United States Department of Agriculture

Greenhouse Gas Emissions Versus Forest Sequestration in Temperate Rain Forests—A Synthesis for Southeast Alaska Communities

David Nicholls and Trista Patterson

Forest Service
Pacific Northwest Research Station
General Technical Report PNW-GTR-918
December 2015

Authors

David Nicholls is a forest products technologist and **Trista Patterson** was an ecological economist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Alaska Wood Utilization and Development Center, 204 Siginaka Way, Sitka, AK 99835.

Cover: Map of southeast Alaska showing the locations of Sitka and Baranof Island.

Abstract

Nicholls, David; Patterson, Trista. 2015. Greenhouse gas emissions versus forest sequestration in temperate rain forests—a southeast Alaska analysis. Gen. Tech. Rep. PNW-GTR-918. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 25 p.

Sitka, Alaska, has substantial hydroelectric resources, limited driving distances, and a conservation-minded community, all suggesting strong opportunities for achieving a low community carbon footprint. In this research we evaluate the level of carbon dioxide (CO_2) emissions from Sitka and compare this to the estimated CO_2 sequestration potential of forest ecosystems. We determine whether a carbon-neutral community is attained when these two factors are balanced.

Our analysis consisted of two parts: estimating anthropogenic CO_2 emissions from Sitka, and comparing this value to estimates of carbon sequestration from forests on Baranof Island in southeast Alaska. We found total estimated anthropogenic emissions from Sitka to be in the range of 100,000 to 150,000 Mg carbon per year. Carbon sequestration by forests on Baranof Island was conservatively estimated to be more than 250,000 Mg carbon per year. This estimate was extrapolated from studies evaluating net ecosystem productivity of forests similar to those in southeast Alaska.

Further reductions in anthropogenic emissions are still possible in Sitka. The expansion of the Blue Lake hydroelectric generating facility (adding up to 34,000 megawatt-hours per year of energy) could further reduce Sitka's carbon footprint.

Keywords: carbon sequestration, net ecosystem productivity, greenhouse gas emissions, temperate rain forest.

Contents

Introduction

Carbon Footprints of Communities in Forested Ecosystems

This research considers the carbon footprint of Sitka, Alaska, including the anthropogenic emissions of its residents, and the carbon sequestration capability of the forest ecosystems on Baranof Island near Sitka. The term "carbon footprint" has many interpretations; a commonly accepted definition is "a certain amount of gaseous emissions that are relevant to climate change and associated with human production or consumption activities" (Wiedmann and Minx 2007). Several evaluations have been conducted at national scales, including Australia (Lenzen and Murray 2001), Ireland (Kenny and Gray 2009), and Austria (Erb 2004). Other studies have considered general methods for national-level footprints (Kitzes et al. 2007, 2009). Still other studies have considered the province (Bagliani et al. 2004) and community levels (Barthelmie et al. 2008).

A key objective for estimating community footprints is to indicate how local actions can reduce particular sources of emissions. These local actions can add up to large reductions when combined across larger geographic scales, and could become an essential feature of reaching global goals articulated by Pacala and Socolow (2004), in which up to 1 billion Mg of carbon dioxide (CO_2) emissions can be avoided annually. The urgency of determining carbon footprints and moving quickly toward mitigation strategies is well illustrated by Rockstrom et al. (2009). In this study, 10 global environmental thresholds, which define the boundaries of a "safe operating space for humanity," were identified and quantified. Six of these thresholds have already been exceeded. Most striking of these indices is the rate of biodiversity loss, which already exceeds the boundary level by more than tenfold.

Estimating and comparing carbon footprints versus planetary biological capacity to support them has become more specific and standardized (GFN 2009). This has aided the challenge of comparative studies addressing issues related to scale (GFN 2009; Wackernagel et al. 1999, 2002). Early footprint theory and estimations were necessarily conceptual in nature (Wackernagel and Rees 1996). In the current study we pose the Sitka example in the same light. We develop connections between a community and the forest within its borders. Methods of quantifying carbon footprints can in some situations be imprecise, and many different approaches are possible. For example, only direct CO_2 emissions could be measured vs. complete life-cycle analysis (LCA) for a range of greenhouse gases. Further, CO_2 emissions are only one portion of greenhouse gas emissions, and have less warming potential than do some other gases; therefore, an accurate carbon footprint would need to consider which greenhouse gases to include. Accurately defining time scales, spatial scales, and vegetation types can further complicate this analysis. One conceptual model to consider would be best described as a "tea-cup" or "terrarium" construct. Here, all carbon cycling would be assumed to take place within a localized closed system that has well defined boundaries, rather than a real-world model of global extent.

Even though a model of closed carbon cycling would not be realistic under actual conditions, it could help define the processes occurring near Sitka. First, Sitka is located in a remote part of southeast Alaska with few nearby cities that could mask the effects of the city's emissions. Second, because Sitka is surrounded by large areas of forest land, carbon sequestration of man-made emissions could reasonably be influenced most directly by nearby forests. Third, Sitka is located on Baranof Island, which serves as a convenient geographic boundary for our analysis. Fourth, although this "teacup" model does not account for the important sequestration or other atmospheric interactions occurring on oceans, and other land cover, the linkage between a community and the services provided by its surrounding forests (Patterson and Coelho 2009, Smith et al. 2011) is important.

Sitka, Alaska, Context

The legal land area of the City and Borough of Sitka, Alaska, is about 7444 km^2 (USDC CB 2012), although most of this area is uninhabited, consisting of mixtures of forest, muskeg, rock, and glaciers. The forested area can further be described in terms of commercial versus noncommercial forests, young-growth versus old-growth trees, hardwoods versus softwoods—each of which could have differing rates of productivity and sequestration. Thus, quantifying the actual forest sequestration, net ecosystem productivity, and role of forest soils is beyond the scope of this study.

Sitka is an island community of close to 8,800 residents (USDC CB 2012), and relies primarily on hydroelectric power, with installed capacity of more than 24 megawatts (MW) (CBS 2011). The 6 MW Blue Lake facility started operation in 1961 and now meets close to 20 percent of Sitka's electrical needs. A second hydroelectric facility (the 18.6 MW Green Lake facility), has been in operation since 1979. In periods of relatively high electrical demand (or low hydropower production) a diesel generator system is available to meet a portion of Sitka's electrical needs. The diesel generator is a last-resort option owing to its high consumption of fuel, even for short periods of operation. For example, during a six-day period in May 2011, Sitka burned 21,866 gallons of diesel fuel to meet the city's electrical demand (CBS 2011).

Sitka has a very limited road system (about 16 miles of primary roads) and therefore very limited transportation needs. Although more than 8,000 registered vehicles are in Sitka (Alaska DMV 2007), many residents drive just a few thousand miles per year, in one study estimated to be 4,380 miles per vehicle per year (Dhittle and Associates, Inc. 2008). Sitka's relatively mild maritime climate results in essentially no air-conditioning needs in summer and a relatively mild winter heating season by Alaska standards. Sitka could become a proving ground for electric vehicles owing to short daily driving requirements, relatively low travel speeds (45 mph or less), and relatively flat terrain. Any significant expansion of Sitka's electric vehicle capacity, however, would not be prudent until Sitka's hydroelectric capacity has been augmented. In other words, large scale use of electric vehicles powered ultimately by diesel generators (and not base-load hydroelectric power) would not make sense, economically or environmentally.

Sitka could become a proving ground for electric vehicles owing to short daily driving requirements, relatively low travel speeds (45 mph or less), and relatively flat terrain.

Research Objectives

The objectives of this research were to evaluate the carbon balances of Sitka, assessing local anthropogenic CO_2 emissions and the carbon sequestration of local forests, as measured by net ecosystem productivity (NEP). By weighing these two quantities against each other, we evaluate whether Sitka is a carbon-neutral community, and describe quantified conceptual connections (such as the forest area needed to sequester emissions from an average resident). These results could help stimulate community planning dialog, or serve as a framework for other communities where estimations may be less straightforward.

Literature Review—Carbon Sequestration as an Ecosystem Service

Carbon Sequestration in Forest Ecosystems

Oceans, peatbogs, grasslands, savanna, and taiga are all important land covers for carbon sequestration, yet of these, forests are most actively managed and planted for this purpose. Globally, about 25 percent of anthropogenic CO_2 emissions are estimated to be sequestered in forests (Nabuurs et al. 2000). More than 66 percent of the global carbon (C) stocks in forest ecosystems are estimated to be in forest soils and peat deposits (Dixon et al. 1994). In the European continent an estimated 7 to 12 percent of anthropogenic emissions (i.e., 135 to 205 Tg per year) are sequestered in forests (Janssens et al. 2003). Here, the changing carbon sink is related primarily to growth of relatively young trees, and is attributable to both tree biomass (about 70 percent of the sink) and soils (about 30 percent of the sink) (Liski et al. 2006, Nabuurs et al. 2000). This estimate compares favorably to Nabuurs et al. 1997, who estimated a whole-tree carbon sink in Europe of about 101.3 Tg C per year (equivalent to 9.5 percent of European Union emissions).

Also in Europe, latitudinal variations in carbon flux have been noted. Valentini et al. (2000) found that forests in boreal regions sequestered very little carbon, whereas Mediterranean forests sequestered up to 5 Mg C/ha/year. This lack of sequestration at high latitudes could be significant given that an estimated 49 percent of carbon in forest ecosystems is contained in high latitude forests (Dixon et al. 1994), with 37 percent of carbon in low-latitude forests and 14 percent in mid-latitude forests.

Net ecosystem productivity can be thought of as the net change in carbon storage of forests over some time interval.

Net ecosystem productivity (NEP) in forests can be defined as "the net carbon accumulation by ecosystems," which incorporates "all the carbon fluxes from an ecosystem, including autotrophic respiration, heterotrophic respiration, losses associated with disturbance, dissolved and particulate carbon losses, volatile organic compound emissions, and lateral transfers among ecosystems" (Randerson et al. 2002). It can be expressed as the change in carbon storage over some time interval. Net ecosystem productivity can also be thought of as the difference between net primary production and respiration. The woody component of NEP can be represented by the sum of live and coarse woody debris stores, measured over a given time interval (Janisch and Harmon 2002). Pregitzer and Euskirchen (2004) studied latitudinal climatic gradients and their effect on the net primary productivity (NPP) and NEP of forest ecosystems. They synthesized 120 papers into a single database and found that forest stand age played an important role in determining the distribution of carbon pools. Aggregated estimates of both NPP and NEP were found to be highest in intermediate-aged stands (i.e., 30 to 120 years in age), whereas older forests were generally less productive. The youngest age class (0 to 10 years old) exhibited negative mean NEP in boreal and temperate biomes. Summary NEP data for temperate forests revealed a peak of 4.5 Mg C/ha/ year occurring in the 11- to 30-year age class.

Six different forest ecosystem carbon pools are generally recognized in the literature; these include live trees, standing dead trees, understory vegetation, down dead wood, forest floor, and soil organic carbon (Smith et al. 2006). However, the most effective strategies for use of forests to sequester carbon depend to a large degree on the current status of the land (Marland and Marland 1992). For forests composed mainly of standing biomass, and also characterized by low productivity, an effective strategy is to protect the existing forest. However, for land containing little biomass, with low productivity, an effective sequestration strategy is to reforest and manage for carbon storage (Marland and Marland 1992). Important questions remain, in southeast Alaska and elsewhere, regarding the rate at which trees are able to sequester carbon and the land area available for reforestation and afforestation.

Under certain conditions, forest stands could contribute significant sequestration potential. For example, Moulton and Richards (1990) estimated that the United States could offset 56 percent of its CO_2 emissions from fossil fuel combustion by planting trees on 140 million ha of marginal crop, pasture, and nonfederal forest lands. They also describe tree planting as an "interim measure" for carbon sequestration in that sequestration rates will inevitably decline over time owing to the maturity and senescence of trees.

The effect of rotation length on carbon sequestration potential was evaluated by Liski et al. (2001), who considered 60-year and 90-year rotation lengths in Finland. Shortening the rotation length by 30 years (to more closely match culmination of mean annual increment) had the effect of decreasing carbon stocks in trees while increasing carbon stocks in soils. The shorter rotation lengths also had the effect of increasing fossil carbon emissions associated with harvesting and manufacture. The sequestration potential of mature forests has also been considered. Harmon et al. (1990) evaluated the sequestration potential of harvested lumber from old-growth forests. They concluded that it would take at least 250 years for the net carbon stored in forests plus "long-lived" wood products to recover the carbon content of the old growth stand prior to harvest. Unmanaged forests in Austria were also found to have higher carbon storage (versus managed forests) (Seidl et al. 2007). Meng et al. (2003) found carbon storage to be higher in undisturbed, naturally growing forests in New Brunswick, Canada, versus those managed by current industrial practices. Under the no-disturbance scenario, forest carbon stocks increased over a period of 60 years, after which they started to decline.

Seely et al. (2002) studied the effect of rotation length on carbon balances of boreal forests using an ecosystem simulation model. Total ecosystem carbon increased with longer rotation ages regardless of species, and primarily resulted from increases in live biomass. However, the proportion of ecosystem carbon in soils decreased with longer rotation lengths. Short rotation scenarios showed reductions in site productivity during subsequent rotations. However, application of nitrogen fertilizer ameliorated this trend, and in some cases increased total carbon storage by up to 9 percent. Carbon stocks in boreal forests were also studied by Garcia-Gonzolo et al. (2007), who considered timber production under several management regimes. Any tree stocking densities that were greater than "business as usual" regimes were found to increase both timber production and ecosystem carbon stocks. Maximum carbon stocks were found under the regime in which no thinning was done before the final harvest.

Active management of forest stands could become an integral part of carbon sequestration while providing economic benefits to landowners. It has been suggested that financial incentives for improved forest management could become attractive to landowners if carbon had a market value of $10 USD per Mg or higher (Birdsey 2006). By comparison, Leighty et al. (2006) used an assumed carbon value of $20 USD per Mg when considering forest biomass in southeast Alaska. The transition path from old-growth to second-growth forests on the Tongass National Forest (NF) occurring over the next several decades could be greatly influenced by both the market value of carbon and forest carbon sequestration potential, among other factors. From a practical standpoint there is very little timber harvested on Baranof Island near Sitka. However, as this region transitions to actively managed second-growth timber in coming decades, harvest levels could change, especially on Prince of Wales Island, where much of the second-growth resource is located.

The subject of carbon neutrality of forests has become quite contentious recently, in part because spatial and temporal scales can be difficult to define, making scientific analysis challenging. Some have suggested that the carbon benefits of forests might be more limited than previously thought; thus it is not accurate to characterize all bioenergy as being "carbon neutral." For example, some studies (Manomet Center for Conservation Sciences 2010) have asserted that wood burned for energy can result in greater life-cycle greenhouse gas emissions than even coal burned to create an equivalent amount of energy. However, it must be realized that forest scale, geographic region, and forest growth rates among other factors all are important in determining carbon balances. Moreover, there are numerous integrated carbon pools involving wood products, bioenergy, and other uses (for direct use and substitutions), making it difficult to assess best practices and policy (Lippke et al. 2011).

Carbon Sequestration From Peat Ecosystems and Wetlands

The carbon balances of wetlands (including peatlands, muskeg, and estuaries) can have important implications in southeast Alaska. Here, peat systems are found intermixed with forests, and four transition zones have been identified within shared peat and forest ecosystems (Hartshorn et al. 2003). Northern peat ecosystems are characterized by relatively low NPP, decomposition, and net CO^2 exchange (Frolking et al. 2002). However, even though carbon sequestration occurs very slowly, substantial quantities of organic carbon can be found within a depth of a few meters because of centuries of accumulation. For example, sequestration rates of 2 to 3 Mg/ha over the past 5,000 to 10,000 years have been evaluated by Gorham (1995). Other research on northern peatlands in North America found net sequestration rates of about 6 Mg C/ha/year, based on eddy covariance techniques (LaFleur et al. 2001). Hartshorn et al. (2003) estimated that peatland-forest ecosystems in southeast Alaska could contain up to 23 kg C/m^2 (23 Mg per ha). These studies indicate the importance of carbon stored in peat, and the important implications for carbon cycles and climate change.

Forest Ecosystem Productivity in Alaska, Canada, and the Pacific Northwest

Carbon sequestration in trees, although not a significant factor in the inhabited portion of Sitka, could be a significant ecosystem service when considering land areas adjacent to Sitka, including Baranof Island and the Tongass NF. The Tongass covers close to 17 million acres and contains an estimated 2.8 ± 0.5 Pg[1] of carbon (equivalent to 7.7 percent of total carbon in U.S. forests) (Leighty et al. 2006). This study identified seven different carbon pools, and found that 66 percent of the total Tongass carbon was stored in soils, 30 percent in aboveground biomass, and 4 percent in roots (Leighty et al. 2006).

Southeast Alaska's Baranof Island contains much of the legal area of the City and Borough of Sitka. Two biogeographical provinces have been identified; eastern Baranof Island and western Baranof Island (Bschor 2008). The combined forest area for these regions is 663,686 ac, of which almost half is productive old-growth forest. Our evaluation will be based on productive old-growth area of 316,651 ac and other forest land area of 347,035 ac (table 1). We estimate the combined carbon sequestration potential of these two biogeographical provinces (rather than separate eastern versus western Baranof Island).

Table 1—Conifer old-growth types by biogeographic province in the vicinity of Sitka, Alaska

Biogeographic province	Total land area	Productive old growth	Other forest lands	Total forest area
		Hectares		
East Baranof Island	159,904	39,613	40,968	80,582
West Baranof Island	323,258	88,529	99,469	187,998
Total (combined)	483,162	128,142	140,437	268,579

Source: Bschor 2008.

[1] Pg = 1 petagram = 10^{15} grams = 10^{9} tonnes.

Goodale et al (2002) evaluated forest carbon sinks in the northern hemisphere, based on forest inventory information, allometric relationships, and supplementary data sets and models. They estimated that, during the early 1990s, northern forests and woodlands provided a total sink for 0.6 to 0.7 Pg C/year, and this consisted of 0.21 Pg C/year in living biomass, 0.08 Pg C/year in forest products, 0.15 Pg C/year in dead wood, and 0.13 Pg C/year in the forest floor and soil organic matter.

Leighty et al. (2006) modeled carbon fluxes on the Tongass NF under five management scenarios, based on combined geographic information system and Forest Inventory and Analysis (FIA) data, for a 200-year period (from 1995 to 2195). They found that additional sequestration of 0.03 to 0.25 Mg C/ ha/year could be possible under a scenario of no harvesting. Mean carbon density has been estimated for hemlock–Sitka spruce stands in the Pacific Northwest (Smith et al. 2006) (table 2). The mean carbon density of 125-year-old stands is estimated to be close to 900 Mg C/ha (excluding soil organic carbon). For 35-year-old stands, carbon density is about 216 Mg C/ha. This is significant from the standpoint of carbon sequestration on the Tongass NF, because many of the mixed stands of young growth and older stands would lie within these age ranges. Note, however, that this data (Smith et al. 2006) is from stands in Oregon and Washington, not southeast Alaska. Based on this research, we can infer average carbon sequestration (total non-soil) in the Pacific Northwest region ranging between 10.0 Mg C/ha/year (35- to 65-year age class) and 5.5 Mg C/ha/year (95- to 125-year age class).

Table 2—Regional estimates of timber volume and carbon stocks for hemlock-Sitka spruce stands with afforestation of land in the Pacific Northwest, West[a]

		Mean carbon density						
Age (years)	**Mean volume**	**Live tree**	**Standing dead tree**	**Understory**	**Down dead wood**	**Forest floor**	**Soil organic**	**Total non-soil**
	Cubic meters per hectare	*Megagrams of carbon per hectare*						
0	0	0	0	4.7	0	0	87.3	4.7
35	413.7	161.0	16.1	2.7	15.9	20.2	98.5	215.8
65	1 119.3	403.3	39.9	2.2	39.8	31.3	111.0	516.4
95	1 672.1	583.0	50.0	2.9	57.5	39.3	115.6	732.7
125	2 103.3	721.0	56.9	3.6	71.1	45.3	116.3	897.8

[a] Volumes are for high-productivity sites that have growth rates greater than 225 ft^3 wood per acre per year.
Source: Smith et al. 2006.

Kurz and App (1999) developed carbon budget models of Canadian forests. They estimated total carbon content (aboveground and belowground) of softwoods in Pacific coastal forests to be 136.7 Mg C/ha (in 1989). Trofymow et al. (2008) developed retrospective carbon budgets for old-growth forests on Vancouver Island, British Columbia. They found that during periods of active logging and slash burning (1930 to 1945), net biome productivity (NBP) varied dramatically from -3 to -56 Mg C/ha/year. When disturbances were minimal (1960 to 1990), the result was a net carbon sink of 3 to 6 Mg C/ha/year.

Pregitzer and Euskirchen (2004) evaluated forest age in relation to net ecosystem productivity (NEP) for temperate forests. They found that NEP was -1.9, 4.5, 2.4, 1.9, and 1.7 Mg C/ha/year across five age classes spanning 200 years. These findings would indicate greatest NEP on sites having trees in the 11- to 30-year age class, which would be considered young growth for comparable sites on the Tongass NF.

Janisch and Harmon (2002) assessed live and dead carbon stores in forests, and their impact on net ecosystem productivity (NEP). They found that transitions from negative to positive NEP occurred between 0 and 57 years after a disturbance, with shorter times to transition occurring as live-tree growth rates increased. However, total carbon stores were not reached until about 200 years after a disturbance. For all of the scenarios evaluated, NEP ranged from about -14.1 to 3.9 Mg C/ha/year.

Materials and Methods

Estimating Net Ecosystem Productivity for Forests Near Sitka, Alaska

We supplemented the research of Leighty et al. (2006) with other international research conducted on similar forest ecosystems (table 3). Based on these diverse studies of net ecosystem productivity throughout Alaska, Canada, and the Pacific Northwest, we used a relatively low (i.e., conservative) value of +1.0 Mg C/ha/year in our analysis. We recognize that this value might not be appropriate for all age classes of timber on Baranof Island. Further, much of the research on forest carbon relations in southeast Alaska is still in progress and considers elements such as soil carbon, streamflow carbon balances, old growth forest dynamics, and the transition to second growth timber. However we feel that our estimates of NEP are conservative, are in general agreement with the composite results of studies in the Pacific Northwest (table 4), and serve a useful estimator for making inferences regarding carbon-neutrality within Sitka and Baranof Island. In our sensitivity analysis we use average NEP values ranging from 0.25 to 2.00 Mg C/ha/year (carbon sink). We compared this to anthropogenic emission values ranging from 100,000 to 200,000 Mg C/year (carbon source) (table 5).

Table 3—International studies estimating net ecosystem productivity (NEP) of forests

Lead author	Year	Estimated carbon sink[a] Low	High	Location	Forest type
		Mg C/ha/yr			
Dolman et al.	2002	3.38	3.38	Netherlands	Temperate coniferous forest
Krankina et al.	2004	0.34	0.36	Northwest Russia	Live forest biomass
Knohl et al.	2003	4.90	4.94	Central Germany	Unmanaged 250-year-old deciduous forest
Granier et al.	2000	-2.57	4.71	Eastern France	Young beech forest
Liski et al.	2006	3.8	3.8	Finland	Study period 1992 to 2004 (Scots pine, Norway spruce, silver birch)
Bottcher et al.	2008	0.6	0.6	Germany	Projected average sink for 2003 to 2043
Gough et al.	2007	0.53	1.35	North America (Great Lakes)	Stands from 6 to 50 years old, following harvest and fire disturbances
Howard et al.	2004	-1.9	0.4	Saskatchewan, Canada	Jack pine stands ranging from 0 to 79 years old
Law et al.	2001	0.76	2.36	Oregon, USA	Ponderosa pine stands in young- and old-growth forests
Average NEP		1.07	2.35		

Table 4—Pacific Northwest regional studies estimating net ecosystem productivity (NEP) of forests

Lead author	Year	Estimated carbon sink[a] Low	Estimated carbon sink[a] High	Location	Forest type
		Mg C/ha/yr			
Leighty et al.	2006	0.03	0.25	Tongass National Forest, Alaska, USA	Western hemlock, Sitka spruce
Smith et al.	2006	5.5	10.0	Pacific Northwest, USA	Western hemlock, Sitka spruce
Harmon et al.	2004	-1.16	1.56	Washington state, USA	Old-growth Douglas-fir
Waring and McDowell	2002	2.07	2.94	Washington state, USA	Douglas-fir stands (20, 70, and 150 years old)
Jassal et al.	2007	8.43	8.43	Vancouver Island, British Columbia, Canada	Intermediate-aged Douglas-fir (56-year-old stand)
Hudiburg et al.	2009	7.8	7.8	Oregon and northern California, USA	Coast Range forests
Morgenstern et al.	2004	2.70	4.20	West coast of Vancouver Island, British Columbia, Canada	Second-growth Douglas-fir (approximately 50 years old)
Humphreys et al.	2006	2.54	4.24	East coast of Vancouver Island, British Columbia, Canada	Second-growth Douglas-fir (approximately 50 years old)
Amiro et al.	2006	0.21	0.68	Saskatchewan, Canada	Mature black spruce
Amiro et al.	2006	1.39	3.61	Saskatchewan, Canada	Mature aspen
Law et al.	2001	0.76	2.36	Oregon, USA	Ponderosa pine stands in young- and old-growth forests
Barr et al.	2002	0.7	2.7	Central Canada	Deciduous **boreal** forest (northern mid-latitude)
Barr et al.	2002	0.6	2.4	Central Canada	Deciduous **temperate** forest (northern mid-latitude)
Seely et al.	2002	1.2	2.5	Northeastern British Columbia	Boreal mixed forest—10 different rotation scenarios
Luyssaert et al.	2007	3.56	4.40	Temperate forest–humid (evergreen)	Values from a comprehensive global database of forest types
Luyssaert et al.	2007	0.52	2.10	Boreal forest–humid (evergreen)	Values from a comprehensive global database of forest types
Average NEP		2.24	3.68		

[a] Net ecosystem productivity; positive values denote ecosystem uptake of carbon.

Table 5—Sitka, Alaska, carbon emissions versus forest sequestration

Mg of carbon sequestered annually[a]		Mg C emitted annually[b]		
		100,000	150,000	200,000
Per hectare	*Total*			
0.25	67,146	-32,854[c]	-82,854	-132,854
0.50	134,293	+34,293	-15,707	-65,707
1.00	268,585	+168,585	+118,585	+68,585
2.00	537,170	+437,170	+387,170	+337,170
2.24[d]	601,630	+501,630	+451,630	+401,630
3.68[e]	988,393	+888,393	+838,393	+788,393

[a] Based on total forested area of 268,585 ha on Baranof Island in Sitka, Alaska.
[b] Based on expected 147,018 Mg C per year emitted by residents of Sitka, Alaska.
[c] Negative signs represent carbon sources; positive signs represent carbon sinks.
[d] Minimum sequestration (from Pacific Northwest and Canada research).
[e] Maximum sequestration (from Pacific Northwest and Canada research).

Estimating Anthropogenic Carbon Emissions for Sitka, Alaska

Few if any comprehensive estimates are available for anthropogenic emissions for Sitka, Alaska. Therefore we base our analysis on statewide CO_2 emissions in Alaska, then discuss factors that could influence Sitka's emissions. Recent estimates for statewide Alaska CO_2 emissions per capita include 75 Mg/year (Borenstein 2007) and between 38 and 44 Mg/year (US EIA 2014). Given the discrepancy between Sitka and statewide values, we choose to use US EPA data of 61.793 Mg per capita per year, which we then applied to Sitka's population (8,747 residents) (table 6). The resulting estimate of 540,503 Mg of CO_2 per year was used as a base value to estimate all anthropogenic emissions for the City and Borough of Sitka. Separately, the Sitka Climate Action Plan (Putz et al. 2010) estimated that close to 3,728 tons of equivalent CO_2 emissions per year can be attributed to municipal operations. However, this analysis does not include residential use, transportation, or industrial emissions, among other categories.

We followed the approach of Bastianoni et al. (2004) in which a geographic accounting of CO_2 emissions is analyzed for each contributing sector within a given physical boundary. In our simplified analysis we consider emissions from industrial, residential, within-city transportation, and electric sectors balanced against sequestration from area forests. Our analysis does not consider embodied carbon in consumer goods transported to Sitka, or attempt to assign the accumulated emissions during production chains, an approach used by Bastianoni et al. (2004). Nor does our analysis account directly for wood harvested for residential energy (i.e., firewood substituting for fossil fuels) or durable wood products that replace more

Table 6—Estimated Sitka, Alaska, carbon dioxide (CO_2) emissions and carbon equivalent

Source	Statewide CO_2 emissions		Estimated Sitka CO_2 emissions	Estimated Sitka carbon emissions
	Teragrams	*Megagrams per capita*[a]	*Megagrams*	*Megagrams*[b]
Commercial	2.12	3.035	26,547	7,221
Industrial	18.16	26.0	227,422	61,859
Residential	1.85	2.649	23,171	6,303
Transportation	17.76	25.427	222,410	60,496
Electric power	3.27	4.682	40,953	11,139
Total	43.15	61.793	540,503	147,018

[a] Based on Alaska population of 698,473, and a Sitka population of 8,747 (USDC CB 2012)
[b] Assumes that 1 Mg of CO_2 contains 0.272 Mg of carbon.
Source: US EPA (2012).

carbon-intensive materials (i.e., wood structural elements substituting for steel). Sustainably harvested wood substituted for fossil fuels could effectively lower the net carbon emissions in Sitka owing to the renewable nature of wood versus fossil fuels. Because of lack of data, flights taken by residents and arrival transport of visiting tourists are also not accounted for. Tourism is prominent in the Sitka economy, and although the carbon footprint for tourism is incorporated into the average Sitka statistics, air and seafare emissions still represent an important gap, as carbon footprints for arrival often constitute more than 85 percent of the total footprint for tourist stays (Patterson et al 2007).

We used statewide emissions as a proxy for Sitka even though there is a limited road system (and therefore limited driving miles), because no local emissions data were available. Dhittle and Associates (2008) estimate average driving of only 4,380 miles per year, which is expected to be less than residents of Anchorage or Fairbanks (where an extensive road system is present). Another offsetting factor is residential heating—because Sitka is in a mild maritime climate, heating needs would likely be less than for residents of Anchorage or Fairbanks. Sitka residents could contribute more emissions from air travel (versus state-wide averages) because Sitka is located on an island; however, we have no data to support this. When considering the combined factors of automobile driving, residential heating, and air transportation (versus other similarly sized communities in Alaska), we feel that using statewide emissions to represent Sitka will provide a conservative analysis.

Results and Discussion

Carbon Sequestration From Local Forests

Of the 17 regional studies reviewed in western North America, almost all indicated positive values for net ecosystem productivity.

Of the 17 studies reviewed from Alaska, Canada, and the Pacific Northwest (table 4), almost all indicated positive forest NEP values. The average minimum NEP for these studies was about 2.24 Mg C/ha/year, and the average maximum value was about 3.68 Mg C/ha/year. Also noteworthy is that only one study considered forest ecosystems in southeast Alaska, and this study indicated relatively low NEP values, ranging from 0.03 to 0.25 Mg C/ha/year (Leighty et al. 2006). When 11 international studies on forest NEP were considered, the average minimum was about 1.07 Mg C/ha/year, and the average maximum was about 2.35 Mg C/ha/year. Because these studies were conducted over diverse ecosystems using various measurement techniques, we would expect wide-ranging results in carbon fluxes. However, the fact that almost all studies indicated positive NEP values is consistent with broad-scale research estimating that global forests act as carbon sinks, and supports our use of positive NEP values in the evaluation of Sitka. Further, because forests near Sitka are part of a temperate rain forest, they do not experience the wildfire-related carbon losses that can occur in fire-prone ecosystems.

Local Energy Use and Carbon Footprint

This research has found that the City and Borough of Sitka, Alaska, can be considered a carbon sink when weighing its anthropogenic emissions versus expected forest sequestration.

This research has found that the City and Borough of Sitka, Alaska, can be considered a carbon sink when weighing its anthropogenic emissions versus expected forest sequestration. In other words, recent emissions and sequestration have resulted in a net annual addition to carbon stored when including the emissions by the residents of Sitka and also the carbon additions to forest. For Sitka, there are great opportunities to expand the use of hydropower to displace fossil fuels for current residential heating needs and future transportation needs. However, this will require careful management of any new electrical generating capacity (expected within the next 10 years), as well as a community-wide commitment to energy conservation. For example, plans are underway for construction to increase the dam height at the Blue Lake hydroelectric facility—a move that would increase generating capacity to 18 MW, and should increase Sitka's overall generating capacity by about 27 percent (CBS 2011). Once this expansion is completed, any "new" electricity could in theory be used to power electric vehicles. However, many have expressed concern that by the time the dam improvements are completed, any excess will be quickly used to meet growing baseline demand.

Therefore, a pathway for Sitka's CO_2 emission reduction needs to be considered holistically, where all energy sources and uses are considered. One such approach is to consider a group of stabilization wedges, where each wedge corresponds to a different area of reduction (Pacala and Socolow 2004). Proposed wedges for Sitka are all designed to reduce fossil fuel consumption, and could include residential energy conservation, increased use of wood energy for home heating, increased use of alternative fuel vehicles (such as electric cars), and increased use of electricity for home heating.

Sitka's limited road system and already high use of renewable hydropower make it ideally suited for low emissions from transportation. New vehicle technologies are likely within the next decade, including improvements to hybrid vehicles and commercialization of electric vehicles. Substantial reductions in Sitka's fossil fuel use could hinge on development of key new technologies, including electric vehicles with a driving range of at least 20 miles (the approximate length of Sitka's road system). Electric vehicles are already starting to be used in Sitka, with an estimated six vehicles already in use. In Petersburg, Alaska, a community of about 3,100 residents, at least eight low-speed electric vehicles have been shipped (Viechnicki 2008). Sitka, Petersburg, and other communities in southeast Alaska that have limited road systems and relatively low driving speeds could be early adopters of electric cars for neighborhood use at relatively low speeds. As new technologies are developed (particularly more efficient batteries), enabling greater driving ranges, communities with more extensive road systems could potentially benefit from electric vehicles. The limited road system in Sitka means not only fewer personal miles driven but also shorter distances for delivering goods and providing services to residents.

Woody biomass supplies and deliveries to Sitka are likely to increase new opportunities for residential heating with wood energy as well as larger bioenergy heating projects. Bioenergy products could include wood chips, firewood, or compressed fuel. This array of products would be influenced by the scale of individual bioenergy projects as well as the aggregate demand from all bioenergy users in Sitka.

Biomass energy could play an integral role in Sitka's energy planning.

Biomass energy could play an integral role in Sitka's energy planning, for both residential and "small-industrial" systems. A general increase in the use of firewood for residential heating has been observed, with users in southeast Alaska burning close to 3.6 cords per heating season (Nicholls et al. 2010). Other potential wood energy users include the Coast Guard base in Sitka for development of wood pellet systems. A limited amount of biomass harvesting has occurred near Sitka, with close to 18 cords being removed from the Starrigavan area in 2008 (Nicholls et al. 2010), supplying several small firewood dealers in Sitka. Increased use of biomass in Sitka, whether for residential or small-industrial users, will likely require some degree of behavioral change among energy consumers as well as successful demonstrations to aid in technology diffusion.

Even if the residential and personal transportation sectors were to become nearly carbon neutral, significant challenges could remain for industrial energy use, marine use, and air transportation.

Even if the residential and personal transportation sectors were to become nearly carbon neutral over the next 10 years, significant challenges could remain when considering industrial energy uses, marine transportation, and air transportation (all of which consume significant amounts of fossil fuels). However, Sitka's island economy and ecosystems could provide important insights into characteristics of community carbon footprints that could potentially be extended to other locations. Sitka's example of building capacity to respond to environmental limitations within its island community underscores that importance of local-scale decisionmaking and how this can translate into much broader scales. Perhaps the greatest element influencing Sitka's carbon footprint is the volatile price of fossil fuels and people's willingness to switch to less expensive heating sources (for example, electric heating or wood) during market fluctuations. Fossil fuel prices also can strongly influence the shipment of consumer goods to Sitka, because very few products are produced locally.

Conclusions

The carbon management implications of forests in southeast Alaska are potentially far-reaching. The Tongass NF is entering into a transition phase in which young-growth timber, regenerated following harvests during the pulp mill era, is beginning to reach merchantable size. How this resource is used for timber, wildlife values, recreation, and other ecosystem services will directly influence carbon sequestration rates. The value of carbon on international markets, although far broader in scope than the southeast Alaska forest base, could have an impact on regional timber management practices and the relative importance of carbon sequestration as an ecosystem service.

Quantified expressions of individual and community reliance on environment may support substantive community discussions, and active planning for change and resilience (Wackernagel et al 2002). Interest and concern are often expressed by Sitka residents on interrelated topics such as climate change, energy planning, and economic development (City of Sitka 2011). However, conceptual linkages between these topics may be difficult to tie to action, especially when issues of scale are involved—such as the role of the individual or small rural community in the growth of global greenhouse gas emissions. This underscores the need for future research in which communities and individuals gain a better understanding of their dependence on the ecosystems of which they are a part. Although reductions in annual carbon emissions and increased sequestration from the Sitka area result in a net annual addition to carbon stored, we need further study and quantification to help motivate additional achievements.

Literature Cited

Alaska Division of Motor Vehicles [Alaska DMV]. 2007. Currently registered vehicles. http://www.state.ak.us/dmv/research/curreg07.htm. (20 October 2014).

Amiro, B.D.; Barr, A.G.; Black, T.A.; Iwashita, H.; Kljun, N.; McCaughey, J.H.; Morgenstern, K.; Murayama, S.; Nesic, Z.; Orchansky, A.L.; Saigusa, N. 2006. Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. Agricultural and Forest Meteorology. 136: 237–251.

Bagliani, M.; Da Villa, E.; Gattolin, M.; Niccolucci, V.; Patterson, T.; Tiezzi, E. 2004. The ecological footprint analysis for the Province of Venice and the relevance of tourism. In: Marchettini, N.; Brebbia, C.A.; Tiezzi E.; Wadhwa, L.C., eds. The Sustainable City III. Southampton, United Kingdom: WIT Press: 123–132.

Barr, A.G.; Griffis, T.J.; Black, T.A.; Lee, X.; Staebler, R.M.; Fuentes, J.D.; Chen, Z.; Morgenstern, K. 2002. Comparing the carbon budgets of boreal and temperate deciduous forest stands. Canadian Journal of Forest Research. 32: 813–822.

Barthelmie, R.J.; Morris, S.D.; Schechter, P. 2008. Carbon neutral Biggar: calculating the community carbon footprint and renewable energy options for footprint reduction. Sustainability Science. 3: 267–282.

Bastianoni, S.; Pulselli, F.M.; Tiezzi, E. 2004. The problem of assigning responsibility for greenhouse gas emissions. Ecological Economics. (49): 253–257.

Birdsey, R.A. 2006. Carbon accounting rules and guidelines for the United States forest sector. Journal of Environmental Quality. (35): 1518–1524.

Borenstein, S. 2007. Texas, Wyoming lead in emissions. USA Today. http://www.usatoday.com/weather/climate/globalwarming/2007-06-02-emissions_N.htm. (12 October 2011).

Bottcher, H.; Freibauer, A.; Obersteiner, M.; Schulze, E.-D. 2008. Uncertainty analysis of climate change mitigation options in the forestry sector using a generic carbon budget model. Ecological Modelling. 213: 45–62.

Bschor, D.E. 2008. Tongass Land Management Plan Amendment: Final Environmental Impact Statement. Juneau, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. Chapter 3.

City and Borough of Sitka [CBS]. 2011. Electric Department. http://cityofsitka.com/government/departments/electric/index.html. (20 October 2014).

Dhittle and Associates, Inc. 2008. City and Borough of Sitka 2008 electric system load forecast. Final report. 34 p. http://www.cityofsitka.com/government/departments/electric/documents/LoadForecastRpt2008-Final.pdf. (20 October 2014).

Dolman, A.J.; Moors, E.J.; Elbers, J.A. 2002. The carbon uptake of a mid latitude pine forest growing on sandy soil. Agricultural and Forest Meteorology 111: 157–170.

Dixon, R.K.; Brown, S.; Houghton, R.A.; Solomon, A.M.; Trexler, M.C.; Wisniewski, J. 1994. Carbon pools and flux of global forest ecosystems. Science. (263): 185–190.

Erb, K-H. 2004. Actual land demand of Austria 1926–2000: a variation on ecological footprint assessments. Land Use Policy. 21(3): 247–259.

Frolking, S.; N.T. Roulet, N.T.; Moore, T.R.; Lafleur, P.M.; Bubier, J.L.; Crill, P.M. 2002. Modeling seasonal to annual carbon balance of Mer Bleue Bog, Ontario, Canada. Global Biogeochemical Cycles. 16(3): 21 p.

Garcia-Gonzalo, J.; Peltola, H.; Gerendiain, A.Z.; Kellomaki, S. 2007. Impacts of forest landscape structure and management on timber production and carbon stocks in the boreal forest ecosystem under changing climate. Forest Ecology and Management. (241): 243–257.

Global Footprint Network [GFN]. 2009. Ecological footprint standards 2009. Oakland, CA: 20 p. http://www.footprintstandards.org. (15 September 2012).

Goodale, C.L.; Apps, M.J.; Birdsey, R.A.; Field, C.B.; Heath, L.S.; Houghton, R.A.; Jenkins, J.C.; Kohlmaier, G.H.; Kurz, W.; Liu, S.; Nabuurs, G.-J.; Nilsson, S.; Shvidenko, A.Z. 2002. Forest carbon sinks in the Northern Hemisphere. Ecological Applications. 12(3): 891–899.

Gorham, E. 1995. The biogeochemistry of northern peatlands and its possible responses to global warming. In: Woodwell, G.M.; Mackenzie, F.T., eds. Biotic feedbacks in the global climatic system). Oxford, United Kingdom: Oxford University Press: 169–187.

Gough, C.M.; Vogel, C.S.; Harrold, K.H.; George, K.; Curtis, P.S. 2007. The legacy of harvest and fire on ecosystem carbon storage in a north temperate forest. Global Change Biology. 13: 1935–1949.

Granier, A.; Ceschia, E.; Damesin, C.; Dufrêne, E.; Epron, D.; Gross. P.; Lebaube, S.; Le Dantec, V.; Le Goff, N.; Lemoine, D.; Lucot, E.; J. M. Ottorini; J. Y. Pontailler; B. Saugier. 2000. The carbon balance of a young beech forest. Functional Ecology. 14: 312–325.

Harmon, M.E.; Ferrell, W.K.; Franklin, J.F. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science. 247(4943): 699–702.

Hartshorn, A.S.; Southard, R.J.; Bledsoe, C.S. 2003. Structure and function of peatland-forest ecotones in southeastern Alaska. Soil Science Society of America Journal. 67: 1572–1581.

Howard, E.A.; Gower, S.T.; Foley, J.A.; Kucharik, C.J. 2004. Effects of logging on carbon dynamics of a jack pine forest in Saskatchewan, Canada. Global Change Biology. 10: 1267–1284.

Hudiburg, T.; Law, B.; Turner, D.P.; Campbell, J.; Donato, D.; Duane, M. 2009. Carbon dynamics of Oregon and Northern California forests and potential land-based carbon storage. Ecological Applications. 19(1): 163–180.

Humphreys, E.R.; Black, T.A.; Morgenstern, K.; Cai, T.; Drewitt, G.B.; Nesic, Z.; Trofymow, J.A. 2006. Carbon dioxide fluxes in coastal Douglas-fir stands at different stages of development after clearcut harvesting. Agricultural and Forest Meteorology. 140: 6–22.

Janisch, J.E.; Harmon, M.E. 2002. Successional changes in live and dead wood carbon stores: implication for net ecosystem productivity. Tree Physiology. 22(2–3): 77–89.

Janssens, I.A.; Freibauer, A.; Ciais, P.; Smith, P.; Nabuurs, G.-J.; Folberth, G.; Schlamadinger, B.; Hutjes, R.W.A.; Ceulemans, R.; Schulze, E.-D.; Valentini, R.; Dolman, A.J. 2003. Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic CO_2 emissions. Science. 300(5625): 1538–1542.

Jassal , R.S.; Black, T.A.; Cai, T.; Morgenstern, K.; Li, Z.; Gaumont-Guay, D.; Nesic, Z. 2007. Components of ecosystem respiration and an estimate of net primary productivity of an intermediate-aged Douglas-fir stand. Agricultural and Forest Meteorology. 144: 44–57.

Kenny, T.; Gray, N.F. 2009. Comparative performance of six carbon footprint models for use in Ireland. Environmental Impact Assessment Review. (29): 1–6.

Kitzes, J.; Galli, A.; Bagliani, M.; Barrett, J.; Dige, G.; Ede**, S.; Erb, K.; Giljum, S.; Haber, H.; Hails, C.; Jolia-Ferrier; L.; Jungwirth, S.; Lenzen, M.; Lewis, K.; Loh, J.; Marchettin, N.; Messinger; H.;** Milne**, K.; Moles, R.; Monfreda, C.; Moran. D.; Nakano, K.; Pyhälä, A.; Rees, W.; Simmons, C.; Wackernagel, M.; Wada, Y.; Walsh, C.; Wiedmann, T. 2009.** A research agenda for improving national ecological footprint accounts. Ecological Economics. 68(7): 1991–2007.

Kitzes, J.; Peller, A.; Goldfinger, S.; Wackernagel, M. 2007. Current methods for calculating national ecological footprint accounts. Science for Environment and Sustainable Society. 4(1): 1–9.

Knohl, A.; Schulze, E.-D.; Kolle, O.; Buchmann, N. 2003. Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. Agricultural and Forest Meteorology. 118: 151–167.

Krankina, O.N.; Harmon, M.E.; Cohen, W.B.; Oetter, D.R.; Zyrina, O.; Duane, M.V. 2004. Carbon stores, sinks, and sources in forests of northwestern Russia: Can we reconcile forest inventories with remote sensing results? Climatic Change. 67: 257–272.

Kurz, W.A.; Apps, M.J. 1999. A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecological Applications. 9(2): 526–547.

Lafleur, P.M.; Roulet, N.T.; Admiral, S.W. 2001. Annual cycle of CO_2 exchange at a bog peatland. Journal of Geophysical Research. 106: 3071–3081.

Law, B.E.; Thornton, P.E.; Irvine, J.; Anthoni, P.M.; Vantuyl, S. 2001. Carbon storage and fluxes in ponderosa pine forests at different developmental stages. Global Change Biology. 7: 755–777.

Leighty, W.W.; Hamburg, S.P.; Caouette, J. 2006. Effects of management on carbon sequestration in forest biomass in southeast Alaska. Ecosystems. 9: 1051–1065.

Lenzen, M.; Murray, S.A. 2001. A modified ecological footprint method and its application to Australia. Ecological Economics. 37: 229–255.

Lippke, B.; Oneil, E.; Harrison, R.; Skog, K.; Gustavsson, L.; Sathre, R. 2011. Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. Carbon Management. 2(3): 303–333.

Liski, J.; Pussinen, A.; Pingoud, K.; Makipaa, R.; Karjalainen, T. 2001. Which rotation length is favourable to carbon sequestration? Canadian Journal of Forest Research. 31(11).

Liski, J.; Lehtonen, A.; Palosuo, T.; Peltoniemi, M.; Eggers, T.; Muukkonen, P.; Mäkipää, R. 2006. Carbon accumulation in Finland's forests 1922–2004—an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil. Annals of Forest Science. 63: 687–697.

Luyssaert, S.; Inglima, I.; Jung, M. et al. [64 authors]. 2007. CO_2 balance of boreal, temperate, and tropical forests derived from a global database. Global Change Biology. 13: 2509–2537.

Manomet Center for Conservation Sciences. 2010. Massachusetts biomass sustainability and carbon policy study: report to the Commonwealth of Massachusetts Department of Energy Resources. Natural Capital Initiative Report NCI-2010-03. Brunswick, ME. 182 p. http://www.mass.gov/eea/docs/doer/renewables/biomass/manomet-biomass-report-full-lorez.pdf. (20 October 2014).

Marland, G.; Marland, S. 1992. Should we store carbon in trees? Water, Air, and Soil Pollution. (64): 181–195.

Meng, F-R.; Bourque, C.P.-A.; Oldford, S.P.; Swift, D.E.; Smith, H.C. 2003. Combining carbon sequestration objectives with timber management planning. Mitigation and Adaptation Strategies for Global Change. (8): 371–403.

Morgenstern, K.; Black, T.A.; Humphreys, E.R.; Griffis, T.J.; Drewitt, G.B.; Cai, T.; Nesic, Z.; Spittlehouse, D.L.; Livingston, N.J. 2004. Sensitivity and uncertainty of the carbon balance of a Pacific Northwest Douglas-fir forest during an El Niño/La Niña cycle. Agricultural and Forest Meteorology. 123: 201–219.

Moulton, R.J.; Richards, K.R. 1990. Costs of sequestering carbon through tree planting and forest management in the United States. Gen. Tech. Rep. GTR-WO-58. Washington, DC: U.S. Department of Agriculture, Forest Service. 47 p.

Nabuurs, G.J.; Paivinen, R.; Sikkema, R.; Mohren, G.M.J. 1997. The role of European forests in the global carbon cycle—a review. Biomass and Bioenergy. 13(6): 345–358.

Nabuurs, G.J.; Mohren, F.; Dolman, H. 2000. Monitoring and reporting carbon stocks and fluxes in Dutch forests. Biotechnology, Agronomy, Society and Environment. 4(4): 308–310.

Nicholls, D.L.; Brackley, A.M.; Barber, V. 2010. Wood energy for residential heating in Alaska: current conditions, attitudes, and expected use. Gen. Tech. Rep. PNW-GTR-826. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 36 p.

Pacala, S.; Socolow, R. 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science. 305(5686): 968–972.

Patterson, T.M.; Coelho, D.I. 2009. Ecosystem services: foundations, opportunities, and challenges for the forest products sector. Forest Ecology and Management. 257: 1637–1646.

Patterson, T.M.; Niccolucci, V.; Bastianoni, S. 2007. Beyond "more is better": Ecological footprint accounting for tourism and consumption in Val di Merse, Italy. International Journal of Ecological Economics. 62: 747–756.

Pregitzer, K.S.; Euskirchen, E.S. 2004. Carbon cycling and storage in world forests: biome patterns related to forest age. Global Change Biology. 10: 2052–2077.

Putz, M.; Olson, P.; Nicholls, D.; Maclane, K.; Neel, D.; Bradley, K.; Campbell, N.; Ozment, J.; Agne, J. 2010. City and Borough of Sitka climate action plan. 70 p. http://www.cityofsitka.com/government/clerk/boards/info/climate/documents/SitkaClimateActionPlan6-11-10.pdf. (20 October 2014).

Randerson, J.T.; Chapin, F.S.; Harden, J.W.; Neff, J.C.; Harmon, M.E. 2002. Net ecosystem production: a comprehensive measure of net carbon accumulation by ecosystems. Ecological Applications. 12(4): 937–947.

Rockström, J.; Steffen, W.; Noone, K.; Persson, A.; Chapin, F.S.; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; Nykvist, B.; de Wit, C.A.; Hughes, T.; van der Leeuw, S.; Rodhe, H.; Sörlin, S.; Snyder, P.K.; Costanza, R.; Svedin, U.; Falkenmark, M.; Karlberg, L.; Corell, R.W.; Fabry, V.J.; Hansen, J.; Walker, B.; Liverman, D.; Richardson, K.; Crutzen, P.; Foley, J.A. 2009. A safe operating space for humanity. Nature. 461: 472–475.

Saah, D.; Patterson, T.; Albert, D.; Rush, K. 2014. Modeling economic and carbon consequences of a shift to wood-based energy in a rural 'cluster'; a network analysis in southeast Alaska. Ecological Economics. 107: 287–298.

Seely, B.; Welham, C.; Kimmins, H. 2002. Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. Forest Ecology and Management. 169: 123–135.

Seidl, R.; Rammer, W.; Jager, D.; Currie, W.S.; Lexer, M.J. 2007. Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. Forest Ecology and Management. 248: 64–79.

Smith, J.E.; Heath, L.S.; Skog, K.E.; Birdsey, R.A. 2006. Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. NE-343. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 222 p.

Smith, N.; Deal, R.; Kline, J.D.; Patterson, T.; Spies, T.; Blahna, D. 2011. Using ecosystem services as a framework for forest stewardship: executive summary. Gen. Tech. Rep. PNW GTR-852. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 46 p.

Trofymow, J.A.; Stinson, G.; Kurz, W.A. 2008. Derivation of a spatially explicit 86-year retrospective carbon budget for a landscape undergoing conversion from old-growth to managed forests on Vancouver Island, BC. Forest Ecology and Management. 256: 1677–1691.

U.S. Department of Energy, Energy Information Administration [US EIA]. 2014. State-level energy-related carbon dioxide emissions, 2000–2011. 21 p. http://www.eia.gov/environment/emissions/state/analysis/pdf/stateanalysis.pdf. (2 March 2015).

U.S. Environmental Protection Agency [US EPA]. 2012. Greenhouse gas emissions program. http://www.epa.gov/climatechange/emissions/state_energyco2inv.html. (5 March 2013).

U.S. Department of Commerce, Census Bureau [USDC CB]. 2012. State and county quick facts, Sitka City and Borough, Alaska. http://quickfacts.census.gov/qfd/states/02/02220.html. (5 March 2013).

Valentini, R.; Matteucci, G.; Dolman, A.J.; Schulze, E.-D.; Rebmann, C.; Moors, E.J.;. Granier, A.; Gross, P.; Jensen, N.O.; Pilegaard, K.; Lindroth, A.; Grelle, A.; Bernhofer, C.; Grünwald, T.; Aubinet, M.; Ceulemans, R.; Kowalski, A.S.; Vesala, T.; Rannik, U.; Berbigier, P.; Loustau, D.; Gudmundsson, J.; Thorgeirsson, H.; Ibrom, A.; Morgenstern, K.; Clement, R.; Moncrieff, J.; Montagnani, L.; Minerbi, S.; Jarvis, P.G. 2000. Respiration as the main determinant of carbon balance in European forests. Nature. 404: 861–865.

Van Kooten, G.C.; Bulte, E.H. 1999. How much primary coastal temperate rain forest should society retain? Carbon uptake, recreation, and other values. Canadian Journal of Forest Research. 29(12): 1879–1890. doi:10.1139/x99-173.

Viechnicki, J. 2008. Low-speed electric cars come to Petersburg. KFSK radio. http://www.kfsk.org/2008/06/11/low-speed-electric-cars-come-to-petersburg/. (20 October 2014).

Wackernagel, M.; Schulz, N.B.; Deumling, D.; Linares, A.C.; Jenkins, M.; Kapos, V.; Monfreda, C.; Loh, J. 2002. Tracking the ecological overshoot of the human economy. Proceedings of the National Academy of Sciences of the United States of America. 99(14): 9266–9271.

Wackernagel, M.; Onisto, L.; Bello, P.; Linares, A.C.; Falfan, I.S.L.; Garcia, J.; Guerrero, A.I.S.; Guerrero, C.S. 1999. National natural capital accounting with the ecological footprint concept. Ecological Economics. 29(3): 375–390.

Wackernagel, M.; Rees, W. 1996. Our ecological footprint: reducing human impact on the Earth. Gabriola Island, BC: New Society Publishers. 160 p.

Waring, R.H.; McDowell, N. 2002. Use of a physiological process model with forestry yield tables to set limits on annual carbon balances. Tree Physiology. 22: 179–188.

Wiedmann T.; Minx, J. 2007. A definition of "carbon footprint." Research Report 07-01. Durham, United Kingdom: ISA*UK* Research & Consulting. 11 p.

Pacific Northwest Research Station

Web site	http://www.fs.fed.us/pnw/
Telephone	(503) 808–2592
Publication requests	(503) 808–2138
FAX	(503) 808–2130
E-mail	pnw_pnwpubs@fs.fed.us
Mailing address	Publications Distribution Pacific Northwest Research Station P.O. Box 3890 Portland, OR 97208–3890

U.S. Department of Agriculture
Pacific Northwest Research Station
1220 SW 3rd Ave., suite 1400
P.O. Box 3890
Portland, OR 97208–3890

Official Business
Penalty for Private Use, $300