Chapter 4. Watershed Carbon Budgets in the Southeastern Alaskan Coastal Forest Region

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4.1. Highlights

- The perhumid coastal temperate rainforest (PCTR) of the North Pacific coast has some of the densest terrestrial carbon stocks in the world. Net carbon balance in this region has a distinct lateral loss vector through both dissolved organic and inorganic carbon.
- Estimates of net ecosystem carbon balance averaged 142 grams of carbon per square meter per year (gC/m^2/yr) and ranged from 117 to 177 gC/m^2/yr among three watersheds in the region, illustrating the net terrestrial carbon gain in coastal forests. These estimates are consistent with carbon gains associated with mature temperate forests worldwide and illustrate the potential for carbon sequestration across a range of landscape types in the PCTR.

4.2. Introduction

Forests worldwide provide a substantial carbon sink of approximately 1.1 ± 0.8 petagrams of carbon per year (PgC/yr) (Pan and others, 2011). The northeast Pacific coastal margin has extensive and densely forested stands across the coastal temperate rainforest biome. The perhumid subregion (PCTR) of this biome includes the coastal forests of southeast Alaska (fig. 4.1). In addition to the extensive forests in the PCTR, sparsely forested and nonforested peatlands with deep (~3–5 meter [m]) organic soils are abundant. The spatial heterogeneity of ecosystems across the PCTR and the variability in the carbon pools associated with these ecosystems creates complex conditions for estimating carbon balance. To develop carbon balance models across the diverse PCTR region, spatially explicit estimates of carbon flux are needed for scaling plot measurements across the varying terrain and ecosystem types (Schimel, 1995).

The PCTR of southeast Alaska has functioned as a carbon sink during the postglacial Holocene as this region is cold and wet and does not have a fire regime. There is little urban development in the region, and the primary sources of disturbance are small-scale wind disturbances leading to gap-phase-type forest structures, and forest harvest, which has been limited to a relatively small portion of the landscape. Mean carbon densities in the region exceed 30 kilograms of carbon per square meter (kgC/m^2) (Heath and others, 2011). About 66 percent of this carbon is belowground, where carbon densities in wetlands are as high as 50 to 90 kgC/m^2 (Leighty and others, 2006). Carbon stocks in the soils and forests of the Tongass National Forest have been estimated to contain 2.8 ± 0.5 petagrams of carbon (PgC) (Leighty and others, 2006). The consideration of the exchange of carbon in both the dense belowground stock and the aboveground biomass pool is essential to accurately estimate carbon balance. In addition, the belowground stock in the PCTR is unfrozen, and the aboveground stock is not subject to fire, making the stability of carbon stocks in the PCTR an important feature of carbon accounting for North America.

Our approach in this chapter is to compare the common carbon balance model used to calculate net ecosystem production (NEP) with the calculation of net ecosystem carbon balance (NECB; Chapin and others, 2006). In areas where major disturbances (such as fire and forest harvest) are absent, as in much of the Alaska PCTR, it has been argued that NEP can be used interchangeably with NECB (Turner and others, 2011). Unlike NECB, however, the NEP model does not account for lateral exports of dissolved carbon in the carbon balance. Dissolved carbon, both in organic and inorganic forms, constitutes a major export vector from both forested and nonforested systems in the PCTR (D'Amore and others, 2015). Using ground-based measurements, we can construct estimates of NECB to compare with NEP estimates to illustrate the importance of accounting for dissolved carbon fluxes in carbon balance models for the Alaska PCTR.

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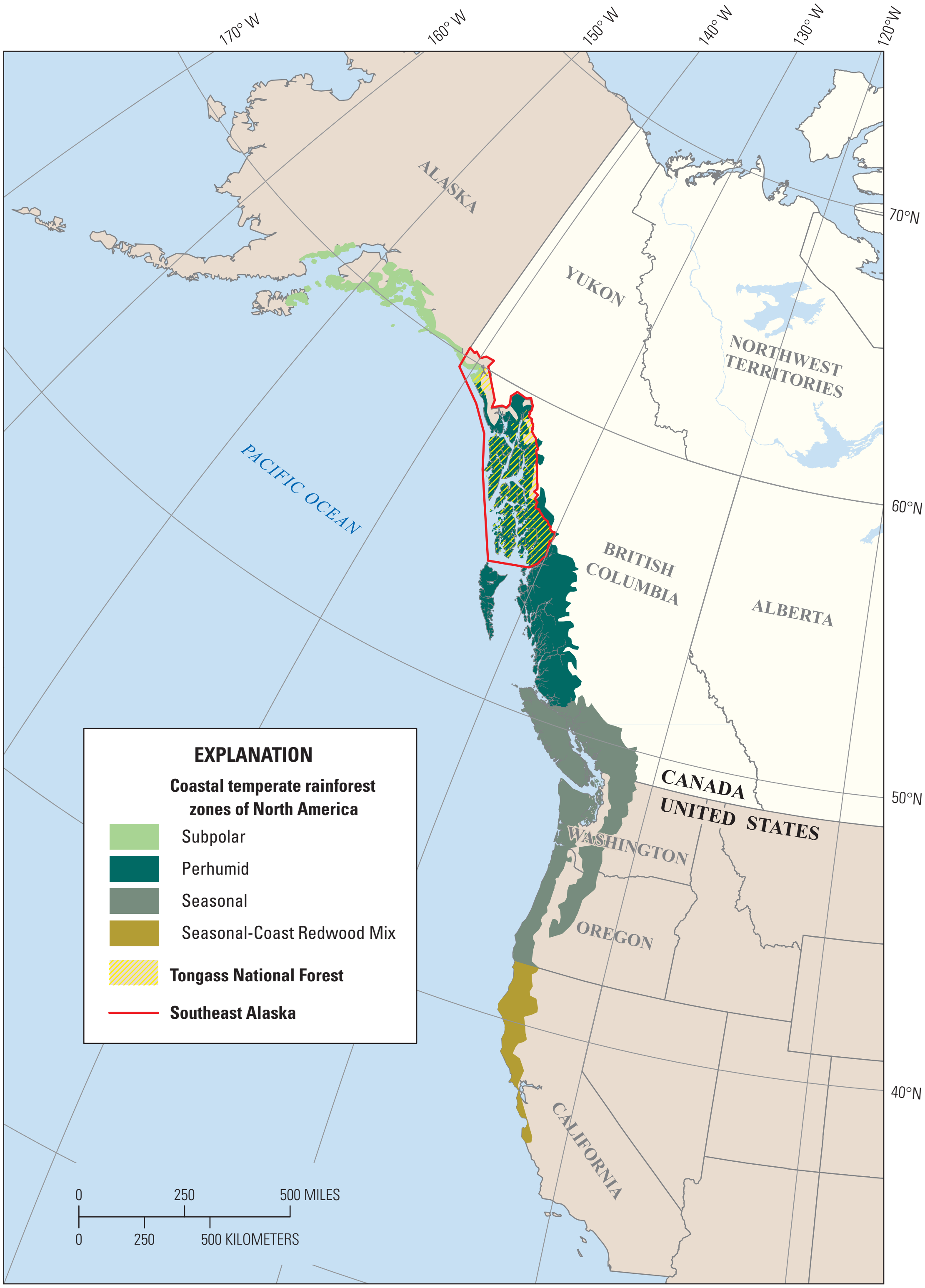


Figure 4.1. North American Pacific coastal temperate rainforest extent. The "panhandle" or southeast Alaska region is noted along with the Tongass National Forest. Adapted from Wolf and others (1995).

The varying distribution of abundant water across the Alaska PCTR creates a mosaic of ecosystem types ranging from well-drained, densely forested uplands to forested wetlands and nonforested peatlands (Neiland, 1971). To measure carbon flows and evaluate terrestrial-aquatic linkages associated with these three ecosystem types, we created a sampling scheme based on a hydropedologic framework (D'Amore and others, 2012). Measurements taken across this framework can then be generalized across the overall landscape. The field measurements can also be used to calibrate carbon budget estimates based on remote sensing or process-based models. The carbon cycle science research program in the Alaska PCTR developed by the U.S. Department of Agriculture Forest Service Pacific Northwest Research Station (PNW) has established a series of plots distributed across component landscape units in three watersheds to estimate major carbon fluxes (fig. 4.2). Data collected from these plots along with remotely sensed estimates of net primary productivity (NPP) were used to determine the NECB for the three PCTR watersheds.

This assessment is primarily a landscape analysis for use in national and regional reporting and evaluations. The process-based Dynamic Organic Soil version of the Terrestrial Ecosystem Model (DOS-TEM) was the main tool used for deriving carbon stock and flux in all regions of Alaska for the assessment. Measurements from the PNW plots were used to calibrate DOS-TEM for the coastal forests region (chapters 6 and 7). In this chapter, we present an alternate approach to estimating carbon stock and flux for coastal forests using the plot-based measurements combined with values of NPP from remote sensing.

4.3. Input Data and Methods

4.3.1. Site Descriptions

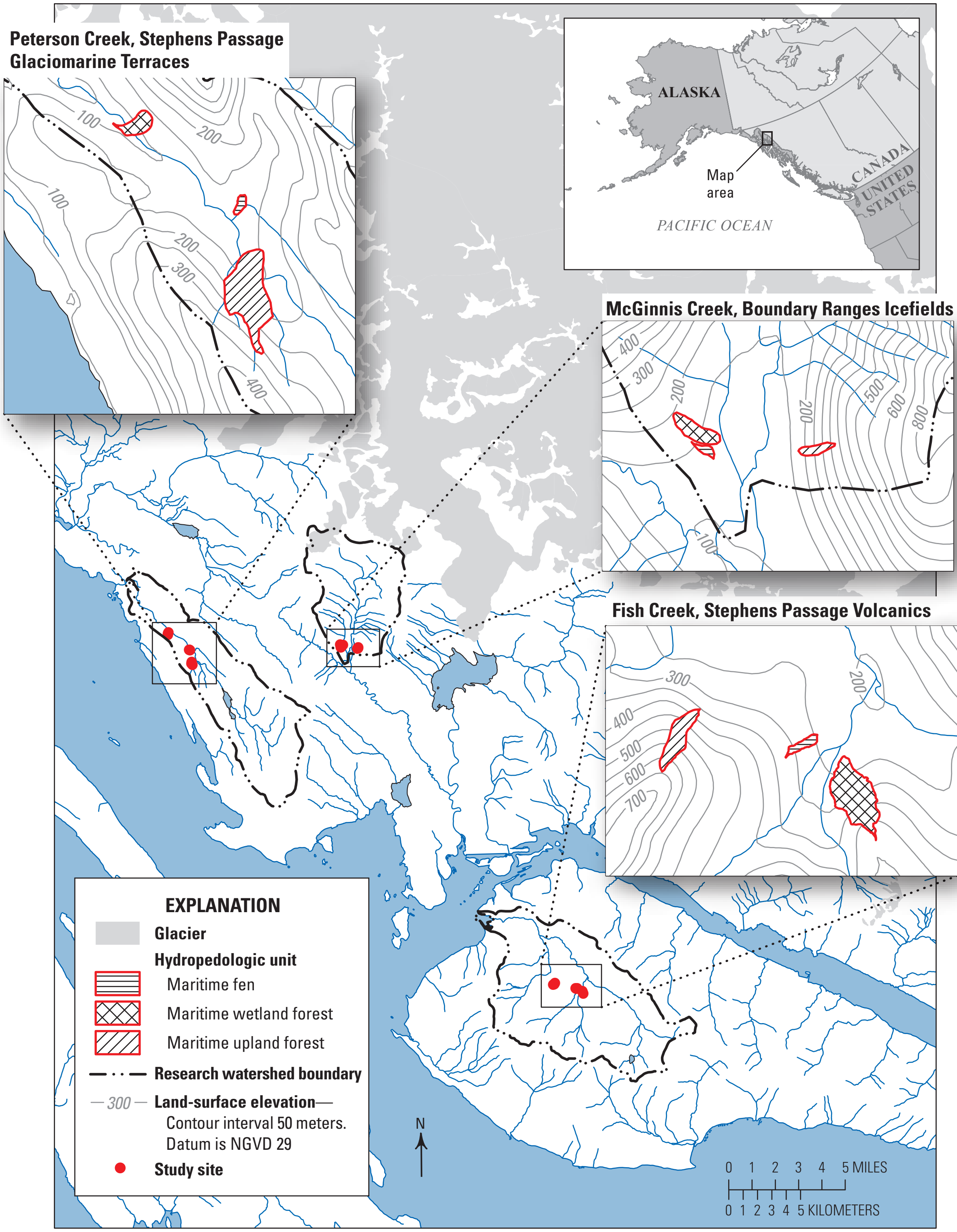
The research was conducted within three watersheds in the Alaska PCTR. The watersheds are located in Juneau, Alaska, with mean annual precipitation of 1,580 millimeters (mm) and mean annual average temperatures ranging from 2 to 9 degrees Celsius (°C). We chose watersheds in three different ecological subsections that represent three distinct landscapes characterized by different lithology and dominant forms of landscape evolution (Nowacki and others, 2001; fig. 4.2). Peterson Creek watershed is a wetland-dominated watershed (53 percent of watershed area) in the Stephens Passage Glaciomarine Terraces ecological subsection that is composed primarily of slowly permeable glaciomarine sediments (Miller, 1973) along with bedrock outcrops that occur on moderate to low slopes. Disturbance in the Peterson Creek watershed is limited to hiking trails in addition to a small area (~4 kilometers [km]) with roads and light rural-residential development near the watershed outlet. In contrast, the McGinnis Creek watershed is composed primarily of recently deglaciated areas within the Boundary Ranges Icefields ecological subsection and has low wetland coverage (less than 5 percent of watershed area). Hiking trails are the only type of anthropogenic disturbance present in the McGinnis Creek watershed. Fish Creek watershed consists of intrusive volcanic and sedimentary rocks in the Stephens Passage Volcanics ecological subsection and has a mix of physiographic features that include alpine, productive temperate rainforest, and wetlands. The Fish Creek watershed contains hiking trails, a road, and a small (~0.01 square kilometer [km^2]) rock pit, but these features cover only a minor portion of the watershed. In addition, a ski area occupies part of the upper Fish Creek watershed, but this area is not included in the final carbon budget estimates owing to the lack of soil map data for the upper watershed (see section 4.3.8).

Within each of the three watersheds we identified three sub-catchments representing discrete hydropedologic units that characterize key ecosystem processes occurring within the vegetated portion of the PCTR landscape: maritime fen, maritime wetland forest, and maritime upland forest (D'Amore and others, 2012; fig. 4.2). A hydropedologic unit (HPU) is "a grouping of variations in soil morphology that directly relate influence of water table regime, flow paths, and soil saturation to soil development" (Gannon and others, 2014). The forms of the HPUs influence soil function including biogeochemistry, runoff production, and vegetation diversity and structure, which all, in turn, affect carbon cycling.

Each HPU type (maritime fen, maritime wetland forest, and maritime upland forest) represents an experimental unit, replicated in each watershed for a total of nine sites in the experimental design (fig. 4.2). Freshwater discharge, dissolved carbon, and soil respiration measurements were collected at the nine sub-catchments at various times from 2006 through 2009.

4.3.2. Soil Respiration Rates

Soil respiration measurements were taken every 2 to 4 weeks during the spring, summer, and fall over a 4-year (yr) period from 2006 through 2009. Measurements were taken on collars constructed of 21-centimeter (cm)-inside-diameter PVC pipe that were permanently installed at the ground surface. The soil respiration collars were deployed in three seven-collar clusters arranged in a 2-m spacing pattern within each HPU for a total of 21 collars per HPU per watershed. Each HPU sampled had a total of 63 collars. Respiration data were collected within 1 to 2 days over the entire study area, for a total of 189 possible measurements at each temporal sampling. All soil respiration measurements were accompanied by a soil temperature measurement (at 10-cm depth) at each collar. Soil respiration measurements were achieved using a dynamic-closed chamber procedure without drawdown



Contours generated from the USGS 2-arc-second National Elevation Dataset, 2008, from seamless.usgs.gov (replaced by The National Map)
Watershed boundaries modified from USDA-NRCS, USGS, and EPA 12-Digit Watershed Boundary Data, 2012
Water features from USDA Forest Service, Tongass National Forest, 2012
Glaciers from Randolph Glacier Inventory, version 5.0

Figure 4.2. Locations of the study sites for three component hydropedologic units (maritime fen, maritime wetland forest, and maritime upland forest) within three watersheds (Peterson Creek, McGinnis Creek, and Fish Creek) on different ecological subsections (Stephens Passage Glaciomarine Terraces, Boundary Ranges Icefields, and Stephens Passage Volcanics) near Juneau, Alaska.

(Nay and others, 1994). The collars were designed to receive a portable closed-chamber field respirometer that used a LiCor 820 infrared gas analyzer (LiCor Inc., Lincoln, Nebr.). We measured soil respiration on coarse woody debris in contact with the soil. Decomposition of aboveground (or aerial) coarse woody debris (that is, snags and elevated logs) was not accounted for, but we make the assumption that this component is small owing to the age of the forest system (Janisch and others, 2005).

Annual fluxes were estimated by combining temperature-dependent models with soil temperature measurements (D'Amore, 2011). Soil respiration measurements were not made during winter; however, owing to the low soil temperatures and snow cover during that period, we believe that the total unaccounted for carbon dioxide (CO_2) flux is small based on our observations of CO_2 flux and soil temperature. We partitioned autotrophic and heterotrophic respiration differently between the maritime wetland forest and maritime upland forest HPUs. Wetland units were estimated to have 40-percent heterotrophic contribution based on peatland measurements in boreal Alaska (McConnell and others, 2013). The maritime upland forests were estimated to have 60-percent contribution from heterotrophic respiration based on measurements in forested systems in British Columbia (Lalonde and Prescott, 2007). The contribution of root respiration to total soil respiration across both maritime wetland forest and maritime fen, and maritime upland forest systems was similar to a 50-percent partitioning based on the overall mean reported in a review of the contribution of root respiration to soil respiration (Hanson and others, 2000). Local measurements indicate that values for root respiration range from 40 to 70 percent (David D'Amore, U.S. Department of Agriculture Forest Service, unpub. data, September 30, 2014).

4.3.3. Dissolved Organic Carbon Export

Stream water dissolved organic carbon (DOC) flux was calculated from continuous discharge measurements combined with intermittent stream water samples of DOC concentration (D'Amore and others, 2015). Concentration-discharge relationships and estimation of DOC flux were calculated using the U.S. Geological Survey Load Estimator program, LOADEST (Runkel and others, 2004). Estimates of annual flux were calculated by interpolation from the concentration-discharge relationship to account for days when stream water DOC concentrations were not measured.

4.3.4. Estimate of Particulate Organic Carbon

Particulate organic carbon (POC) was not measured in the study. We estimated POC for each HPU from our measured DOC values based on the proportion of POC:DOC from similar regions (Hope and others, 1994).

4.3.5. Estimate of Dissolved Inorganic Carbon

Dissolved inorganic carbon (DIC) estimates were derived from stream water concentrations measured in outlet streams from each HPU. DIC fluxes were derived from the relationship between stream water DIC concentration and flux in similar systems (Worrall and others, 2005). A relationship between annual stream water DIC concentration and annual DIC flux was constructed from published values of bicarbonate (HCO_3^-) and partial pressure of CO_2 (pCO_2) in stream water (Worrall and others, 2005). The total annual export of DIC was estimated based on measured stream water HCO_3^- and pCO_2 values from the HPU streams.

4.3.6. Estimate of Net Primary Productivity

Net primary productivity (NPP) estimates at a 1-km resolution were obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite MOD17 project (Zhao and others, 2005; ftp://ftp.ntsg.umt.edu/pub/MODIS/NTSG_Products/MOD17/GeoTIFF/MOD17A3/GeoTIFF_30arcsec/). Refer to the MOD17 User's Guide (Heinsch and others, 2003) for a detailed description of the MOD17 algorithm. Raster datasets of total annual NPP were downloaded for 2006 through 2009, overlapping the time period of our field sampling. Using ArcGIS software (Esri, 2012), we created a single output raster containing the average annual total NPP for the 2006–2009 period across the three study watersheds using the following general formula:

$$\text{Integer}(\text{Mean}(\text{2006 Total NPP, 2007 Total NPP, 2008 Total NPP, 2009 Total NPP}) + 0.5) \quad (4.1)$$

Average annual NPP data were missing for 2.5 percent (2.91 km^2) of the McGinnis Creek watershed (fig. 4.3, white pixels). These areas are composed of a mix of bare rock, snow, alpine vegetation, alder-covered slopes, and high-elevation forest. NPP values for these "no data" cells were estimated by taking the average NPP of surrounding pixels having similar land cover.

We concluded that these remote sensing values were a reasonable estimation of the average total NPP based on comparisons with similar coniferous forests in the Pacific Northwest. However, the estimated NPP values for maritime fen were extremely high compared to published values for similar fen ecosystem NPP estimates based on ground surveys (Asada and Warner, 2005; Wania and others, 2009). We attributed this to the inclusion of forested areas mixed within the maritime fens in the 1-km MODIS pixels. In order to avoid a greatly biased estimate of maritime fen productivity, we used a fixed input value of 177 grams of carbon per square meter per year ($gC/m^2/yr$) calculated from the average reported NPP for peatlands in two studies (Asada and Warner, 2005; Wania and others, 2009).

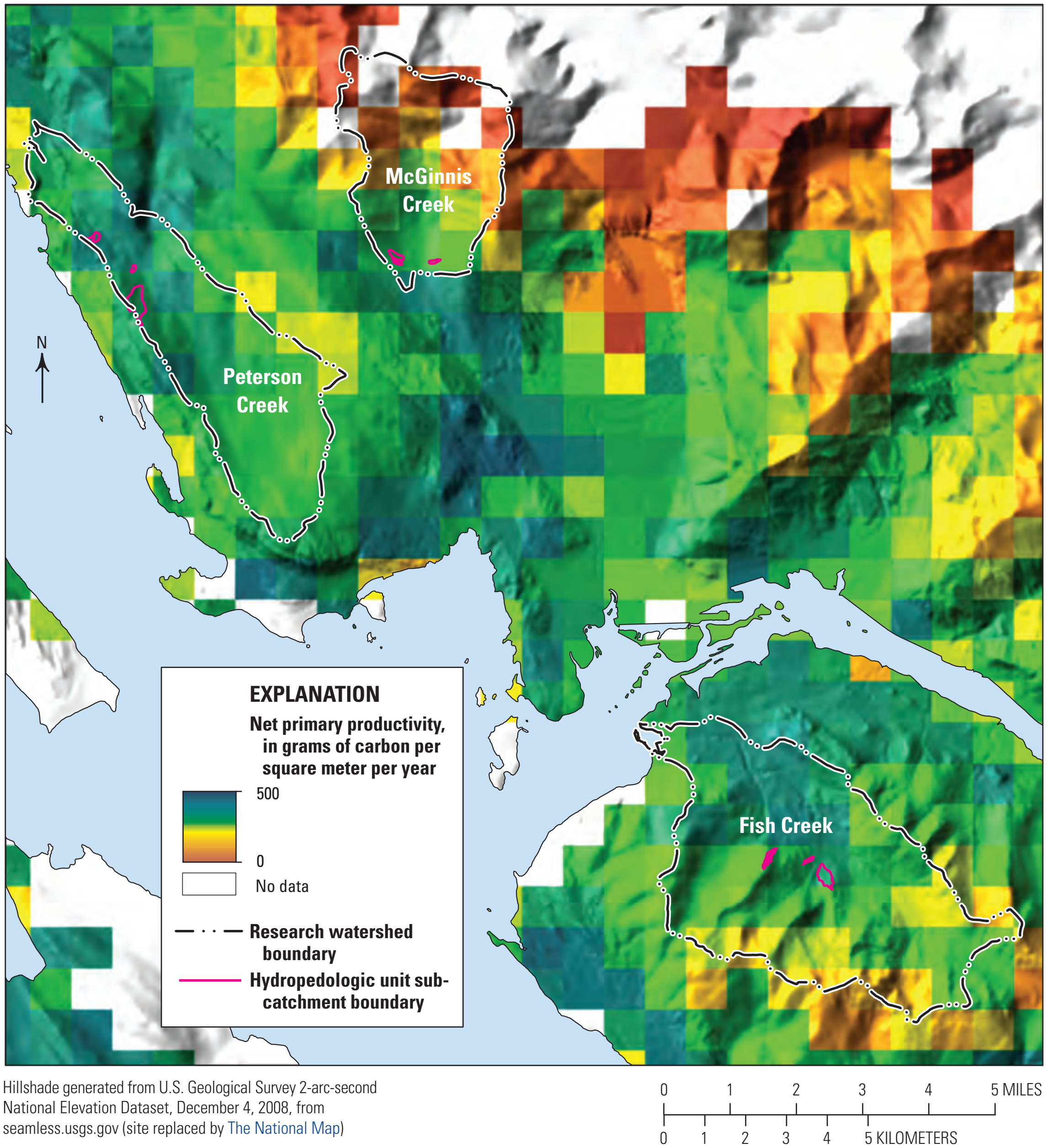


Figure 4.3. Distribution of 2006–2009 average total net primary productivity across the three research watersheds and hydropedologic sub-catchments in southeast Alaska. Net primary productivity data from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite MOD17 project (Zhao and others, 2005). See figure 4.2 for location.

4.3.7. Carbon Budget Model

We used both the NEP (equation 4.2) and NECB (equation 4.3) accounting methods to determine the carbon flux from HPU sub-catchments and the larger watersheds. The NECB method includes the exchange of CO_2 from the atmosphere to the terrestrial ecosystem, losses owing to lateral transfers of dissolved carbon, and losses from major ecosystem disturbances such as fire and forest harvest. NEP and NECB are similar in that heterotrophic respiration is subtracted from NPP estimates in both cases; however, NECB accounts for the additional loss of carbon (exports) from the ecosystem. In this study, the only additional export of carbon in the watersheds was the lateral export of DOC, POC, and DIC as there was no forest harvest removal or other large disturbances occurring in the study area.

$$NEP = NPP - HR \tag{4.2}$$

$$NECB = NEP - DOC - POC - DIC \tag{4.3}$$

where

NEP	is net ecosystem productivity,
NECB	is net ecosystem carbon balance,
NPP	is net primary productivity,
HR	is heterotrophic soil respiration,
DOC	is dissolved organic carbon,
POC	is particulate organic carbon, and
DIC	is dissolved inorganic carbon.

Fluxes of methane (CH_4), carbon monoxide (CO), and volatile organic compounds (VOCs) are also considered in the calculation of the NECB (Chapin and others, 2006); however, we did not have adequate site-specific measurements to include these additional components into the overall NECB budget. In the Alaska PCTR, annual fluxes of CH_4, CO_2, and VOCs and their overall effect on NECB are assumed to be small (chapter 7; Zhuang and others, 2007; U.S. Environmental Protection Agency, 2014). So although we are likely over-estimating the NECB by excluding CH_4, CO_2, and VOC fluxes from the budget, we do not believe that omitting these three elements will appreciably change our results or conclusions.

4.3.8. Alaska Assessment Vegetation Components

NECB and NEP were calculated for each watershed using two methods of spatial assignment for carbon flux. The first approach defined HPUs according to mapped soil drainage classes (DCs). The soil DC was created as a weighted average of the soil map unit (SMU) component DCs in the Tongass National Forest soil geographic information system (GIS) dataset (U.S. Department of Agriculture Forest Service, unpub. data, 2014). The soil DC categories and associated values are as follows: very poorly drained (1), poorly drained (2), somewhat poorly drained (3), moderately well drained (4), and well drained (5). The DCs were divided into three bins that corresponded to the drainage characteristics of the HPUs:

Drainage Class (DC)	Hydropedologic Unit (HPU)
$0 < DC < 1.5$	Maritime fen
$1.5 \le DC < 3.5$	Maritime wetland forest
≥ 3.5	Maritime upland forest

SMUs classified as alpine soils, which existed in both the Fish Creek and McGinnis Creek watersheds, did not follow the assignment rules in the above table. Alpine SMUs had average DC values ranging from 2.63 to 4.45, which would have placed alpine areas into the wetland or upland forest HPUs, leading to inflated estimates of alpine productivity. Instead, alpine SMUs were assigned to the lower productivity maritime fen HPU. NECB and NEP flux densities were then calculated for each HPU in the three experimental watersheds using remotely sensed inputs (NPP) and field measurement outputs (DIC, DOC, HR, POC). Next, annual NECB and NEP fluxes were computed by extrapolating the HPU flux density estimates across each HPU's total area (fig. 4.4).

The second approach used the vegetation map developed for this assessment to delineate HPUs (fig. 4.5). This vegetation map is a 1-km-resolution map derived from several input variables as described in chapters 1 and 2. Maritime fen, maritime wetland forest, and maritime upland forest already exist as vegetation classes in the vegetation map; therefore, these classes were used to represent the HPUs. The subsequent calculation of NECB and NEP flux density and total flux followed the same method as above for soil DCs. We excluded the portion of the Fish Creek watershed where SMU mapping was absent from the vegetation map carbon balance calculations.

The two approaches for defining HPUs (SMU DCs versus vegetation map classes) enabled us to compare NECB results from the more finely resolved HPU map derived from the SMU DCs with the NECB results based on aggregating HPUs by the more generalized vegetation map. SMU data were not available for nearly half of the Fish Creek watershed (fig. 4.4). Therefore, in order to compare carbon balance estimates between the SMU-DC-based and vegetation-map-based HPUs, we limited the area over which the carbon balance was calculated in the Fish Creek watershed to only the portion where SMUs were present. In the McGinnis Creek watershed, the vegetation map identified a large portion of the area as rock and ice, which decreased the area of the watershed that contained any carbon. This altered the comparison of the total carbon in the watershed calculated from the vegetation map HPU versus the SMU-DC HPU.

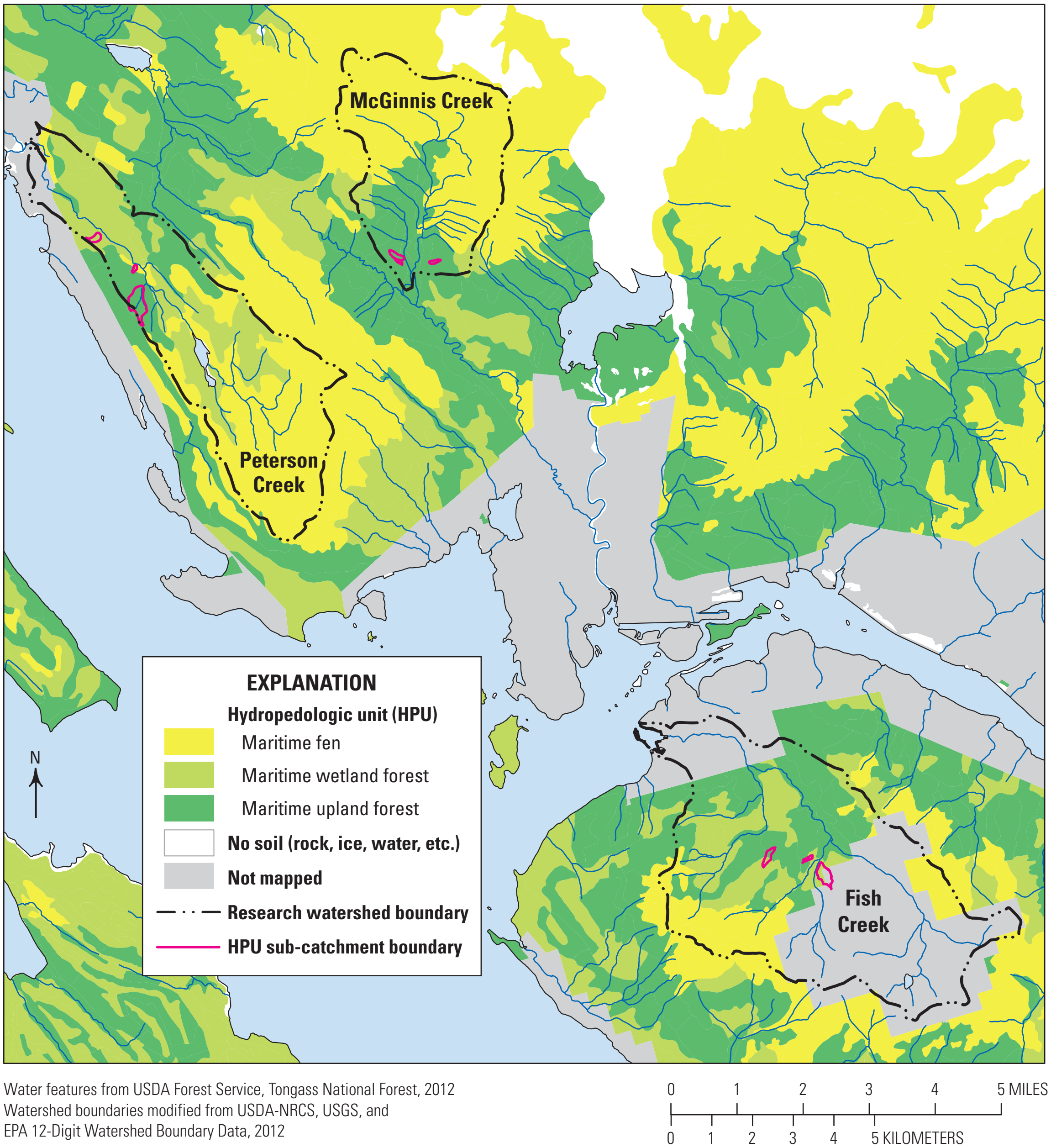


Figure 4.4. Distribution of hydropedologic units derived from soil map unit drainage classes. See figure 4.2 for location.

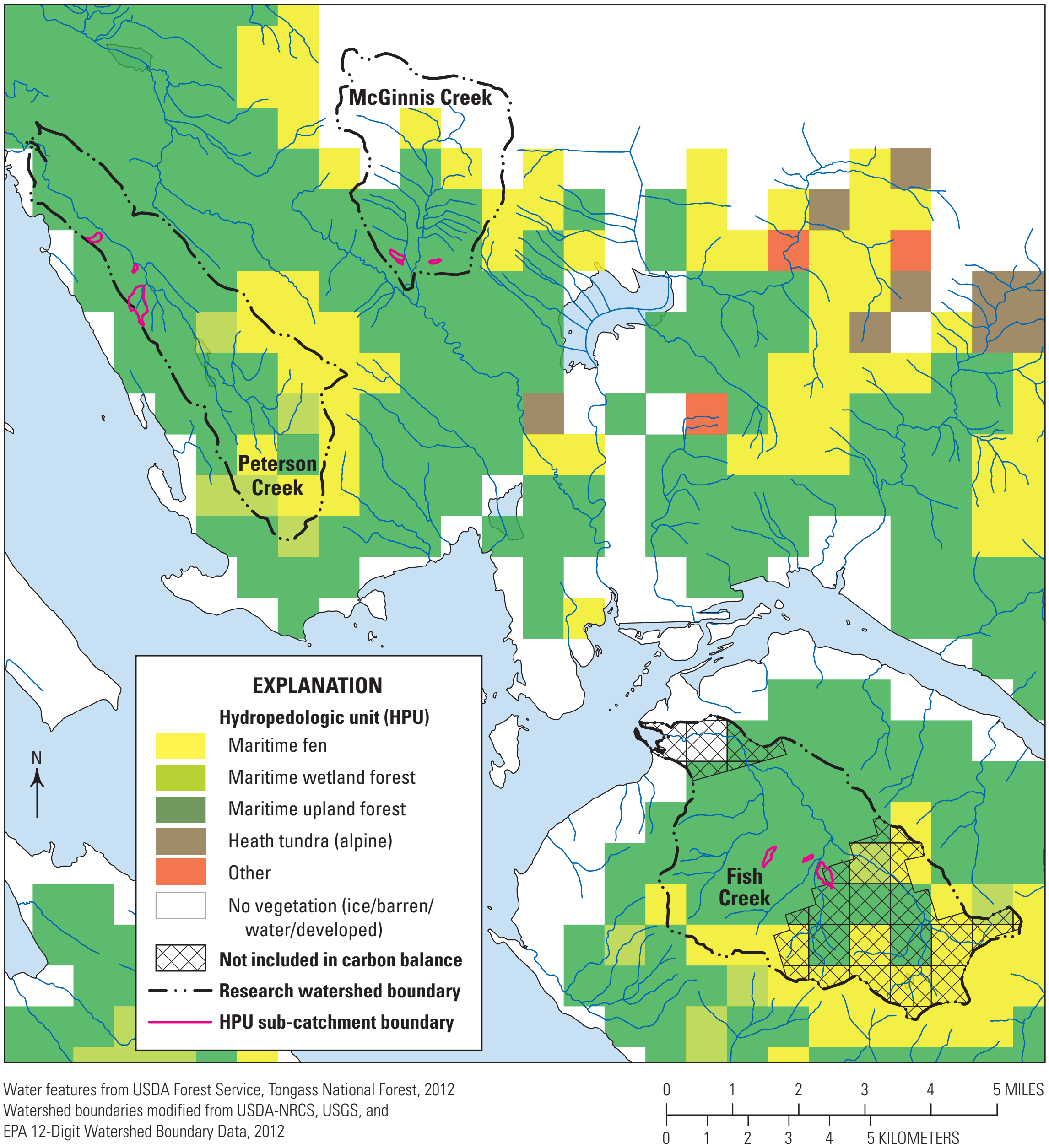


Figure 4.5. Distribution of hydropedologic units derived from the vegetation map developed for this assessment. See figure 4.2 for location.

4.3.9. Geographic Information System Analysis

We used ArcGIS to combine the average annual total NPP raster for 2006–2009 with the SMU, vegetation map, and watershed boundary datasets. Before the datasets were combined, the NPP raster was projected to Alaska Albers (North American Datum of 1983) using nearest neighbor resampling and snapped to the vegetation map raster. The Alaska Albers projection was used for all GIS data. Both the NPP and vegetation map rasters were converted to vector polygon datasets and combined with the SMU and watershed boundary polygons. The combined dataset was exported to a spreadsheet for the carbon balance accounting.

4.4. Results

4.4.1. Watershed Net Ecosystem Carbon Budgets

Each of the watersheds had a net gain in carbon stock calculated from both the NEP and NECB carbon balance models (table 4.1). The calculation method had a notable effect on the amount calculated for each watershed overall. The NEP values were 18 percent, 32 percent, and 51 percent higher than the NECB values in the Peterson Creek, McGinnis Creek, and Fish Creek watersheds, respectively. The lowest unit-area carbon accretion values were in the youngest landscape of the postglacial McGinnis Creek watershed. The highest values were calculated in Peterson Creek, whereas Fish Creek values were intermediate between the other two watersheds.

Net carbon balance tended to increase with stand age, until it appeared to reach a plateau at 200 years (fig. 4.6). Owing to the limited number of data points used in the assessment, it was not possible to make definitive statements regarding these trends, but the overall carbon balance was consistent with the expected phases of stand development in southeast Alaskan coniferous forests. The increase was greatest during the period of stem exclusion (~100–200 yr). The plateau in net balance occurred in the range of understory re-initiation (~200–400 yr). There was an outlier in the trend from the Fish Creek maritime upland forest where the net carbon balance calculated as NECB was much lower than the general trend in the rest of the data. The discrepancy in this value was due to the high rate of DIC loss in this HPU. The remaining carbon loss values were similar to the other HPUs.

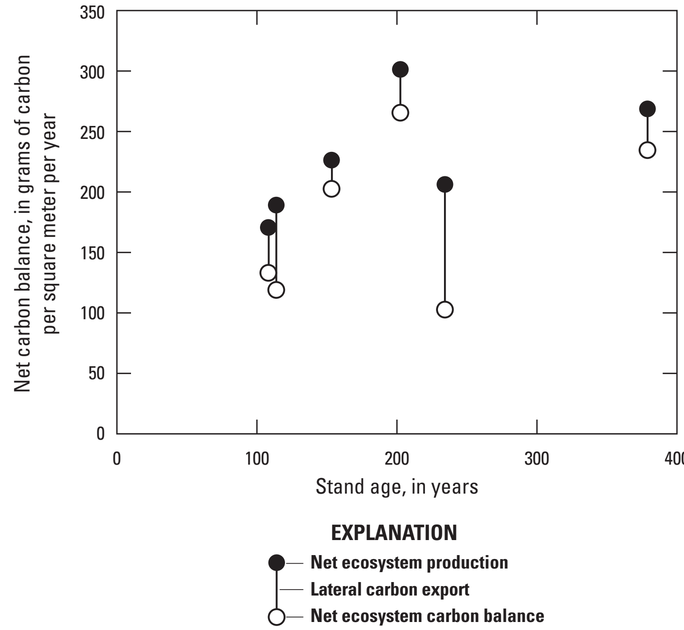


Figure 4.6. Average stand age compared to net carbon balance as both net ecosystem production (NEP) and net ecosystem carbon balance (NECB). The difference in these two values is the amount of lateral carbon export added to the NEP to calculate NECB.

4.4.2. Comparison of Carbon Budgets from Drainage Class Versus Vegetation Map Hydropedologic Units

All watersheds had a net gain in carbon calculated by either the finer resolution DC HPUs or the less highly resolved vegetation-map-based HPUs. The area-weighted average NECB calculated for the three watersheds using the DC HPUs was 148 gC/m^2/yr, with an NEP of 194 gC/m^2/yr (table 4.1), very similar to the average vegetation map NECB of 142 gC/m^2/yr, with a NEP of 193 gC/m^2/yr (table 4.2). The watershed totals for NEP and NECB were also of roughly similar magnitude in both models. Therefore, the details regarding the implications of the magnitude of the carbon balance and patterns among landscape units and watersheds are discussed relative to values in table 4.1.

4.4.3. Relationship of Carbon Budget Estimates to Measures of Net Primary Productivity and Net Ecosystem Production in Other Systems

Examining the relationship of NPP with NEP and NECB provides a means for evaluating our carbon budget estimates (Pregitzer and Euskirchen, 2004). The modeled ratios of NPP:NEP and NPP:NECB were consistent with the regression model for these measures in ecosystems worldwide (fig. 4.7). In addition, the model estimates ranged along the mean ratio of NPP to NEP and NECB along a similar slope as the world biome model. The shift in the relationship of NPP to NEP and NECB was evident in each comparison among the models. The reduction in NEP using NECB was consistent across the watershed partitioning.

A major influence on the relationships illustrated in figure 4.7 was the value for NPP calculated for each SMU-DC HPU and vegetation map HPU. The NPP estimates varied among the HPUs coincident with the range of ecosystem types located within the watershed (tables 4.1, 4.2). In table 4.1, the highest mean NPP was in the Fish Creek watershed with 305 gC/m^2/yr, closely followed by the Peterson Creek watershed with

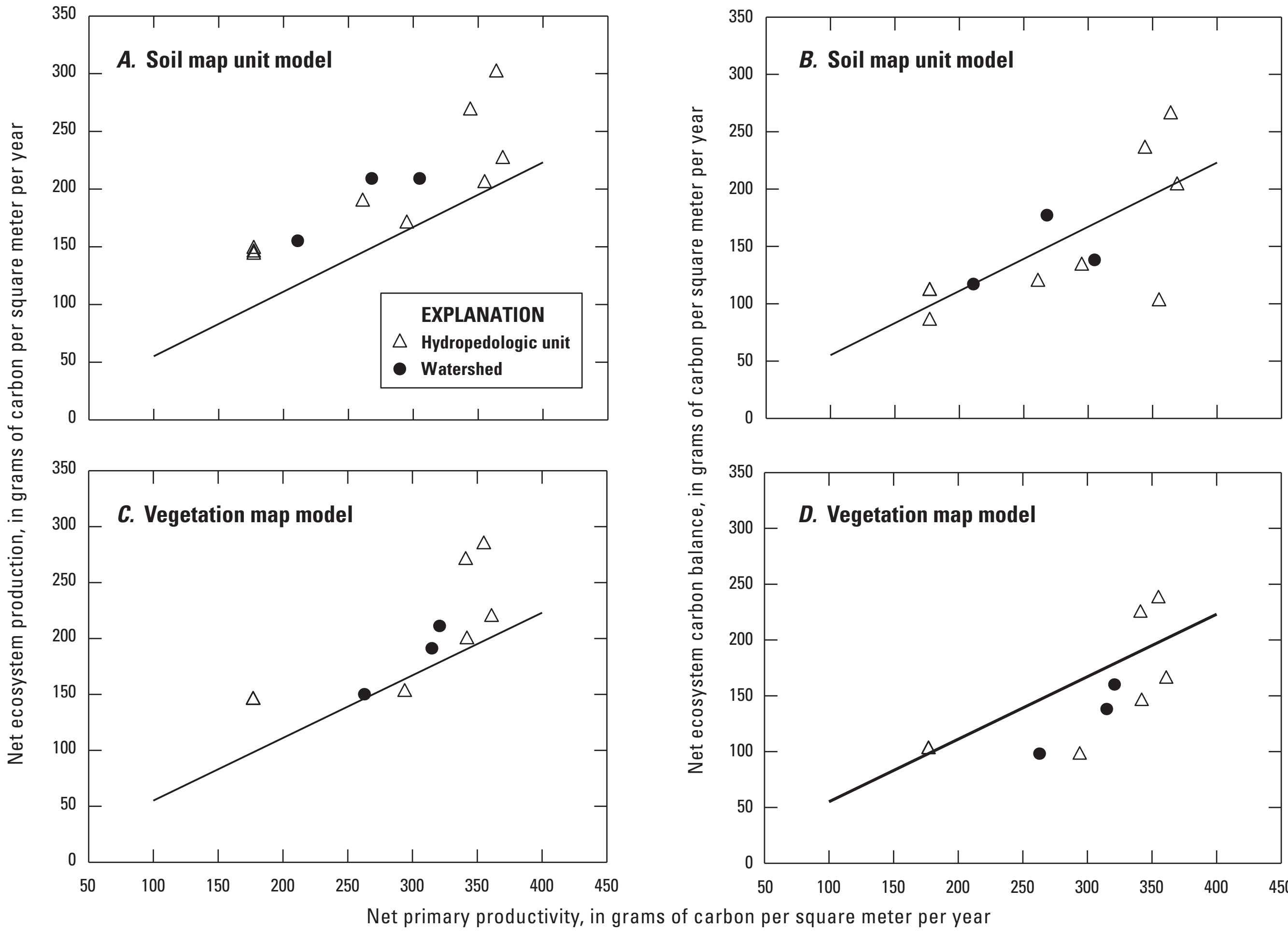


Figure 4.7. Comparison of ratios of net primary productivity (NPP) to both net ecosystem production (NEP) and net ecosystem carbon balance (NECB) calculated in each hydropedologic unit and watershed in both the finer scale SMU drainage class model and the coarser vegetation map model. The regression line is derived from values for worldwide forests (Pregitzer and Euskirchen, 2004) and used as a comparison to the values calculated in the present study. The graphs are for *A*, soil map unit drainage class NPP:NEP; *B*, soil map unit drainage class NPP:NECB; *C*, vegetation map NPP:NEP; and *D*, vegetation map NPP:NECB.

268 gC/m^2/yr. These estimates were influenced primarily by the amount of mature forest in the watersheds. The Peterson Creek watershed is completely located on uplifted marine sediment, which has promoted the development of wetland (maritime fen and maritime wetland forest) plant communities. The lowest mean watershed NPP was in the McGinnis Creek watershed with 211 gC/m^2/yr. This value was likely due to extensive areas with early successional alpine vegetation, bare rock, and ice. The mean values for all watersheds were below 400 gC/m^2/yr, which is at the low range of values for similar forests of the Pacific Northwest where NPP values are often greater than 500 gC/m^2/yr (Hudiburg and others, 2009).

4.4.4. Soil Carbon Export Pathways

Heterotrophic respiration was the largest export pathway among the various export components of the NECB (equation 4.3) and accounted for 57 percent, 60 percent, and 65 percent of the carbon export in the Fish Creek, McGinnis Creek, and Peterson Creek watersheds, respectively. Estimated heterotrophic respiration rates were 56 gC/m^2/yr, 59 gC/m^2/yr, and 96 gC/m^2/yr in the McGinnis Creek, Peterson Creek, and Fish Creek watersheds, respectively (table 4.1).

The export of DOC from the Peterson Creek, McGinnis Creek, and Fish Creek watersheds was 19 gC/m^2/yr, 20 gC/m^2/yr,

Table 4.1. Carbon balance, inputs, and outputs in three watersheds in the Alaskan coastal forest region modeled from hydropedologic units defined by soil map unit drainage classes.

[Flux: NPP, net primary productivity from remote sensing (MODIS); Rs, soil respiration; HR, heterotrophic respiration based on proportional estimate of autotrophic to heterotrophic respiration; DOC, stream water dissolved organic carbon; DIC, stream water dissolved inorganic carbon; POC, estimated particulate organic carbon; NEP, calculated net ecosystem production from NPP and HR; NECB, calculated net ecosystem carbon balance from NPP, HR, DOC, DIC, and POC. Units: yr, year; km^2, square kilometer; gC/m^2/yr; gram of carbon per square meter per year; MgC/yr, megagram of carbon per year; n.d., no data]

Watershed (ecological subsection)	Hydropedologic unit	Stand age (yr)	Area (km^2)	Flux density (gC/m^2/yr)								Annual flux (MgC/yr)	
				NPP	Rs	HR	DOC	DIC	POC	NEP	NECB	NEP	NECB
Peterson Creek (Stephens Passage Glaciomarine Terraces)	Maritime fen	n.d.	12.24	177	85	34	20	7	5	143	111	1,751	1,361
	Maritime wetland forest	203	8.17	364	159	63	21	10	5	301	265	2,458	2,167
	Maritime upland forest	154	3.33	369	238	143	9	12	2	226	203	753	675
	Watershed	**n.d.**	**23.74**	**268**	**132**	**59**	**19**	**8**	**5**	**209**	**177**	**4,962**	**4,203**
McGinnis Creek (Boundary Ranges Icefields)	Maritime fen	n.d.	11.81	177	72	29	24	7	6	148	111	1,751	1,309
	Maritime wetland forest	114	.60	261	181	72	50	7	13	189	119	113	71
	Maritime upland forest	109	4.49	295	208	125	6	29	2	170	133	763	599
	Watershed	**n.d.**	**16.90**	**211**	**112**	**56**	**20**	**13**	**5**	**155**	**117**	**2,627**	**1,979**
Fish Creek (Stephens Passage Volcanics)	Maritime fen	n.d.	4.91	177	79	32	30	23	8	145	85	714	419
	Maritime wetland forest	379	5.72	344	189	75	19	9	5	268	235	1,536	1,343
	Maritime upland forest	234	8.24	355	249	150	17	82	4	205	102	1,692	842
	Watershed	**n.d.**	**18.87**	**305**	**187**	**96**	**21**	**45**	**5**	**209**	**138**	**3,942**	**2,604**
Study area		**n.d.**	**59.51**	**264**	**144**	**70**	**20**	**21**	**5**	**194**	**148**	**11,531**	**8,786**

Table 4.2. Carbon balance, inputs, and outputs in three watersheds in the Alaskan coastal forest region modeled from hydropedologic units defined by vegetation map classes.

[Flux: NPP, net primary productivity from remote sensing (MODIS); Rs, soil respiration; HR, heterotrophic respiration based on proportional estimate of autotrophic to heterotrophic respiration; DOC, stream water dissolved organic carbon; DIC, stream water dissolved inorganic carbon; POC, estimated particulate organic carbon; NEP, calculated net ecosystem production from NPP and HR; NECB, calculated net ecosystem carbon balance from NPP, HR, DOC, DIC, and POC. Units: yr, year; km^2, square kilometer; $gC/m^2/yr$, gram of carbon per square meter per year; MgC/yr, megagram of carbon per year; n.d., no data]

Watershed (ecological subsection)	Hydropedologic unit	Stand age (yr)	Area (km^2)	Flux density ($gC/m^2/yr$)								Annual flux (MgC/yr)	
				NPP	Rs	HR	DOC	DIC	POC	NEP	NECB	NEP	NECB
Peterson Creek (Stephens Passage Glaciomarine Terraces)	Maritime fen	n.d.	5.01	177	79	32	25	12	6	145	102	729	513
	Maritime wetland forest	203	3.25	341	179	72	30	9	8	270	224	878	728
	Maritime upland forest	154	16.42	361	237	142	11	41	3	219	165	3,600	2,705
	Watershed	**n.d.**	**24.68**	**321**	**197**	**110**	**16**	**31**	**4**	**211**	**160**	**5,206**	**3,945**
McGinnis Creek (Boundary Ranges Icefields)	Maritime fen	n.d.	2.36	177	79	32	25	12	6	145	102	344	241
	Maritime wetland forest	n.d.	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Maritime upland forest	109	6.58	294	237	142	11	41	3	152	97	998	639
	Watershed	**n.d.**	**8.94**	**263**	**195**	**113**	**14**	**34**	**4**	**150**	**98**	**1,341**	**880**
Fish Creek (Stephens Passage Volcanics)	Maritime fen	n.d.	3.00	177	79	32	25	12	6	145	102	436	306
	Maritime wetland forest	379	.02	355	179	72	30	9	8	284	237	6	5
	Maritime upland forest	234	15.85	342	237	142	11	41	3	199	145	3,159	2,296
	Watershed	**n.d.**	**18.87**	**315**	**212**	**125**	**13**	**37**	**3**	**191**	**138**	**3,601**	**2,607**
Study area		**n.d.**	**52.49**	**309**	**202**	**116**	**15**	**33**	**4**	**193**	**142**	**10,148**	**7,433**

and 21 gC/m^2/yr (table 4.1). The DOC estimates were much more closely aligned than heterotrophic respiration export among the watersheds. The export of DOC accounted for 12 percent, 20 percent, and 21 percent of the total carbon export from the Fish Creek, Peterson Creek, and McGinnis Creek watersheds, respectively.

The export of DIC from the Peterson Creek, McGinnis Creek, and Fish Creek watersheds was 8 gC/m^2/yr, 13 gC/m^2/yr, and 45 gC/m^2/yr (table 4.1). This disparity was driven by high values in the maritime upland forest at Fish Creek. The high calculation of DIC flux from the maritime upland forest had considerable leverage on the total carbon balance for the Fish Creek watershed.

The export of POC from each of the watersheds was 5 gC/m^2/yr (table 4.1). These values vary with the amount of DOC owing to the construction of the model for the prediction of POC driven by DOC. These estimates of POC export accounted for about 4 percent of the total carbon export in the McGinnis Creek, Fish Creek, and Peterson Creek watersheds. The export of POC was the smallest of all the soluble carbon components.

4.5. Discussion

4.5.1. Watershed Carbon Budgets

The visual evidence of abundant woody debris and deep organic soils was consistent with the hypothesis that the PCTR forest and maritime fen ecosystems have been a net sink for carbon during the Holocene. The actual size of the sink was uncertain given the variability in NPP and exported amounts. The modeled carbon budgets indicate that all three study watersheds were net sinks during the period of observation (2006–2009), which agrees with the finding that the North American continent was a sink for carbon during the 2000–2010 decade (King and others, 2015). Our results are also consistent with other studies that have estimated northern high-latitude forests as carbon sinks (Houghton, 2003). For example, mature forest stands (80–200 yr) in the Pacific Northwest had estimated carbon sinks of 286 gC/m^2/yr, whereas older forests (>200 yr) had rates of 165 gC/m^2/yr (Turner and others, 2000). Given that these estimates did not account for lateral carbon losses in the budget, the calculated carbon values using our modeling approach seem to be reasonable carbon budget approximations for the observed watersheds.

In addition to the net carbon balance estimates, the calculated ratio of NPP to NECB in the PCTR was very similar to the average ratio compared to other forested ecosystems (fig. 4.7). The overall watershed estimates and the components (hydropedologic units) within the watershed matrix are in good agreement with the trend. In particular, the maritime fen and maritime wetland forest communities are well represented among the units and contribute considerably to the carbon balance among the watersheds. The relationship illustrated by the model fit in figure 4.7 indicates that the trajectory of NECB is positive, or a net sink for carbon, in the PCTR ecosystem.

Average annual temperature decreased (–0.056 °C per decade; National Oceanic and Atmospheric Administration, National Centers for Environmental Information, 2015) and precipitation increased over the 1981–2010 normal period for Juneau, and average annual temperatures during the 2006–2009 study period were –0.445 to –1.06 °C cooler than the 1981–2010 average (5.56 °C; National Oceanic and Atmospheric Administration, National Centers for Environmental Information, 2015); however, the Alaska PCTR is predicted to warm by 4 to 6 °C by the end of the century and precipitation is predicted to increase (Melillo and others, 2014). Changes in temperature and precipitation lead to variability in the carbon balance by influencing a host of interconnected processes, such as respiration, photosynthesis, and the occurrence of natural disturbance events (Reichstein and others, 2013). For example, average annual soil respiration increased with average annual temperature (National Oceanic and Atmospheric Administration, National Centers for Environmental Information, 2015) at our three study watersheds, suggesting that warmer temperatures in the Alaska PCTR may lead to increases in HR, the largest soil carbon export pathway. Increased HR with increased temperature has been reported in other studies, but the resulting effect on NPP and NECB also depended on other factors, such as the amount and timing of precipitation and presence or absence of disturbance (Arnone and others, 2008; Hirata and others, 2014). Previous carbon balance modeling in Alaska has focused on the arctic and northern interior regions. Models including the Alaska PCTR are difficult to validate because of the lack of data (chapter 7). How climate variability will influence the carbon balance in the Alaska PCTR is highly uncertain. There is a clear need for more field experiments to fill the existing data gap in Alaska's highly productive coastal forests.

4.5.2. Landscape Variability and Carbon Balance

The watersheds in the study have varying geologic and geomorphic histories that influence the carbon balance through both the uptake of atmospheric carbon and the loss of carbon via the multiple export pathways. The variability in the low and high net balance estimates can be explained by the relative postglacial development of the watersheds. The hydropedologic units used in the landscape partitioning reflect the dominant underlying influence on carbon cycling in the watersheds.

The watersheds provide surrogates for many PCTR watershed types, including early seral/postglacial, windthrow-derived forests, and mature or late seral forest communities. The estimates in the two older watersheds reflect the underlying geomorphic history but are also driven by stand age and vegetation type. Peterson Creek has evidence of a large, regional windthrow event, which has been associated with stands originating in the decade beginning around 1880 (Harris, 1989; Nowacki and Kramer, 1998). The average stand age in Peterson Creek is consistent with this period of disturbance in the maritime upland forest. The maritime wetland forest is somewhat older, but still in the mature stand development phase. The average age of the Fish Creek stands is older, and the aspect of the watershed protects it from the prevailing storm winds from the southeast and southwest.

4.5.3. Potential Application of the Vegetation Map for Regional Carbon Modeling

Our approach using two types of landscape stratification reveals the potential for variability when estimating a carbon balance over smaller areas (such as, subwatershed-scale). It is reasonable to expect discrepancies in carbon balance estimates between the two stratification methods owing to the different resolution and origin of the input data (SMU polygons versus the 1-km vegetation map pixels). However, the consistency across larger areas in the final study results indicates that the alternative scaling approach models are comparable. The consistent array of the carbon balance estimates among varying landscape units and watersheds along with similar regression relationships for NPP:NEP and NPP:NECB (fig. 4.7) illustrate that these carbon balance estimates can be reliably extrapolated to the broader region.

4.5.4. Evaluation of Regional Net Primary Productivity Estimates

The NPP estimate from MOD17 has several challenges that make accurate estimates problematic in the coastal temperate rainforest. One of the more significant obstacles to accurate measurements is the common occurrence of cloud cover, which contaminates some of the satellite source data used for deriving NPP. Cloud-contaminated input data are estimated in the MOD17 product by linear interpolation between the previous and next cloud-free periods (Heinsch and others, 2003). In the three experimental watersheds, the percentage of days during the growing season that NPP values were estimated because of cloud cover ranged from 63 to 93 percent (average 76 percent). The coarse resolution of the MOD17 input climate and vegetation datasets and the biophysical assumptions used in the MOD17 algorithm also contribute to uncertainties in the NPP values (Heinsch and others, 2006).

Studies evaluating the accuracy and utility of MODIS NPP estimates at various scales are limited owing to a lack of empirical validation data and the difficulty of comparing plot-level measurements to a 1-km MODIS grid cell (Turner and others, 2006), and no such assessments have been made for the Alaska coastal forest region. MODIS appears to capture the general variability in the magnitude of NPP in comparison to local data, but has also been shown to overestimate NPP at low-productivity sites and underestimate NPP at high-productivity sites in North America (Turner and others, 2006) and to overestimate NPP in some forests in the northeastern United States (Tang and others, 2010). Nevertheless, at the regional scale MODIS NPP can be useful for broad estimates, and regional estimates can also be improved by incorporating ancillary datasets (Heinsch and others, 2006; Pan and others, 2006). Despite the limitations inherent in the MOD17 product, our estimates of NECB, even at the watershed scale, compared favorably with other reported values in the literature. This general agreement with other findings provides us some assurance that the MODIS data will be useful for providing NPP values for NECB accounting across the expanse of the PCTR. Future work on NEP estimates in the region should include other potential sources of data for NPP, such as other remote sensing products or plot-based estimates.

4.5.5. Net Ecosystem Carbon Balance as a Land Management Tool for the Perhumid Coastal Temperate Rainforest

The carbon-dense region of the PCTR has become a focus for carbon cycling research owing to the large accumulations of carbon in old-growth forests and the potential for accumulating carbon in young-growth forests. Mature forests can continue to sequester carbon (Harmon and others, 1990), and Luyssaert and others (2008) have proposed that old forests retain their sink strength longer than previously thought. Carbon sequestration in this region may provide a long-term reservoir and continuing sink in Alaska and is therefore a key piece of the carbon budget for Alaska and North America. Clearly it is important to use the NECB model for PCTR watersheds, as it illustrates the importance of accounting for lateral carbon losses. It is notable that heterotrophic respiration accounted for only 57 to 65 percent of the carbon export from the watersheds. This is in contrast to most temperate ecosystems where heterotrophic respiration typically accounts for 70 to 90 percent of the carbon export. More accurate regional carbon balance models will need to consider the lateral loss of carbon. Forest inventory measurements do not account for soil carbon or the overall balance in forested ecosystems. This may lead to disparate estimates and conclusions regarding the total carbon balance.

4.6. Conclusions

Watershed NECB estimates for the period of observation (2006–2009) indicate that the Alaska PCTR is a net carbon sink and that carbon is accreting at rates consistent with values for mature (100–300 yr) conifer forests in the Pacific Northwest. Stratifying the landscape into hydropedologic units for the purpose of estimating carbon balance inputs and outputs representative of the dominant landscape processes in a region provides a means to estimate watershed carbon balance and address terrestrial ecosystem heterogeneity. The approach of extrapolating the hydropedologic unit estimates across larger areas can provide preliminary estimates of ecosystem carbon balance, and continued field measurements can improve the accuracy of the predictions within each unit and across varying site conditions.

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