Terrestrial Fluxes of Sediments and Nutrients to Pacific Coastal Waters and Their Effects on Coastal Carbon Storage Rates

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Chapter 11 of

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Edited by Zhiliang Zhu and Bradley C. Reed

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Chapter 11. Terrestrial Fluxes of Sediments and Nutrients to Pacific Coastal Waters and Their Effects on Coastal Carbon Storage Rates

By Brian A. Bergamaschi[1], Richard A. Smith[2], Michael J. Sauer[1], and Jhih-Shyang Shih[3]

11.1. Highlights

- Riverborne fluxes of total organic carbon, total nitrogen, and total suspended sediment to the Pacific coastal waters of the Western United States under baseline (1992) conditions were estimated at 1.60, 0.40, and 66.78 Tg/yr, respectively. The projected (2050) future fluxes of these same constituents under a regionally downscaled land-use and land-cover (LULC) scenario aligned with the Intergovernmental Panel on Climate Change's (IPCC's) A2 scenario were 1.62, 0.50, and 63.78 Tg/yr, respectively, which indicated a projected change of –1.4 percent, +27.7 percent, and −4.5 percent, respectively.
- The southern California region exhibited the largest projected proportional changes in flux values under the IPCC A2 scenario compared with the baseline conditions, largely due to projected changes in population and urban development.
- For the Pacific coastal waters of the Western United States, the projected nitrogen fluxes were particularly elevated under the IPCC A2 scenario conditions compared with the baseline conditions, suggesting a possible increase in the frequency and duration of coastal and estuarine hypoxia events and harmful algal blooms.
- The projected carbon storage in coastal environments (those supported by terrestrial processes) represented a significant sink for carbon compared with terrestrial biomass carbon sinks; also, the projected carbon storage was sensitive to changes in land use and population. The estimated rate of carbon storage in Pacific coastal waters was 2.02 TgC/yr under baseline conditions. The projections of land use and population changes through 2050 under the IPCC A2 scenario had a small effect on projected coastal carbon storage processes, reducing carbon storage rates to 1.93 TgC/yr, a –4.4 percent change over baseline conditions.
- The results of this modeling exercise indicate that the projected size of the carbon sink associated with terrestrial exports is substantial and sensitive to anthropogenic activity. Thus, future evaluations of how land-use policy and management actions may alter carbon storage may benefit from an evaluation of the effects of prospective alterations in terrestrial processes on coastal carbon storage rates.

11.2. Introduction

This chapter assesses the effect of terrestrial processes on carbon storage rates in the Pacific coastal waters of the Western United States as part of the larger assessment of carbon stocks, carbon sequestration, and greenhouse-gas (GHG) fluxes in ecosystems of the Western United States. In order to model the baseline (1992) and projected (2050) fluxes of total organic carbon (TOC), total nitrogen (TN), and total suspended sediment (TSS) to the coastal waters, the results of LULC mapping and modeling described in chapter 2 and models of future land-use and land cover (LULC) change scenarios were required. The results of the baseline and future potential carbon fluxes and burial in the Pacific coastal waters presented in this chapter were used in an integrated analysis (chapter 12) to assemble a regional estimate of the baseline and projected amounts of carbon stored in ecosystems of the Western United States. The relation between this chapter and the other chapters is depicted in figure 1.2 of chapter 1 of this report.

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Globally, coastal ocean processes account for the removal of an estimated 1.1 petagrams of carbon per year (PgC/yr) from the atmosphere through the processes driving the production of carbon by phytoplankton and the burial of organic carbon in sediments (Hedges and Keil, 1995; Sarmiento and Gruber, 2002; Muller-Karger and others, 2005; Hales and others, 2006; Dunne and others, 2007). This carbon sink is greater than the terrestrial biomass carbon sink (Sarmiento and Gruber, 2002) and is also susceptible to disruption by anthropogenic activities in terrestrial systems. In particular, changes to the supply of sediments and nutrients to coastal oceans can alter the magnitude of this carbon sink; ample evidence exists that they already have been significantly altered by anthropogenic activity (Syvitski and others, 2005; Boyer and others, 2006).

The inputs of sediment and nutrients from the terrestrial environment to the coastal waters exert significant control on the carbon storage processes in the marine coastal systems. Although the vast majority of carbon buried in coastal sediments or exported to the deep ocean has a marine provenance (Blair and others, 2004; Burdige, 2005), the fluxes of nutrients from the continents support coastal phytoplankton production and sediment fluxes aid the transport of this material from the photic zone to the deep ocean and bury it outside of the zone of oxygen penetration, where mineralization rates are dramatically reduced. Thus, to quantify the anthropogenic effects on the carbon storage rates in coastal environments, it is necessary to quantify the fluxes of TOC, TN, and TSS exported from terrestrial environments to coastal oceans, all of which have been demonstrably affected by anthropogenic activity (U.S. Climate Change Science Program, 2007).

The properties of the watersheds that drain into the Pacific coastal waters and the physical attributes of the adjacent continental shelf affect the rate of carbon storage that occurs under current conditions and how it may be altered in the future. Globally, large river deltas are responsible for much of the coastal carbon burial because of their high productivity and rapid sediment accumulation rates (Blair and others, 2004; Syvitski, 2011); however, because of the relatively steep bathymetry just offshore of the Western United States, there are few accreting delta systems associated with large river mouths. For example, the relatively steep bathymetry prevents the formation of a distinct accreting delta for the fourth largest river in the United States, the Columbia River. Instead, sediment from the Columbia River is deposited in deeper waters, relatively far from the mouth (Gross and Nelson, 1966; Sternberg, 1986). The Western United States possesses additional physiographic characteristics, however, that do act to increase the storage of carbon. Discharge into the Pacific coastal waters is dominated by small, mountainous rivers, which carry high loads of sediment and nutrients. These rivers tend to be short, draining watershed areas with high relief, and their mouths typically discharge near the coast rather than into an estuary (Milliman and Syvitski, 1992; Wheatcroft and others, 2010). Globally, the sediment discharge from small, mountainous river systems accounts for nearly half the coastal sediment that buries carbon (Milliman and Syvitski, 1992; Leithold and others, 2005; Wheatcroft and others, 2010).

The amount of sediment and nutrients delivered to coastal oceans has changed considerably over the past several decades, significantly altering patterns of coastal carbon burial (Leithold and others, 2005; Syvitski and others, 2005; Mayorga and others, 2010). Increasing population and changes in land use are expected to accelerate these changes (Harrison and others, 2005; Syvitski and others, 2005; Mayorga and others, 2010). Although much of the discharge into Pacific coastal waters is from small, mountainous rivers, both the Columbia and Sacramento Rivers (the two largest rivers in the Western United States) drain areas of intensive agriculture and carry elevated nutrient loads to coastal waters, thus promoting higher phytoplankton production (Hales and others, 2008). The riverborne supply of these external nutrients to Pacific coastal waters is important because phytoplankton production supported by the externally supplied nutrients contributes to the potential net removal of carbon from the atmosphere.

The estimates of carbon storage rates in the Pacific coastal waters can be complicated by a decoupling in the timing of sediment and nutrient supply. The burial of the phytoplankton biomass in the coastal sediments requires coherence between inputs of nutrients and inputs of sediments—phytoplankton production must occur near the time of the episodic delivery of the sediments (Wheatcroft and others, 2010). Although nutrients supporting phytoplankton production in Pacific coastal waters are largely supplied by the summer upwelling of nutrient-rich, deep-ocean water, the nutrient supply by rivers is also significant, particularly in Oregon and Washington (Hales and others, 2008). Any increases or decreases in the nutrient supply by rivers will affect the potential productivity in the adjacent coastal area. Changes in nutrient supply can be caused by changes in population, river discharge, agricultural practices, reforestation, and many other similar land-use- or climate-related variables (Billen and Garnier, 2007). Under the projected future conditions, an increase in nutrients associated with the sediment contained in discharge waters could have the potential to improve the efficiency of carbon transport and burial.

This coastal assessment focused exclusively on characterizing the potential magnitude of processes in the coastal marine system that have been, and potentially could be, affected by changing land use and population (fig. 2.1). The focus was only on the terrestrial sources of nutrients and sediments that influence marine carbon storage rates and not on marine processes such as the upwelling of oceanic nutrients, which also significantly contribute to primary productivity and total carbon storage rates in coastal waters. To accomplish this task, the fluxes of total organic carbon (TOC), total nitrogen (TN, organic and inorganic), and total suspended sediment (TSS) to coastal waters were estimated on the basis of current and projected land use using a model that was calibrated using long-term water quality and stream discharge data. The baseline and projected amounts of carbon that were buried were estimated according to established models of oceanographic processes (Armstrong and others, 2002; Dunne and others, 2007).

The geographic extent of the assessment was from the northern to the southern borders of the Western United States and included all of the watersheds that drain this region into the adjacent coastal waters (herein referred to as the “Pacific coastal waters”). The coastal waters of the Gulf of California, which receives the discharge of the Colorado River, were not included because other sources of discharge into those coastal waters extended beyond the geographic boundary of the conterminous United States. The assessment considered only processes affected by the terrestrial supply of nutrients and sediments to coastal waters. These processes extended from the coast into the deep ocean with no western boundary because carbon exported into the deep ocean was presumed to be sequestered (Sarmiento and Gruber, 2002, Hales and others, 2006).

The riverine delivery of carbon, nutrients, and sediment to coastal waters can be estimated from routine monitoring data, provided that the records cover a sufficient length of time and include accurate streamflow measurements (Cohn and others, 1992). Determining the sources of the transported material is much more difficult, however, especially in the case of large rivers with heterogeneous basin characteristics. Isotopic methods have been developed to distinguish specific classes of sources of nutrients (for example, atmospheric or sewage effluent) with good success, but require specialized analytical procedures and have not been used historically in broad-scale, long-term monitoring programs (Kendall and McDonnell, 1998). There has been considerable progress in the past two decades: (1) development of statistical modeling approaches, which can be used to identify the sources of constituents; (2) continuing development of geographic information systems (GIS) technology; and (3) availability of spatial data on basin characteristics (Peters, 1984; R.A. Smith and others, 1997; Goolsby and others, 1999). The use of the SPARROW model (a “spatially referenced regression on watershed attributes” water-quality model; R.A. Smith and others, 1997) for regional interpretations of contaminant sources is now a routine part of the U.S. Geological Survey’s water-quality assessment activities (Preston and others, 2011).

11.3. Input Data and Methods

The modeling approach used here divides the analysis of Pacific coastal waters into three components: (1) the supply of TOC, TN, and TSS from terrestrial systems to the coastal ocean, (2) phytoplankton production supported by terrestrial nutrients, and (3) storage rates of carbon in coastal sediments or deep ocean waters. The first model component assesses the TOC, TN, and TSS supply from rivers to the coastal ocean under baseline (1992) and projected (2050) conditions.

A hybrid statistical-mechanical modeling approach was used to calculate the fluxes of TOC, TN, and TSS from rivers to the coastal waters. The SPARROW model (R.A. Smith and others, 1997; Schwarz and others, 2006) consists of process-based mass-transport components for water flow paths, in-stream processing, and mass-balance constraints on model inputs, losses, and outputs (Schwarz and others, 2006). Modeled estimates of TSS, TN, and TOC fluxes were produced for each coastal or inland hydrologic unit (by 12-digit hydrologic unit code; U.S. Department of Agriculture, Natural Resources Conservation Service, 2012) that produced runoff to the western coast of the United States. Both the baseline LULC and LULC projections by the “forecasting scenarios of land cover change” (FORE–SCE) model, as described in chapter 2 of this report, were included in the SPARROW modeling process. Estimates of TOC that were developed using a different modeling approach (presented in chapter 10 of this report) agree with those presented here. The SPARROW model, however, permits assessment using the future potential land use and population conditions in 2050, which are presented in chapter 2.

For surface-water monitoring stations that had sufficient data on discharge and water quality, parameters were estimated by spatially correlating the stream data with georeferenced data on the constituent sources (for example, atmospheric deposition, fertilizers, human and animal wastes) and delivery factors (for example, precipitation, topography, vegetation, soils, and water routing). Parameter estimation ensured that the calibrated model would not be more complex than can be supported by the data.

SPARROW models describe mass transport in watersheds as three sequential processes: (1) source supply, (2) land-to-water transport, and (3) channel-network transport (R.A. Smith and others, 1997). Data describing these processes are developed on a stream reach and associated catchment basis. There are approximately 13,000 reaches or catchments in the Western United States assessment area and 63,000 reaches or catchments in the national-scale data set, which were used to calibrate the models. Table 11.1 provides information on the TOC, TN, and TSS models used here to quantify the flux of material to coastal waters. More detailed information is available from the references provided in the table.

The source variables (table 11.1) were of particular importance because they served as the basis for translating the projected LULC changes under the A2 scenario (from the Intergovernmental Panel on Climate Change’s Special Report on Emissions Scenarios, IPCC–SRES; Nakicenovic and others, 2001) into changes in coastal delivery of TOC, TN, and TSS from the baseline period to 2050. The IPCC–SRES scenarios are discussed in more detail in chapter 6 of this report. Table 11.2 summarizes the correspondence between the LULC classes and the SPARROW model’s source categories. An underlying assumption made in modeling the future changes in coastal flux was that the rate of the source supply will change in proportion to the LULC changes in each

Table 11.1. Variables used in the SPARROW models of total organic carbon, total nitrogen, and total suspended sediment fluxes, and their sources.

[SPARROW, "spatially referenced regressions of watershed attributes" water-quality model]

Model	Number of sites	Coefficient of determination (R^2)	Source variables	Reference
Total organic carbon (TOC)	1,125	0.928	Cultivated land, pasture, deciduous forest, evergreen forest, mixed forest, rangeland, urban land, wetlands, in-stream photosynthesis	Shih and others (2010)
Total nitrogen (TN)	425	0.933	1990 population, atmospheric total nitrogen deposition, corn or soybean fertilizer, alfalfa fertilizer, wheat fertilizer, other crop fertilizer, farm animal waste, forest, barren land, shrubland	Alexander and others (2008)
Total suspended sediment (TSS)	1,828	0.711	Urban area, forest, crop and pasture land, Federal land, other marginal land, channel storage and erosion	Schwarz (2008)

Table 11.2. Assumed correspondences between the SPARROW model's source categories and the land-use and land-cover classes used in this assessment.

[See chapter 2 of this report for definitions of the LULC classes. LULC, land use and land cover; NA, not applicable; SPARROW, "spatially referenced regressions of watershed attributes" water-quality model]

Total organic carbon (TOC) model		Total nitrogen (TN) model		Total suspended sediment (TSS) model	
Model source	Land use and land cover class	Model source	Land use and land cover class	Model source	Land use and land cover class
Cultivated land	Agriculture	Human population	Developed land	Developed land	Developed land
Pasture	Hay/pasture	Atmospheric nitrate (NO_3) deposition	Developed land	Forested land	Deciduous, evergreen, mixed forests
Deciduous forest	Deciduous forest	Fertilizer nitrogen applied to agriculture	Agriculture	Federally managed land	Barren land, grassland and shrubland
Evergreen forest	Evergreen forest	Nitrogen content of farm animal waste	Grassland and shrubland	Crop and pasture land	Agriculture
Mixed forest	Mixed forest	Forest	Deciduous, evergreen, mixed forests	Other land	Barren land, grassland, and shrubland
Rangeland	Grassland and shrubland	Barren land	Barren land	Stream channels	No LULC correspondence; assumed to be constant
Developed land	Developed land	Shrubland	Shrubland	NA	NA
Wetlands	Herbaceous and woody wetland	NA	NA	NA	NA
In-stream photosynthesis	No LULC correspondence; assumed to be constant	NA	NA	NA	NA

model's catchment. The A2 scenario was selected because it is consistent with this assumption in one important aspect: it projects that population growth by 2050 (+48 percent) may be nearly matched by an increase in area classified as developed land (+46 percent). Thus, for example, the change in the value of the population variable in the TN model within each catchment was approximated by the projected change in the developed land area presented in chapter 6 of this report. The A2 scenario also assumed that environmental sustainability remains approximately constant, which is reflected in the LULC and SPARROW modeling (Sohl, Sleeter, and Zhu, 2012; also see chapter 6 of this report). Thus, for example, the per-acre fertilizer application rates and point and nonpoint pollution-control efficiencies are assumed to remain constant.

The 90-percent confidence intervals for the coastal flux estimates in table 11.3 were developed through a "bootstrap" procedure in which 200 equally likely estimates for each entry in the table were randomly generated on the basis of the error characteristics of the model determined during calibration. The width of the confidence intervals surrounding the 1992 and 2050 flux estimates included both coefficient error and residual (that is, model specification) error (Schwarz and others, 2006). It was assumed that the residual errors of the flux estimates for individual coastal rivers within each region reflected idiosyncrasies of the river watersheds. The estimated errors surrounding the "percent-change" estimates for each coastal river, however, were assumed to be caused only by coefficient error on the basis of the further assumption that the idiosyncrasies of a given river can be assumed to be the same in 1992 and 2050. Thus, the confidence intervals for the percent-change estimates were smaller than those for the separate 1992 and 2050 flux estimates.

The effects of climate change have not been specifically modeled because there is no known consensus regarding their effects on nutrients or biota in the coastal ocean. Although the effects of climate change may alter TOC, TN, and TSS fluxes in the future, LULC is expected to be the main driver of the variability in these parameters between 1992 and 2050, suggesting that uncertainty in the model is controlled by LULC. The A2 scenario was chosen to represent the projected changes in coastal carbon sequestration stemming from LULC. The use of the A2 scenarios limits the SPARROW model's runtime and represented a worst-case scenario for population increase and anthropogenic emissions with continued regional fragmentation in economic growth and technology. In contrast to the other IPCC–SRES scenarios (A1B and B1), environmental protection and sustainability were not considered to be important in A2.

Table 11.3. Estimates of total organic carbon, total nitrogen, and total suspended sediment fluxes to the Pacific coastal waters of the conterminous United States (with 90-percent confidence intervals) and the total carbon burial rate under baseline (1992) and projected (2050) conditions.

[A2 scenario selected from Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios (Nakicenovic and others, 2001). Numbers may not sum precisely due to rounding. Tg/yr, teragrams per year; TgC/yr, teragrams of carbon per year]

Variables	Region	1992 baseline estimate (90-percent confidence interval)	2050 projected estimate under A2 scenario (90-percent confidence interval)	Percent change (90-percent confidence interval)
Total organic carbon flux (TgC/yr)	Southern California	0.04 (0.01 to 0.08)	0.04 (0.02 to 0.10)	18.2 (17.95 to 18.45)
	Northern California	0.32 (0.13 to 0.71)	0.33 (0.13 to 0.73)	2.5 (2.43 to 2.57)
	Oregon and Washington	1.24 (0.49 to 2.97)	1.25 (0.49 to 2.99)	0.6 (0.56 to 0.64)
	Total	1.60 (0.63 to 3.77)	1.62 (0.64 to 3.82)	1.4 (1.34 to 1.46)
Total nitrogen flux (Tg/yr)	Southern California	0.04 (0.01 to 0.10)	0.05 (0.03 to 0.13)	31.7 (31.52 to 31.88)
	Northern California	0.06 (0.02 to 0.15)	0.08 (0.13 to 0.19)	34.7 (34.18 to 35.22)
	Oregon and Washington	0.29 (0.09 to 0.72)	0.37 (0.12 to 0.93)	25.7 (24.88 to 26.52)
	Total	0.40 (0.13 to 0.96)	0.50 (0.17 to 1.24)	27.7 (27.00 to 28.40)
Total suspended sediment flux (Tg/yr)	Southern California	6.27 (0.22 to 19.88)	7.69 (0.27 to 24.28)	22.7 (22.20 to 23.20)
	Northern California	19.75 (0.69 to 55.44)	19.31 (0.65 to 54.39)	−2.2 (−2.68 to −1.72)
	Oregon and Washington	40.76 (0.65 to 111.5)	36.78 (0.53 to 99.24)	−9.8 (−10.37 to −9.23)
	Total	66.78 (1.55 to 187.8)	63.78 (1.45 to 178.9)	−4.5 (−4.91 to −4.09)
Total carbon burial rate (TgC/yr)	Southern California	0.12 (0.01 to 0.39)	0.16 (0.01 to 0.52)	33.5 (33.8 to 35.2)
	Northern California	0.65 (0.29 to 1.87)	0.67 (0.06 to 1.93)	3.6 (2.9 to 4.5)
	Oregon and Washington	1.25 (0.03 to 3.51)	1.1 (0.03 to 3.05)	−12.1 (−11.8 to −13.2)
	Total	2.02 (0.06 to 5.78)	1.93 (0.09 to 5.50)	−4.4 (−4.7 to −4.2)

Sediment and carbon transport from the surface ocean into the deep ocean and carbon burial in sediments were modeled using the methods presented by Dunne and others (2007). This approach modeled the transport of terrestrial and marine, photosynthetically derived carbon to the sediment surface in coastal waters or to the deep ocean using an empirical modeling approach. The same approach was used to model sedimentation to the pycnocline. A hypsographic valuation of the bathymetric properties of the sediment deposition zones was determined by using a GIS and the NOAA bathymetric database. The burial of organic carbon in sediments was modeled as a function of the sediment deposition rate (Berger, 1989, Dunne and others, 2007) with no net deposition assumed above 10 meters because of wave- or event-driven resuspension of sediment. Sediment in the water column above 10 m depth was presumed to be transported to deeper regions with a 50 percent loss in carbon by mass and no dissolution of terrestrial sediments during transit (Armstrong and others, 2002). Carbon buried in sediments below the depth of oxygen penetration or transported to the deep ocean below the level of the pycnocline was considered to be “stored” for the purpose of this assessment, as this carbon has mean turnover times of hundreds to thousands of years (Hedges and Keil, 1995). The 90-percent confidence intervals for the coastal carbon accumulation shown in table 11.3 were developed using the confidence intervals from the flux estimates and assumed no additional error in the coastal model. Note that the modeling effort did not include an evaluation of silica, iron, and other micronutrient fluxes or of the coastal phytoplankton production that such fluxes may affect.

11.4. Results

11.4.1. Flux of Organic Carbon, Nitrogen, and Suspended Sediment to Coastal Waters

The model estimates of TOC, TN, and TSS fluxes to the Pacific coastal waters under baseline and projected (2050) conditions and based on the IPCC–SRES scenario A2 are presented in tables 11.3 and 11.4. Estimates are presented for each of the three physiographic provinces in the region: southern California (northern boundary at latitude 37°), northern California (to the Oregon State line), and the Pacific Northwest, which includes the States of Oregon and Washington.

11.4.1.1. Total Organic Carbon

The total baseline flux of TOC to the Pacific coastal waters for the three regions was estimated to be approximately 1.6 TgC/yr (tables 10.3, 10.4; fig. 11.1*A–C*). About 78 percent of the total flux was delivered to coastal waters of Oregon and Washington, reflecting the interaction of a large coastal drainage area, high streamflows, and extensive forest cover in the region (table 11.4; fig. 11.1*C*). By contrast, a much lower estimated baseline TOC flux (2 percent of total) was delivered from the smaller and drier Southern California region, largely from urban sources. The estimated baseline TOC flux from the Northern California region (especially that draining to San Francisco Bay) reflects a combination of urban and agricultural sources (table 11.4; fig. 11.1*C*). The model estimates of TOC yield to the coastline after in-stream losses are subtracted are shown in figure 11.1*B*. Regardless of the TOC source, the catchments with the highest coastal yield are typically located either near the coast or near large rivers, which tended to have low in-stream loss rates (Alexander and others, 2000). It should be noted that the preponderance of evidence suggests that terrestrial organic carbon borne by rivers into the coastal ocean is largely remineralized, and little is stored (Hedges and others, 1997; Blair and others, 2004; Burdige, 2005).

The estimated projected changes in TOC flux to the coastal waters from the 1992 to 2050 (tables 11.3, 11.4; fig. 11.1*D–G*) were relatively small in the two northern regions, but the estimated projected change was greater (more than 18 percent) in the Southern California region, where population and urban development were projected to increase dramatically by mid-century. The near absence of change in total TOC flux from Oregon and Washington (0.8 percent) over the period masked the occurrence of more substantial but opposing trends in the region: a decreasing flux from the loss of forest and forested wetlands versus an increasing flux from population growth.

11.4.1.2. Total Nitrogen

The SPARROW model estimated a baseline total TN flux of 0.395 Tg/yr (tables 11.3, 11.4; fig. 11.2*A–C*). As with TOC, approximately three quarters of the estimated TN flux entered the Pacific coastal waters from the large, wet parts of Oregon and Washington, where forest cover and atmospheric deposition together supplied about 63 percent of the regional flux (table 11.4). Farther south, in the northern and southern California regions, TN was mainly from urban sources (table 11.4).

The estimated TN flux from all three coastal regions was projected to greatly increase (table 11.4), mainly because of the importance of urban and atmospheric sources of nitrogen (and, to a lesser extent, agricultural sources in the northern California region). Under the A2 scenario, the U.S. population was projected to increase to 417 million by 2050, and nationwide agricultural production was projected to increase substantially in order to meet elevated worldwide demand. The estimated TN flux from all three regions was projected to increase more than 25 percent, with increases in the northern California region alone projected to be a third more than the baseline estimate (table 11.3; fig. 11.2*D–G*).

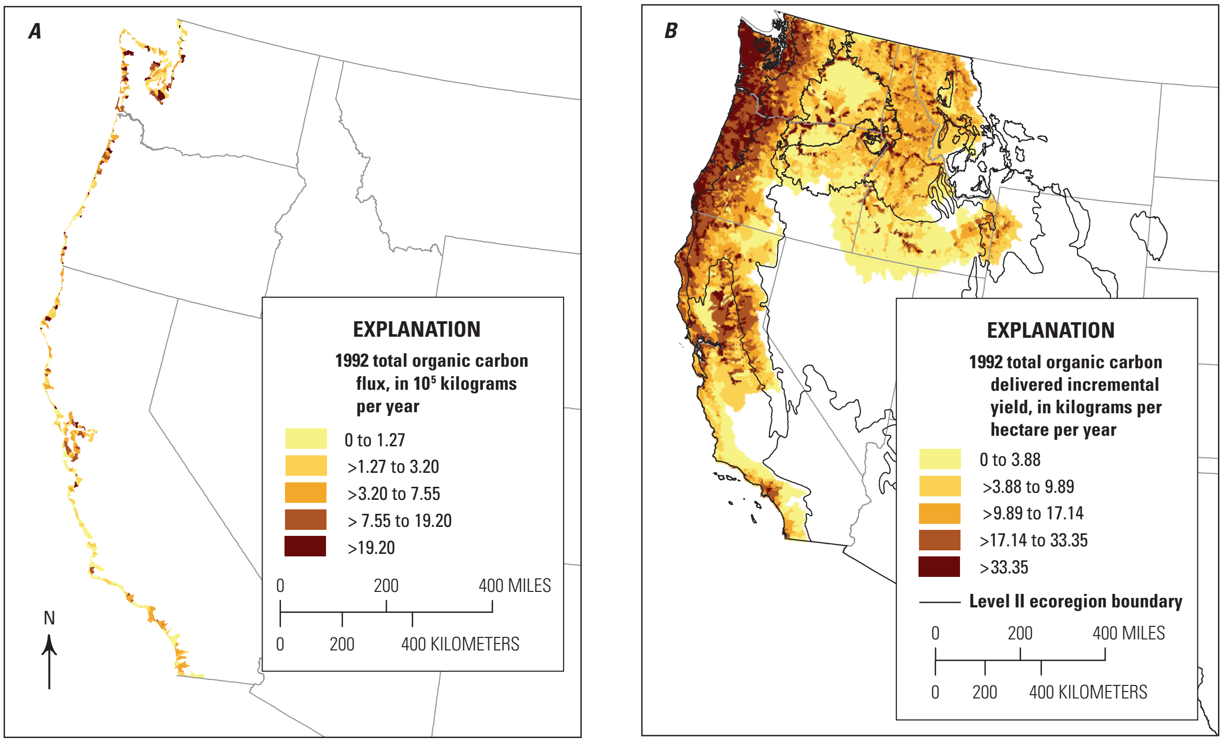
Table 11.4. Estimates of total organic carbon, total nitrogen, and total suspended sediment fluxes to the Pacific coastal waters of the conterminous United States by source of the fluxes, under baseline (1992) and projected (2050) conditions.

[Numbers may not sum precisely due to rounding. Gg/yr, gigagrams per year; GgC/yr, gigagrams of carbon per year]

Source	Southern California			Northern California			Oregon and Washington		
	1992	2050	Change	1992	2050	Change	1992	2050	Change
Total organic carbon (GgC/yr)									
Cultivated land	3.38	2.64	−0.74	24.24	23.67	−0.57	71.43	74.67	3.24
Deciduous forest	0.33	0.33	−0.01	5.87	5.85	−0.02	26.74	27.12	0.38
Evergreen forest	5.52	5.46	−0.06	96.16	95.00	−1.16	387.83	375.65	−12.18
Mixed forest	2.94	2.91	−0.03	25.34	25.79	0.45	72.10	68.79	−3.31
Urban land	17.53	25.01	7.49	19.74	31.73	12.00	31.35	54.97	23.62
Wetlands	0.67	0.51	−0.16	24.04	21.47	−2.56	57.86	53.19	−4.67
In-stream photosynthesis	5.33	5.33	0.00	126.17	126.17	0.00	593.73	593.73	0.00
Total	35.71	42.19	6.49	321.55	329.68	8.13	1,241.1	1,248.1	7.07
Total nitrogen (Gg/yr)									
Population	37.39	50.76	13.36	26.55	42.11	15.56	22.27	38.97	16.70
Atmospheric deposition	0.37	0.72	0.36	5.82	11.53	5.71	65.02	128.71	63.69
Corn and soybean	0.03	0.02	−0.01	1.02	1.01	−0.02	4.97	5.06	0.09
Alfalfa	0.04	0.03	−0.01	1.43	1.47	0.04	6.87	7.19	0.33
Wheat	0.03	0.03	0.00	0.57	0.56	−0.01	8.49	8.62	0.13
Other crops	2.33	1.69	−0.64	5.91	6.08	0.17	26.40	27.70	1.30
Farm animal waste	0.20	0.17	−0.03	3.58	3.22	−0.36	15.27	14.76	−0.51
Forest	0.29	0.28	0.00	13.40	13.27	−0.13	120.76	118.43	−2.33
Barren land	0.04	0.04	0.00	0.40	0.36	−0.04	15.85	12.29	−3.56
Shrubland	0.30	0.27	−0.03	1.47	1.44	−0.03	8.17	7.85	−0.32
Total	41.02	54.01	13.00	60.15	81.04	20.89	294.06	369.57	75.51
Total sediment supply (Gg/yr)									
Urban	1,646.68	3,094.10	1,447.40	4,020.00	6,598.27	2,578.08	4,105.60	5,076.30	970.67
Forest	36.05	35.65	−0.40	576.30	573.32	−3.01	963.74	945.16	−18.58
Federal land	2,715.14	2,800.60	85.48	7,231.00	4,995.05	−2,235.84	12,033.00	8,237.03	−3,796.00
Crop and pasture land	240.03	240.85	0.82	999.40	1,042.56	43.14	2,541.20	2,878.60	337.36
Grassland, shrubland, barren land	1,260.02	1,149.60	−110.45	3,968.00	3,143.52	−823.93	3,056.40	1,581.30	−1,475.10
Channel storage or erosion	367.61	367.61	0.00	2,956.00	2,956.70	0.00	18,063.00	18,063.00	0.00
Total	6,265.50	7,688.40	1,422.80	19,751.00	19,309.40	−441.56	40,763.00	36,781.30	−3,981.70

11.4.1.3. Total Suspended Sediment

The total baseline TSS flux to the three Pacific coastal regions averaged 66.8 Tg/yr (tables 11.3, 11.4; fig. 11.3*A*–*C*). Again, there was a pronounced increasing gradient in flux from south to north, with Oregon and Washington coastal waters receiving more than half of the total (61 percent). The important sources of transported sediment in the three regions (table 11.4; see also table 11.2) included urban runoff, but also soil loss from several types of sparsely vegetated land cover types, including rangeland, shrubland, grassland, and barren land, much of which is Federally owned. Of note, however, is that the major source of sediment in Oregon and Washington was stored and eroded sediment from stream channels in the region, as was estimated in SPARROW's TSS model calibration (Schwarz, 2008).



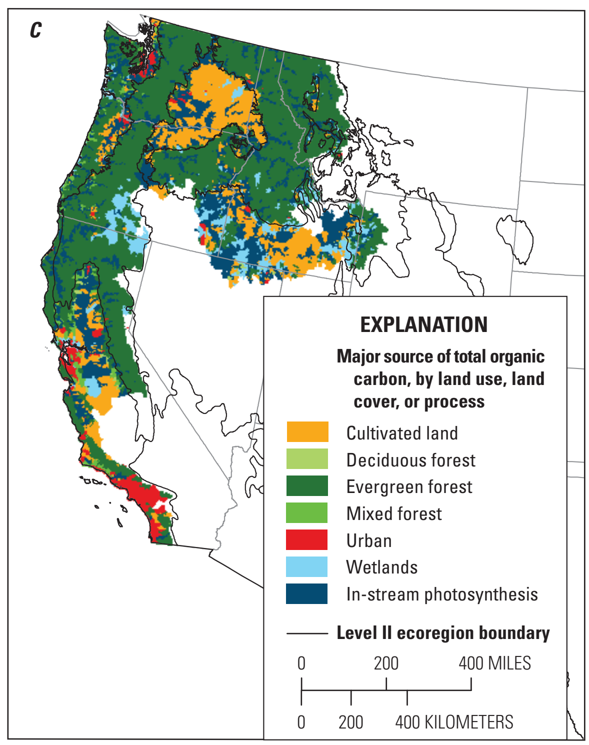
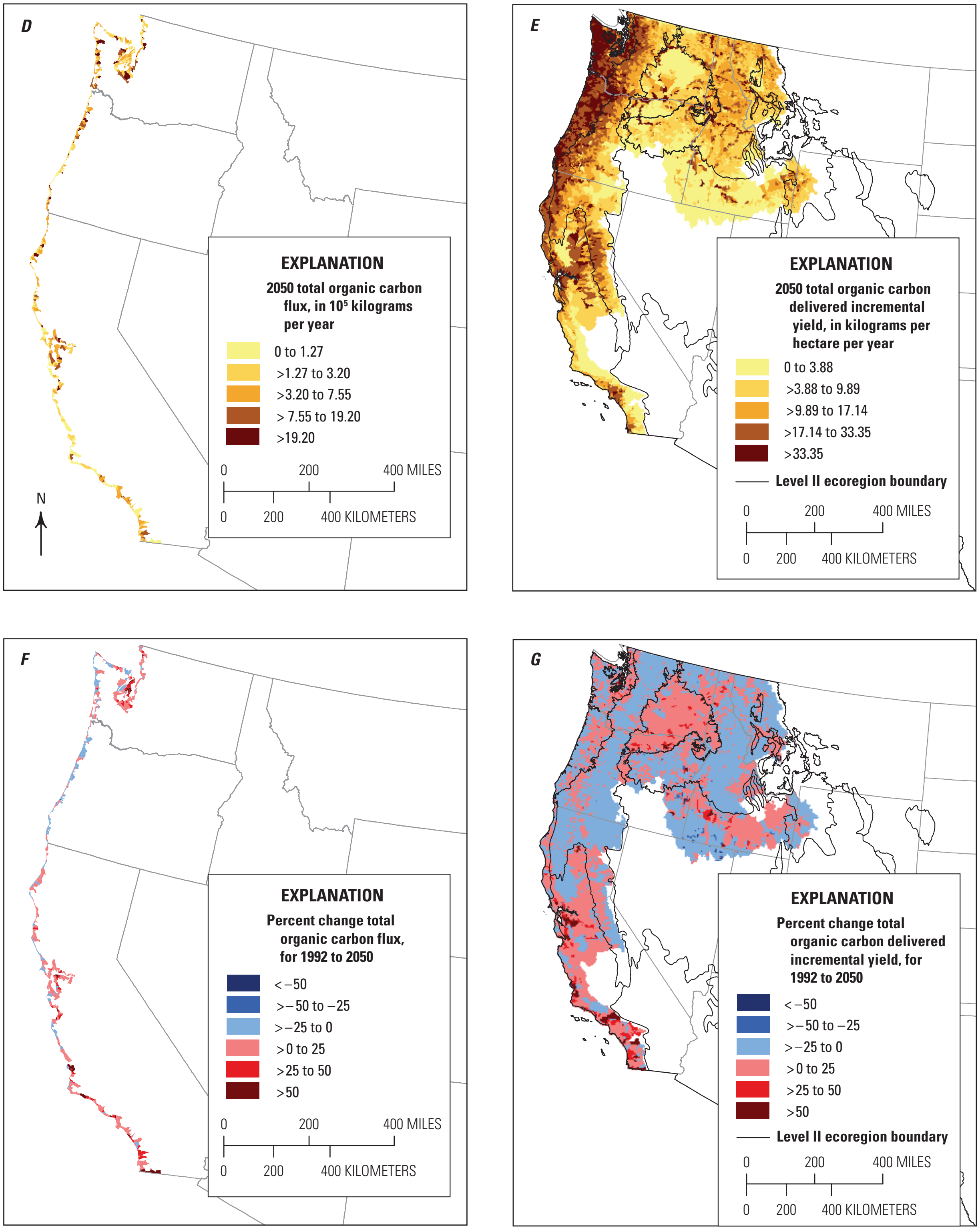


Figure 11.1. Maps showing total organic carbon flux and yield under baseline (1992) and projected (2050) conditions with projected percent change between 1992 and 2050. Flux is to Pacific coastal waters and yield is from catchments draining to Pacific coastal waters of the conterminous United States. *A*, Estimated coastal flux of total organic carbon (TOC) in 10^5 kilograms per year (kg/yr) under baseline (1992) conditions. *B*, Estimated delivered yield (in kilograms per hectare per year, kg/ha/yr) of TOC from catchments draining to Pacific coastal waters under baseline (1992) conditions. Delivered yield reflects the effects of in-stream carbon losses occurring during transport from the outlet of a catchment through the stream and river system to coastal waters. *C*, Major sources of TOC in model catchments under baseline (1992) conditions. *D*, Projected estimates of coastal flux of TOC (in 10^5 kg/yr) under future (2050) conditions based on IPCC–SRES scenario A2. *E*, Projected estimates of delivered yield (in kilograms per hectare per year, kg/ha/yr) of TOC from catchments draining to the Pacific coastal waters under future (2050) conditions. Delivered yield reflects the projected effects of in-stream carbon losses occurring during transport from the outlet of a catchment through the stream and river system to coastal waters. *F*, Projected percent change in estimated coastal flux of TOC between 1992 and 2050 based on IPCC–SRES scenario A2. G, Projected percent change in yield of TOC from catchments between 1992 and 2050 based on IPCC–SRES scenario A2. IPCC–SRES, Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000).



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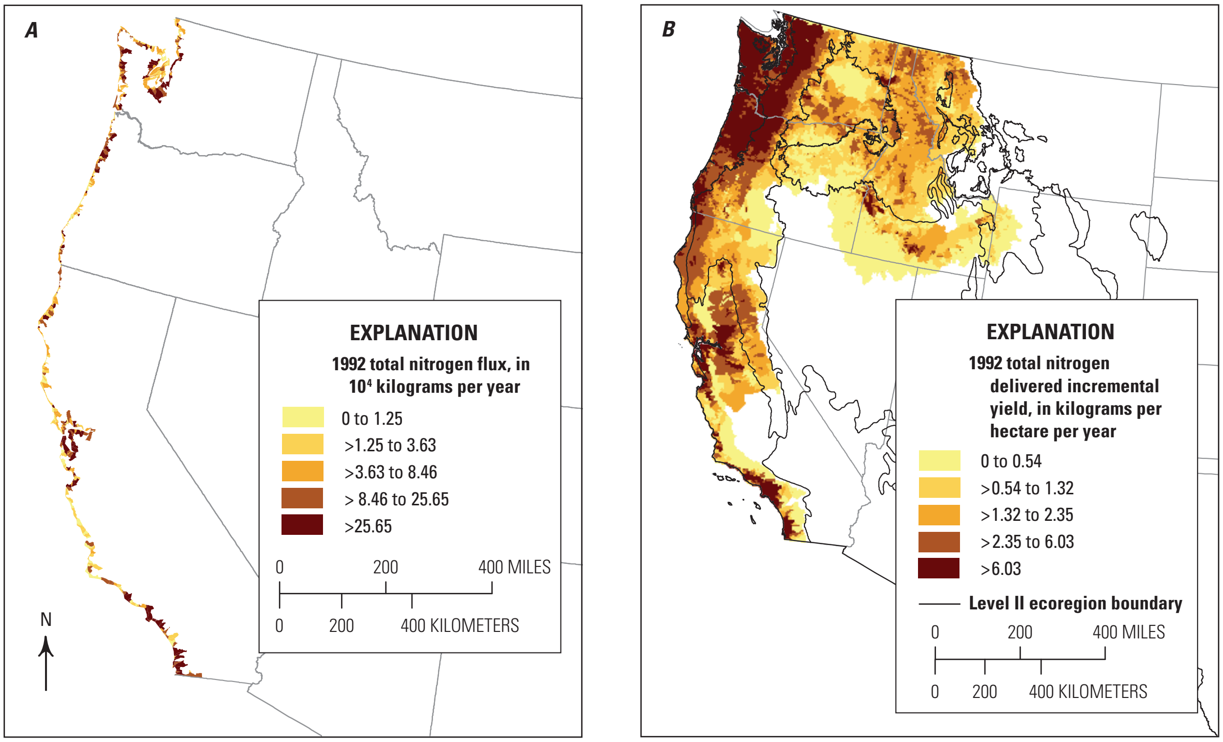


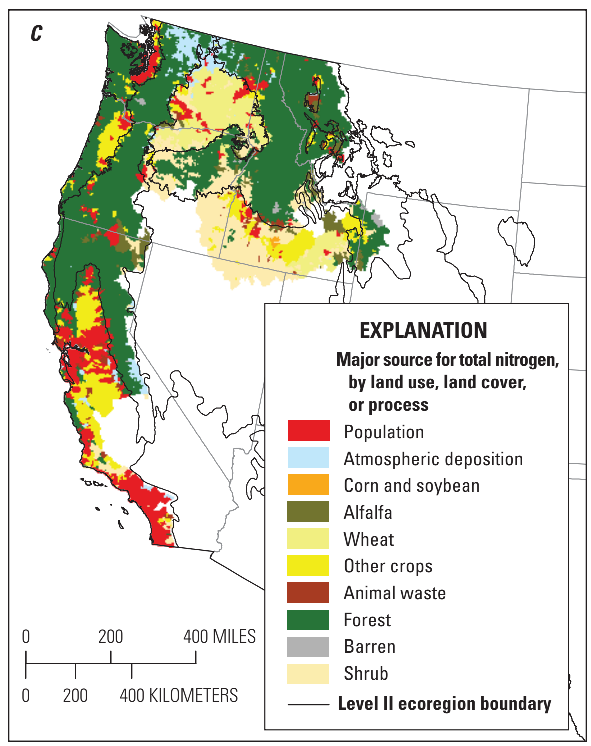
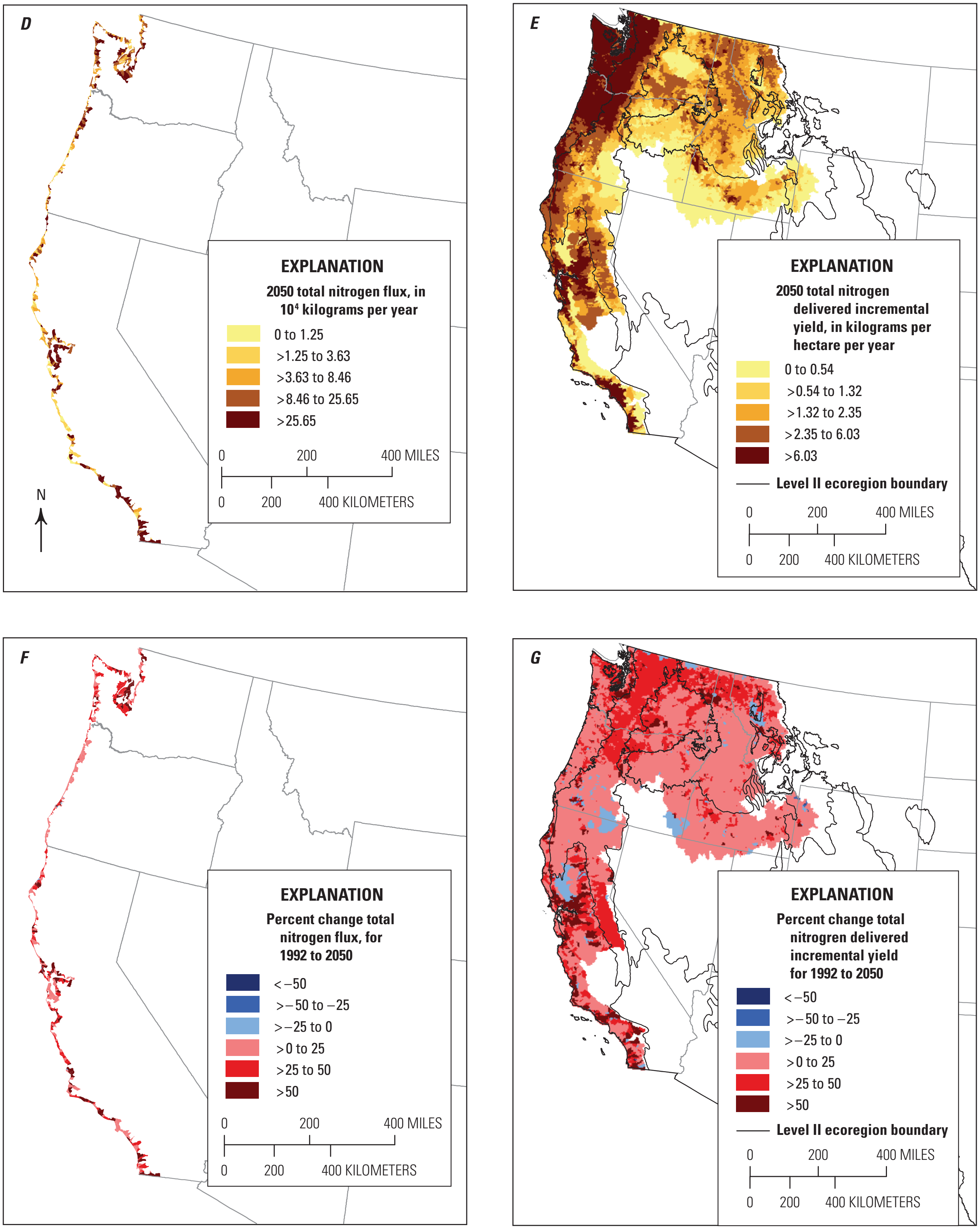


Figure 11.2. Maps showing total nitrogen flux and yield under baseline (1992) and projected (2050) conditions with projected percent change between 1992 and 2050. Flux is to Pacific coastal waters and yield is from catchments draining to Pacific coastal waters of the conterminous United States. *A*, Estimated coastal flux of total nitrogen (TN) in 10^5 kilograms per year (kg/yr) under baseline (1992) conditions. *B*, Estimated delivered yield (in kilograms per hectare per year, kg/ha/yr) of TN from catchments under baseline (1992) conditions. Delivered yield reflects the effects of in-stream nitrogen losses occurring during transport from the outlet of a catchment through the stream and river system to coastal waters. *C*, Major sources of TN in model catchments under baseline (1992) conditions. *D*, Projected estimates of coastal flux of TN (in 10^5 kg/yr) under future (2050) conditions based on IPCC–SRES scenario A2. *E*, Projected estimates of delivered yield (in kilograms per hectare per year, kg/ha/yr) of TN from catchments draining to Pacific coastal waters under future (2050) conditions. Delivered yield reflects the projected effects of in-stream nitrogen losses occurring during transport from the outlet of a catchment through the stream and river system to coastal waters. *F*, Projected percent change in estimated coastal flux of TN between 1992 and 2050 based on IPCC–SRES scenario A2. *G*, Projected percent change in yield of TN from catchments between 1992 and 2050 based on IPCC–SRES scenario A2. IPCC–SRES, Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000).



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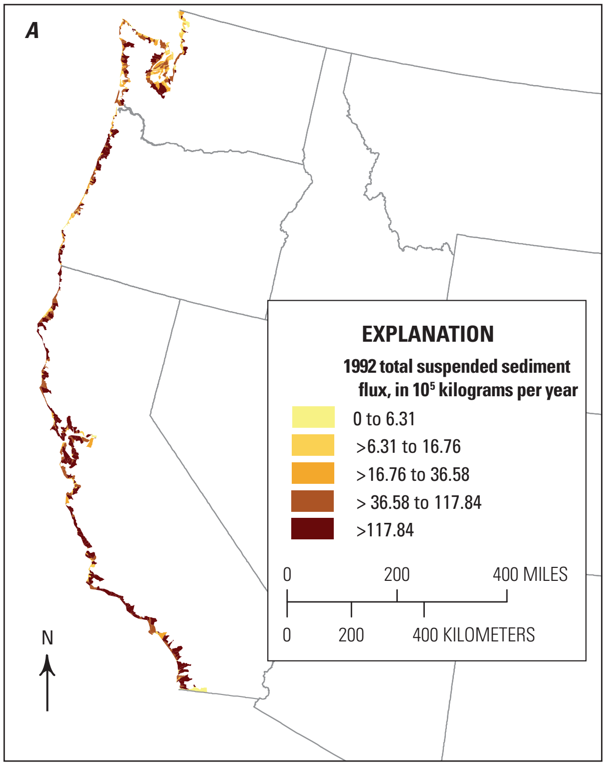

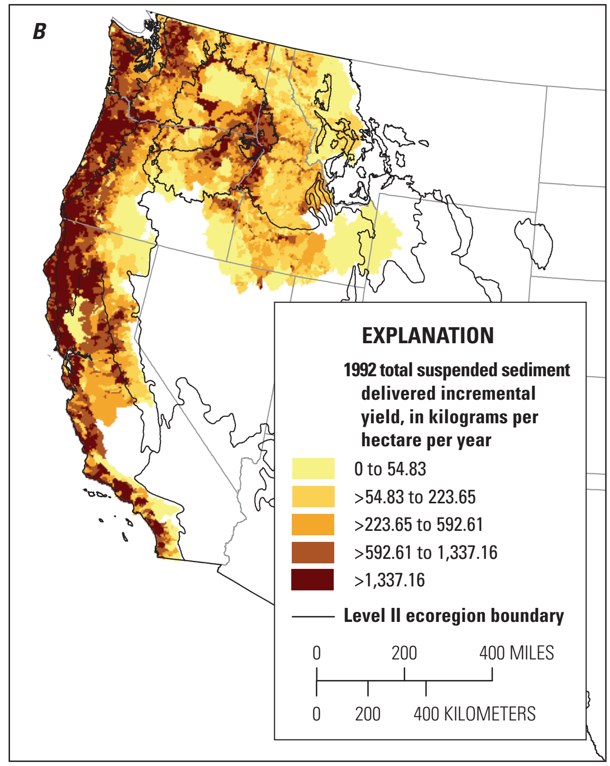

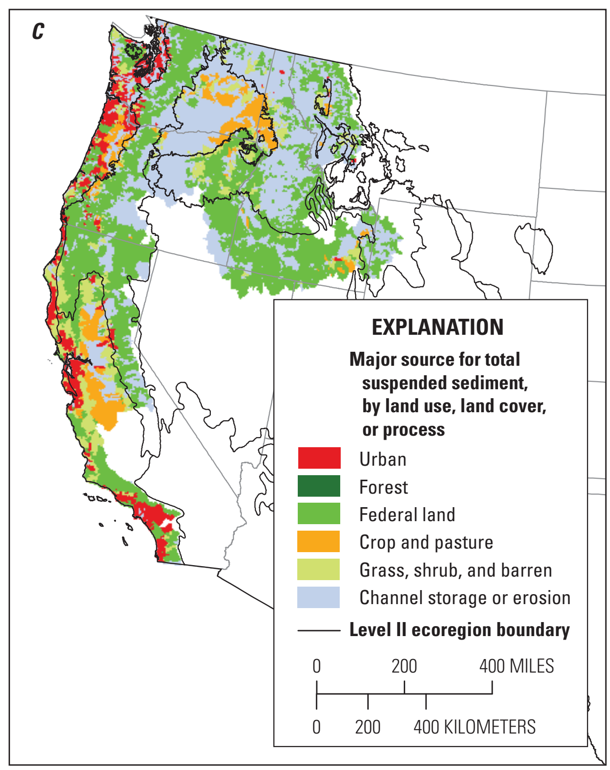

Figure 11.3. Maps showing total suspended sediment flux and yield under baseline (1992) and projected (2050) conditions with projected percent change between 1992 and 2050. Flux is to Pacific coastal waters and yield is from catchments draining to Pacific coastal waters of the conterminous United States. *A*, Estimated coastal flux of total suspended sediment (TSS) in 10^5 kilograms per year (kg/hr) under baseline (1992) conditions. *B*, Estimated delivered yield (in kilograms per hectare per year, kg/ha/yr) of TSS from catchments draining to Pacific coastal waters under baseline (1992) conditions. Delivered yield reflects the effects of in-stream suspended-sediment losses occurring during transport from the outlet of a catchment through the stream and river system to coastal waters. *C*, Major sources of TSS in model catchments under baseline (1992) conditions. *D*, Projected estimates of coastal flux of TSS (in 10^5 kg/yr) under future (2050) conditions based on IPCC–SRES scenario A2. *E*, Projected estimates of delivered yield (in kilograms per hectare per year, kg/ha/yr) of TSS from catchments draining to Pacific coastal waters under future (2050) conditions. Delivered yield reflects the projected effects of in-stream suspended-sediment losses occurring during transport from the outlet of a catchment through the stream and river system to coastal waters. *F*, Projected percent change in estimated coastal flux of TSS between 1992 and 2050 based on IPCC–SRES scenario A2. G, Projected percent change in yield of TSS from catchments between 1992 and 2050 based on IPCC–SRES scenario A2. IPCC–SRES, Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (Nakicenovic and others, 2000).

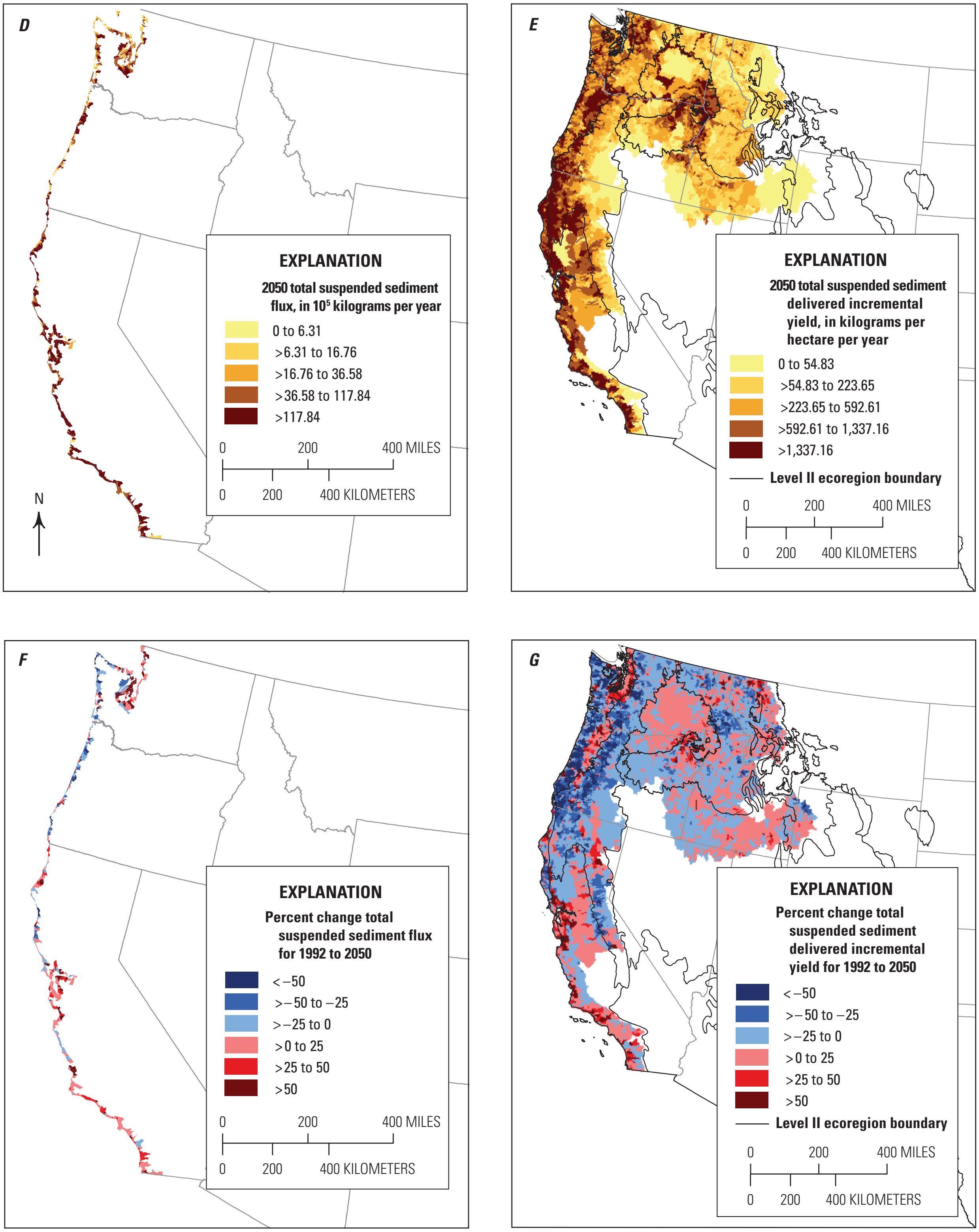

Figure 11.3.—Continued

The projected future regional changes in TSS flux to the Pacific coastal waters were mixed and included a substantial increase (23 percent) in the southern California region and decreases of 10 and 2 percent, respectively, in Oregon and Washington and in the northern California region (tables 11.3, 11.4; fig. 11.3*D–G*). The reasons for the projected changes in TSS flux vary. The large projected increase in the southern California region stemmed from projections of continued urban development, and the moderate projected decrease in Oregon and Washington stemmed largely from the projected development of marginal lands (table 11.4).

11.4.2. Carbon Processes in Coastal Waters

The baseline rate of coastal carbon storage due only to terrestrial processes in Pacific coastal waters was estimated to be 0.12 TgC/yr for the southern California region, 0.65 TgC/yr for the northern California region, and 1.25 TgC/yr, for Oregon and Washington (table 11.3). For all three regions combined, the baseline rate of total carbon storage due only to terrestrial processes was 2.0 TgC/yr (table 11.3). From 1992 to 2050, the total baseline carbon storage due only to terrestrial processes in Pacific coastal waters was roughly 100 TgC. The results suggest that under baseline conditions, approximately 82 percent of this carbon was stored at water depths less than 100 m. Between water depths of 50 and 100 m, relatively little carbon storage was due to burial in sediments (17 percent), whereas between 0 and 50 m, a moderate amount of carbon storage was due to burial in sediments (70 percent). Approximately 18 percent of the total carbon stored was in water depths below 100 m. These estimates were generally in agreement with previous estimates of sediment and carbon transport to Pacific coastal waters (Sternberg, 1986; Hales and others, 2006).

Most of the current and projected carbon storage in Pacific coastal waters occurred in regions of high nutrient and sediment load, with an estimated 62 percent of the modeled baseline carbon storage occurring in the coastal waters of Oregon and Washington (table 11.3). The Columbia River alone discharged 27.9 TgC/yr of sediment, resulting in a model-estimated rate of coastal carbon storage of 0.9 TgC/yr or 46 percent of the total carbon stored in Pacific coastal waters. The San Francisco Bay region also contributed significant nutrient and sediment fluxes and accumulated significant carbon, according to the model; however, much of this production and storage likely occurred within the San Francisco Bay, which was not modeled separately.

The changes in sediment and nutrient loadings to Pacific coastal waters under the projected land-use and population changes envisioned in the IPCC–SRES A2 scenario resulted in a change in the estimated projections of carbon that was transported and buried in the deep ocean. Under the A2 scenario in 2050, the rate of carbon storage in Pacific coastal waters was projected to increase by 33 percent in the southern California region and by 4 percent in the northern California region (table 11.3). In Oregon and Washington, however, where most of carbon storage presently occurs, the model projected a 12 percent decline in the rate of carbon storage. Taken together, the cumulative effect of projected land-use change by 2050 under the A2 scenario was a decrease in the projected rates of carbon storage in Pacific coastal waters by 4 percent overall. This decrease corresponded to a projected decrease in the total carbon storage to 112 TgC over the 58 years between 1992 and 2050, for a net difference of 3 percent.

The nutrient fluxes that support phytoplankton production Pacific coastal waters are largely supplied by seasonal upwelling (Kudela and others, 2006; Hales and others, 2008). Nevertheless, higher rates of annual phytoplankton production have been observed close to rivers (Kudela and others, 2006; Hales and others, 2008), and the model results indicated the total nitrogen supply to Pacific coastal waters may support up to 15 percent of the total production under baseline conditions (G.C. Anderson, 1964; Kudela and others, 2006). The projected cumulative changes to the rate of carbon storage in Pacific coastal waters that were due to a projected increase in nutrient exports by 2050 under the A2 scenario were relatively minor in comparison to the changes due to sediment flux; even though the projected increase in total nitrogen flux due to land-use and population change was in the range of 28 percent, there was less than a 3 percent projected increase in the total nutrients available to support phytoplankton production.

11.5. Discussion

The results indicate that the rate of carbon storage in the Pacific coastal waters that resulted directly from terrestrial processes contributed significantly to the carbon balance of the Western United States under both baseline and projected future conditions. The rate of modeled carbon storage that was due to terrestrial fluxes accounted for half to two thirds of the total estimated carbon storage in the same region (3 to 4 TgC/yr) (Hales and others, 2008). The rate of modeled carbon storage due to terrestrial fluxes is comparable to the estimated 1.2 TgC/yr rate in inland reservoirs (chapter 10), but much lower than the estimated 86 TgC/yr rate in terrestrial ecosystems (chapter 5).

The majority of terrestrial contribution to coastal carbon storage occurred in the coastal waters of Oregon and Washington under both the baseline and projected future conditions because of the large discharge of nutrients and sediments from the rivers located in that region. Sediment discharge and carbon storage was also high in the vicinity of the Eel River in the northern California region and near San Francisco Bay, but much lower in the southern California region.

The majority of the coastal carbon sequestration related to terrestrial processes resulted from the transport of TOC below the level of the pycnocline rather than burial in sediments. Of the total carbon stored, the model results suggested that approximately 70 percent was directly transported to the deep ocean and approximately 30 percent was buried in coastal sediments. For the amount buried in sediments, the model results indicated that approximately 70 percent was buried at depths less than 50 m, approximately 15 percent was buried between 50 m and 100 m depth, and the remainder (approximately 15 percent) was buried in the deep ocean. The decreased burial in the deeper zones was because of the lower sediment flux in this region and the deeper water column. These results agree with Dunne and others (2007), who suggested that previous ocean models of carbon storage rates did not account for the appreciable carbon storage that occurs in shallow coastal sediments.

The projected increase in sediment flux in the southern California region (23 percent from the baseline flux) corresponded with a projected increase in carbon storage rates in coastal waters, but the projected overall decline in sediment flux in the other regions resulted in an overall decrease in the projected coastal carbon storage rates for the region. The increase in carbon storage rates in southern California was driven by the elevated modeled fluxes from small, mountainous rivers in southern California which respond more sensitively to land-use and population changes than larger river systems, such as those in northern California and the Pacific Northwest.

Small, mountainous rivers were important generally to coastal carbon storage processes despite their relatively small watershed areas because of their large sediment loads (Milliman and Syvitski, 1992; Blair and others, 2004). For example, in 1992, the modeled sediment discharge from the Columbia River was 28 Tg/yr, while the discharge from small, mountainous rivers was 21 Tg/yr for the same year. Small, mountainous rivers, therefore, contributed 75 percent of the sediment discharge of the fourth largest river in the United States. These results indicated that small, mountainous rivers should be included in estimates of terrestrial and ocean carbon balances and that focusing only on large river systems may significantly underestimate fluxes and coastal carbon storage. The model results suggest that under the land-use projections of scenario A2 in 2050, rates of carbon storage due to small, mountainous rivers was projected to decrease by 12 percent; however, and perhaps more importantly, nutrient discharges for these rivers were projected to increase by 26 percent.

The concomitant increase in sediment and nutrients in small, mountainous rivers has the potential to increase carbon storage rates beyond that which was estimated by the model because the projected increase in nutrients may stimulate additional phytoplankton production at the same time and location that sediment fluxes are projected to increase (Wheatcroft and others, 2010). Normally, phytoplankton production is elevated in the summer due to the upwelling of nutrient-rich waters, while sediment flux peaks in winter with peak river discharge (Wheatcroft and others, 2010). The projected coincidence of phytoplankton production and sediment concentration is expected to accelerate the transport of phytoplankton carbon from the surface ocean to the deep ocean (Armstrong and others, 2009) and, therefore, increase carbon burial efficiency.

The projected increases in nutrient fluxes that would result from land-use and population changes under the A2 storyline in 2050 may have additional effects that were not captured by the model. Depending on future water-quality regulations and the form of the nutrients, the additional nutrients may (1) exacerbate hypoxia that has been periodically observed at the mouth of the Columbia and elsewhere on the Pacific Coast or (2) stimulate the production of harmful algal blooms (Glibert, 2010). Despite the obvious deleterious effects on water quality, broader areas of hypoxia in surface or bottom water will likely increase the rates of carbon storage in these regions (Bergamaschi and others, 1997).

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