate from at least the 1980s. Given that the boreal potentially constitutes the largest terrestrial carbon source in the world, in one of the most rapidly warming parts of the globe (Walsh, 2014), how we manage these stocks will be influential on future climate dynamics.

1. Introduction

The boreal ecosystem constitutes about a third of the Earth's extant forests (FAO, 2006) and a substantial portion of the remaining large tracts of continuous forest (Bradshaw et al., 2009), as well as containing an estimated one third of the stored terrestrial carbon stocks (IPCC, 2007; Pan et al., 2011). Largely ignored in the context of international efforts to mitigate climate change through management of carbon storage and flux (Moen et al., 2014), the boreal zone has been considered by many to be a carbon sink (Jobbágy and Jackson, 2000; Ciais et al., 2010; Pan et al., 2011). This net carbon uptake is derived primarily from the expansion of the boreal forest following the deglaciation that occurred after the Last Glacial Maximum of 19–26.5 kyr ago (Adams et al., 1990; Foley et al., 1994) and the accumulation of carbon in deep peatlands (with peatland formation peaking around 7–8 kyr ago) (Gorham et al., 2007). However, and particularly important for the ongoing management of carbon stocks in the context of climate change, it appears that the strength of this sink has been weakening (Stephens et al., 2007; Bonan, 2008; Hayes et al., 2011), with estimates suggesting that some regions might well be hovering near zero flux intensity or will soon become a net source (Bonan, 2008; Kurz et al., 2008b). The direction of flux and pace of conversion from sink to source appear to be driven at least in part by the relatively rapid temperature rise in the boreal region compared to other parts of the globe. Assessment of historical and current temperature regimes suggests greater rates of warming at high northerly latitudes over the 20th century, and particularly during the later decades of that century, than during the last 1000 years (Mann et al., 1999; Serreze et al., 2000; IPCC, 2001, 2007). Future scenarios also indicate a high probability that warming trends will continue and possibly increase during the coming century, further altering natural disturbance regimes through modified frequency and severity for both wildfire (Flannigan et al., 2005; Balshi et al., 2009; Tchebakova et al., 2009) and insect outbreaks (Bale et al., 2002; Dymond et al., 2010; Gustafson et al., 2010), as well as increasing rates of permafrost loss (Vitt et al., 2000; Schuur et al., 2008; Grosse et al., 2011).

Reliable estimates of total carbon storage and flux across this expansive region are required to craft government policies that effectively foster sustainable development and climate change mitigation. Likewise, assessing alternative forest management strategies as mitigation measures under changing environmental circumstances will be based, at least in part, on the same critical carbon accounting information. To address this data need, there has been enormous growth over the past three decades in the number of studies examining boreal carbon; a search for "boreal AND carbon" identified only two papers in the Web

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of Science® database during 1982–1983 versus 1066 papers published during 2012–2013.

Yet there is high uncertainty associated with these estimates (Shvidenko et al., 2010; Hayes et al., 2012). Substantial differences have been identified among 'bottom-up' forest inventory-based assessments of regional and global carbon stocks and flux due to the use of different biomass density estimates in combination with different, and sometimes even similar, forest area assessments (Fang et al., 2006; Houghton et al., 2007). This approach is also plagued by irregular updating of forest inventory data for some of the regions involved (Potapov et al., 2011). Similarly, 'top-down', atmosphere-based models have produced variable estimates attributed to gaps in spatial and temporal sampling effort, as well as measurement, modelling and scaling errors associated with the differing approaches used (Dargaville et al., 2006; Ciais et al., 2010). For example, permafrost deposits constitute a substantial storage pool for carbon in the boreal that is at risk from rising air temperatures (Grosse et al., 2011; O'Donnell et al., 2011). Yet quantifying both storage and flux from permafrost in the context of the boreal is confounded by datasets created to address issues across the northern cryosphere, rather than separating Arctic/tundra from strictly boreal deposits (McGuire et al., 2010; Grosse et al., 2011) (but see Tarnocai, 1998, 2000). Likewise soil carbon, which in the boreal accounts for at least three times the carbon that is stored in vegetation (Malhi et al., 1999), is often determined using model predictions rather than repeated soil measurement over sufficient time sequences at permanent sample plots (Häkkinen et al., 2011). Those assessments of soil carbon stores available are frequently made to only ≤1 m depth and consequently ignore any stores below (Jobbágy and Jackson, 2000; Seedre et al., 2011), although soils below 1 m are considered by many (e.g., Deluca and Boisvenue, 2012) not to contain substantial amounts of carbon (but see Tarnocai et al., 2009; Jorgenson et al., 2013; Kuhry et al., 2013; Hugelius et al., 2014). Equally problematic is the relatively young age of the soils underlying the boreal forest; they are highly variable in depth and are frequently shallow with limited development of mineral horizons due to recent glacial activity, particularly at the northern limit of the boreal zone (Sanborn et al., 2011). Consequent models built to extrapolate soil carbon stores from local- to regional- or biome-level scales are hampered by their capacity to incorporate this variability in the extent of soil types and depth, as well as the depth to which sampling for carbon density has been done.

Despite these uncertainties, a standardised inventory approach to examine and compare the available data can be effective in identifying broader trends, but also gaps and weaknesses in the information available. Our aims are therefore to provide comprehensive, global and up-to-date estimates of carbon storage and flux in the boreal zone.

2. Methods

We compiled a detailed list of scientific publications (mainly primary, peer-reviewed literature, but including books, and government and NGO reports) that reported carbon density (quantity per unit area), total carbon stores or carbon flux from within the boreal region. We searched Web of Science® using the terms 'boreal', 'carbon', 'flux' and 'storage' in different combinations to identify the primary literature, and cross-referenced papers in reference lists to identify missing source literature. We took values as presented when in either Pg (10^{15} g) or Mg (10^{6} g) C ha^{-1}, or converted from reported values into these units. We recorded area extent as reported or estimated based on references provided in each paper. Most papers could be divided into one or more regional foci: circum-boreal, Russia, Canada, Scandinavia (i.e., Fennoscandia) and Alaska, and reported carbon values for one or more main components of the system—vegetation (both above- and below-ground, living and dead biomass), soils (typically the mineral horizons, but sometimes including organic horizons as well as forest-based peat) and peatlands.

2.1. Carbon stores

Carbon stores estimated for the boreal ecosystem among regions were generally restricted to particular components of the broad categories of 'vegetation', 'soils' and 'peatlands'. For example, many studies reported values for live biomass only, live and dead biomass, above- or below-ground biomass only, soils to a depth of 1 m only, soils to a depth of 3 m only, cryosols only, mineral soil horizons or mineral and organic soil horizons combined, peatlands to a depth of 1 m only, or average-depth peatlands only. In some instances, determining the exact components to which the estimates were attributed was difficult or impossible. As such, our reported ranges should be considered approximate only.

Furthermore, most papers approximated stores based on differing estimates of spatial extent for the various ecosystem components. We were therefore obliged to standardize all estimates to densities (Mg C ha^{-1}) first, and then estimate mean densities over comparable components (live biomass only, etc.). We then took standard area estimates for either circum-boreal or regional extents and multiplied these by the standardised density ranges to provide total carbon estimates. For vegetation and soils, we used the same spatial extents to estimate total stores, but peatland extent is considerably smaller, so we used the relevant extents for all peatland estimates (where appropriate, we averaged these across studies reporting different values within regions). In some cases, peatland extent was not specifically categorised into 'boreal' and 'tundra' biomes (i.e., the two were combined), so we have indicated where inflations due to the inclusion of strictly non-boreal peatlands likely occurred. As is common in such accounting-type summaries, our geographical sampling range was limited to that available in the literature. Consequently, our findings reflect a general scarcity of observations for high-latitude locations and a bias towards study of the more productive, southern portion of the boreal forest for both measures of carbon stocks and flux (Hayes et al., 2012); for example, unmanaged northern forests in boreal Canada were not included in assessments of carbon budgets for that region (Kurz et al., 2009).

2.2. Carbon flux

As for carbon density and total stocks, we estimated mean carbon dynamics across the boreal zone by standardising estimates of carbon flux, typically expressed as either a total exchange per unit time (e.g., Pg C year^{-1}) or exchange per unit area per unit time (e.g., Mg C ha^{-1} year^{-1}). Our principal aim was to estimate the range of net flux density, i.e., whether a study measured net carbon uptake ('sink') or release ('source'). We standardised all estimates to flux density (Mg C ha^{-1} year^{-1}) based on area of extent provided in each study, or applied area estimates from other relevant studies. In all analyses of carbon flux density we based our assessment on both the entire dataset compiled as well as using just those data from studies where area of extent was provided.

Given recent observations that, at least in certain parts of the boreal forest, the region has become a net carbon source (see more below), we attempted to divide estimates into decadal spans to examine if any temporal trends were apparent. Most carbon flux estimates date back only to the 1980s, so we estimated decadal trends in the 1980s, 1990s and 2000s, with one study projecting dynamics to 2050 (Metsaranta et al., 2010) and one study projecting to 2100 (Yarie and Billings, 2002). Many modelling studies in particular estimated carbon dynamics over longer periods (e.g., over the entire last century, late post-glacial, etc.), or examined particular forest stand types (e.g., a particular species composition, only young and growing; only recently disturbed) often across limited spatial scales. We excluded these studies from mean flux density estimates. Estimates spanning two decades (e.g., 1985–1995) were included in the means of both decades (e.g., '1980s' and '1990s'), so there is some inevitable overlap among decades (i.e., trends should be viewed partially as 'running' means).