Chapter 6
The Effects of Land Cover and Land Use Change on the Contemporary Carbon Balance of the Arctic and Boreal Terrestrial Ecosystems of Northern Eurasia

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Abstract Recent changes in climate, disturbance regimes and land use and management systems in Northern Eurasia have the potential to disrupt the terrestrial sink of atmospheric CO_2 in a way that accelerates global climate change. To determine the recent trends in the carbon balance of the arctic and boreal ecosystems of this region, we performed a retrospective analysis of terrestrial carbon dynamics across northern Eurasia over a recent 10-year period using a terrestrial biogeochemical process model. The results of the simulations suggest a shift in direction of the net flux from the terrestrial sink of earlier decades to a net source on the order of 45 Tg C year^{-1} between 1997 and 2006. The simulation framework and subsequent analyses presented in this study attribute this shift to a large loss of carbon from boreal forest ecosystems, which experienced a trend of decreasing precipitation and a large area burned during this time period.

6.1 Introduction

Carbon dioxide concentrations in the atmosphere have been rapidly increasing over the last century and an increase in global surface air temperature (Jones and Moberg 2003; Hansen et al. 2006), particularly since the 1980s (Alley et al. 2003; Johannessen et al. 2004), has been attributed to this increase in radiatively active gases (IPCC 2007). Terrestrial ecosystems have potentially critical, but not fully known, feedbacks with a changing climate as a function of surface energy balance and the patterns of sources and sinks of atmospheric carbon dioxide (CO_2) and other greenhouse gases (Chapin et al. 2008; Field et al. 2007; Houghton 2003). In addition to climate forcings, natural disturbances and human activities can substantially alter the patterns and affect the underlying processes that create and transform these terrestrial sources and sinks (Houghton et al. 2004; Schimel et al. 2001).

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Recent studies have revealed surface air temperature increases on average of 0.35°C per decade from 1970 to 2000 for terrestrial regions between 50 and 70°N (Euskirchen et al. 2007; Serreze and Francis 2006). Elevated CO_2 levels and warmer temperatures may create a negative feedback to climate through expansion of higher productivity ecosystems into arctic regions (Tape et al. 2006; Sturm et al. 2001) and increased carbon (C) uptake by vegetation (Kimball et al. 2007). These processes are potentially offset, or even overtaken, by positive feedbacks through changes in surface energy balance (Chapin et al. 2005; Brovkin et al. 2006) and increased CO_2 respiration and methane (CH_4) release from arctic tundra and boreal forest soils (Zhuang et al. 2007). Further, evidence suggests that changes in climate are increasing the frequency and severity of forest fires (Kasischke and Turetsky 2006; Soja et al. 2007) and insect outbreaks (Kurz et al. 2008), creating a large source of CO_2 to the atmosphere from boreal forest regions. Potential longer-term mitigation of this source (i.e., negative feedbacks on climate forcing) by changes in energy balance following disturbance is not completely understood (Randerson et al. 2006a; Goetz et al. 2007).

6.1.1 Scope and Objectives of the Analysis

The objective of this analysis is to determine the recent trends in the terrestrial C balance of Eurasian arctic and boreal ecosystems, with a focus on the role of land-cover and land-use change processes in these dynamics. Studies based on inversion modeling or forest inventory data are able to provide estimates of net C exchange between the land and the atmosphere as well as the total terrestrial C budget, respectively. While such approaches can be used to generate overall estimates of terrestrial C exchange, they do not individually consider the effects of particular controlling factors (i.e., land-cover/land-use and other environmental changes) and thus do not allow for explicit valuation of the underlying mechanisms that drive these exchanges. Furthermore, these studies that have been conducted to date are not sufficiently current as to ascertain the latest trends in the terrestrial C dynamics or their response to recent changes in disturbance, land use and environmental conditions.

Process-based simulation modeling is a fundamental tool for understanding and reducing uncertainty with respect to ecosystem responses to climate and disturbance, and for extrapolating these processes over time and space – the key step in predicting the future response of climate and ecosystem function. Simulation frameworks can be designed to assess the influence of various controlling factors on C dynamics and quantify their effects (e.g., McGuire et al. 2001). To understand the role of land cover and land use change on regional C balance, it is necessary to evaluate their effects in the context of other climatic and environmental changes. An approach based on ecosystem process simulation modeling, then, can be used to extrapolate estimates of C exchange beyond the spatial and temporal extents of the inverse modeling and inventory data studies described above, as well as to investigate hypotheses relating to the attribution of mechanisms and controlling factors in determining C balance.

For this study, we employ a terrestrial ecosystem biogeochemistry model, driven by spatially- and temporally-explicit climatology, ecological data, disturbance, and land-cover/land-use data sets, to perform a retrospective analysis of terrestrial C dynamics across Northern Eurasia over the last decade (1997–2006). To drive these simulations, we used updated and contemporary input data sets to generate more up-to-date (through 2006) estimates of C balance than previous studies, incorporating recent changes in climate, disturbance and land use across the region. The simulation framework was designed to investigate the individual effects of changing atmospheric CO_2, atmospheric chemistry and climate variability, fire, forest management and agricultural land use. This study design provided the opportunity to evaluate the effect of the recent trends in land cover and land use change, in the context of other factors, on the contemporary C balance of the region. The goal of the analysis was to detect any recent changes in the C balance of Northern Eurasian ecosystems, with respect to earlier studies, and to identify the factors driving these changes.

6.2 Methods

6.2.1 Overview

To evaluate the relative importance of land-cover/land-use change (LCLUC) factors and non-LCLUC factors on terrestrial C dynamics in Northern Eurasia, we conducted five model simulations using different combinations of factors (see Section 6.2.4) as driving variables into the Terrestrial Ecosystem Model (TEM). For non-LCLUC factors, we considered CO_2 fertilization, and the combined effects of climate variability, ozone pollution and atmospheric nitrogen (N) deposition on terrestrial C balance. For LCLUC factors, we considered disturbance by wildfire, and the land uses of agriculture (row crops and pastures) and timber harvest. Here, we report on the comparison of model estimates of C stocks and fluxes among the simulations for the analysis time period of 1997 to 2006. To initialize the C, N and water pools for the beginning of the analysis period (i.e. January 1997), we simulated C dynamics since the year 1000 in each model run. The methods used to generate comprehensive and continuous driving variables for year 1000–2006 were specific to each input data set, and are described below.

6.2.2 The Terrestrial Ecosystem Model

The Terrestrial Ecosystem Model (TEM) is a process-based ecosystem model that uses spatially referenced information on atmospheric chemistry, climate, elevation, soils, and land cover to estimate monthly terrestrial C, N, and water fluxes and pool

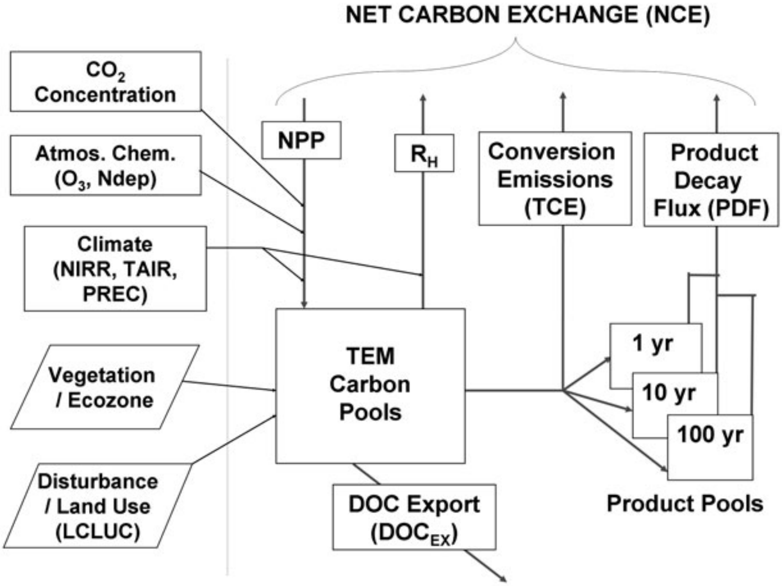

Fig. 6.1 A conceptual illustration of the effects of CO_2 fertilization, atmospheric chemistry, climate variability, vegetation type, land use and multiple disturbances on terrestrial C dynamics, as simulated by the Terrestrial Ecosystem Model (TEM). This diagram depicts Net Carbon Exchange (NCE) of the terrestrial system with the atmosphere as the balance between C inputs via net primary production (NPP) and C losses to the atmosphere through heterotrophic respiration (R_H), the direct emissions due to disturbance and land use conversion (TCE) and the combined flux from the decay of the three post-disturbance product pools (PDF). For this study, TEM calculates the overall C balance for the system as Net Ecosystem Carbon Balance (NECB), which includes NCE plus additional C losses from the terrestrial system through the leaching flux of dissolved organic C via stream export (DOC_{EX})

sizes. Driven by these various input data sets, TEM can be set up to incorporate the effects of both LCLUC and non-LCLUC factors on terrestrial C dynamics (Fig. 6.1). TEM is well-documented and has been used to examine patterns of terrestrial C dynamics across the globe, including how they are influenced by multiple factors such as CO_2 fertilization, climate change and variability, row-crop agriculture, wildfire and ozone pollution (Melillo et al. 1993; McGuire et al. 1997, 2000a,b, 2001, 2004; Tian et al. 1998, 1999, 2000, 2003; Xiao et al. 1998; Prinn et al. 1999; Reilly et al. 1999, 2007; Clein et al. 2000, 2002; Webster et al. 2003; Zhuang et al. 2003, 2006, 2007; Felzer et al. 2004, 2005, 2007; Brovkin et al. 2006; Euskirchen et al. 2006; Balshi et al. 2007; Sokolov et al. 2008).

For this study, we used a version of TEM that has been modified from Felzer et al. (2004), which simulated ozone pollution effects, to also include the influence of permafrost dynamics (Zhuang et al. 2003; Euskirchen et al. 2006), atmospheric N deposition, dissolved organic carbon (DOC) leaching, wildfire, pastures and timber harvest on terrestrial C dynamics. To simulate the effects of N deposition, NH_x

and NO_y from prescribed atmospheric sources are added to the available N pool within TEM for potential uptake by microbes and vegetation. DOC is assumed to be produced by the incomplete decomposition of soil organic matter (SOM) and DOC leaching losses are associated with water yield from the ecosystem. The treatment of permafrost dynamics, and their influence on the availability of SOM for decomposition, has also been modified in this new version of TEM. Instead of a fixed rooting depth, the amount of SOM available for decomposition in a particular month is determined by the proportion of the SOM found within a varying active layer depth. As the permafrost thaws and the active layer depth increases, the relative amount of SOM available to decompose increases.

The TEM is calibrated to site-specific vegetation parameters (Raich et al. 1991; McGuire et al. 1992; Clein et al. 2000; 2002, 2007; Euskirchen et al. 2006) and extrapolated across the study area based on spatially-explicit time-series data organized on a 0.5° latitude by 0.5° longitude grid. The model uses a monthly time-step to simulate ecosystem dynamics for each "cohort" in a non-spatial mosaic of cohorts representing unique vegetation types and disturbance histories within each grid cell. In this study, we simulate terrestrial C dynamics under four different land uses (natural, row-crop agriculture, pasture, timber harverst) along with the influence of wildfire and the conversion of land from one use to another on these dynamics. The simulation of these LCLUC dynamics by TEM have been described previously for natural ecosystems (e.g., Melillo et al. 1993; Tian et al. 1999), row-crop agriculture (Felzer et al. 2004), wildfire (Balshi et al. 2007), and the conversion and abandonment of land to/from row-crop agriculture (McGuire et al. 2001; Felzer et al. 2004).

6.2.3 Driving Data Sets

To extrapolate TEM across Northern Eurasia, we incorporated driving data sets that have (1) spatial variability, but no temporal variability (elevation and soil texture); (2) temporal variability, but no spatial variability (atmospheric CO_2 concentration); and (3) temporal and spatial variability (air temperature, precipitation, solar radiation, AOT40 ozone (O_3) index (a measure of the accumulated hourly ozone levels about a threshold), atmospheric N deposition, and land cover including fire disturbance. The non-temporal-varying spatial datasets were aggregated to 0.5° spatial resolution, with elevation based on the TerrainBase v1.1 data set from the National Geophysical Data Center, Boulder, CO (NGDC 1994) and soil texture from the Global Gridded Surfaces of Selected Soil Characteristics data set (Global Soil Data Task Group 2000).

Most of the temporally varying datasets have been used in previous studies, but needed to be extended from 2000 or 2002 to 2006, as well as "backcasted" to year 1000 of the model initialization period, for use in this study. Global annual atmospheric CO_2 data are from the Mauna Loa station (Keeling and Whorf 2005). Atmospheric CO_2 concentration for the time period of years 1000–1900 was held constant at the year 1901 level (296.3 ppm). Monthly surface air temperature (TAIR, °C), precipitation (PREC, mm), and incident short-wave solar radiation (NIRR, W m^{-2}) data derived from observations for the period 1901–2002, gridded at 0.5° resolution, were obtained from the Climate Research Unit (CRU; University of East Anglia, UK; Mitchell and Jones 2005). The CRU climate variables were extended to 2006 with National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis one data sets (NOAA-ESRL Physical Sciences Division, Boulder, CO, USA) using a regression procedure based on data anomalies from a 10-year (1993–2002) mean for each variable (see Drobot et al. 2006). These data sets were back-casted to year 1000 by a repeating 30-year cycle of the 1901–1930 monthly data to initialize the C pools with climate variability (except for the simulation without climate variability, where 1901–1930 monthly means were used to drive the model for each year). The ozone (O_3) pollution data set used in this study, represented by the AOT40 index, is based on Felzer et al. (2005) and covers the time period from 1860 to 2006. Before 1860, the ozone level in each 0.5° grid cell was assumed to equal the AOT40 of 1860 (which is equal to zero). The atmospheric N deposition data were based on Van Drecht et al. (2003), extended from 2000 to 2006 by adding the difference in annual N deposition rate from 1999 to 2000 to succeeding years, for each 0.5° grid cell (e.g., 2001 N deposition rate = 2000 + (2000–1999), etc.). For years 1000–1859, annual N deposition was assumed to equal the per grid cell rates in 1860.

To enable the evaluation of different LCLUC activities, we have developed a number of spatially explicit LCLUC time series data sets to prescribe the timing, area and distribution of historical LCLUC, including wildfire, over Northern Eurasia. The distribution of vegetation types was derived from the 1-km Global Land Cover Characterization (GLCC; Loveland et al. 2000) data set, which was translated to the upland arctic, boreal and temperate ecosystem types for which the TEM is calibrated. The translated vegetation map was aggregated to the 0.5° grid matching the input climate data sets, but the area represented by each unique vegetation type within a grid cell was retained as an individual, non-spatial cohort. A more detailed description of the creation of this vegetation data set is given in Krankina et al. (see Chapter 5, this volume).

To represent the influence of land-use change on terrestrial carbon dynamics, TEM now uses a dynamic cohort approach. In this approach, TEM initially assumes a grid cell is covered by undisturbed natural vegetation, or "potential vegetation", which is represented by initial cohorts that collectively sum to the entire land area of the grid cell. When a disturbance occurs, a new cohort is formed and a certain amount of land area within the grid cell is then subtracted from the potential vegetation cohort and assigned to the new disturbed cohort. As time progresses in the TEM simulation and more disturbances occur, more cohorts are added to the grid cell. As each disturbance and its effects are tracked separately within TEM, different types of disturbances within a grid cell can be considered simultaneously and allows TEM to consider the impacts of multiple disturbances on terrestrial C and N dynamics (details for the input data on vegetation disturbances are given in Chapter 5, this volume).

For Eurasia, the land use transitions data set was backcasted to the start of the initialization period by linearly "ramping-up" the transitions rates from 0% per year (for each $1^\circ \times 1^\circ$ grid cell) in year 1000 to the year 1700 rates. The data were extended by simply using the 2000 rates for year 2001–2006.

6.2.4 Simulation Framework

To quantify the effects of the various controlling factors considered in this study on terrestrial C dynamics in Northern Eurasia, we conducted a series of five model simulations. The simulation framework was designed to allow an analysis of the relative contribution of LCLUC and non-LCLUC factors to the overall C balance of the system over the recent 10-year period (Table 6.1). Each simulation, labeled S1 through S5, builds upon the potential vegetation data set by incorporating an additional transient data set at each successive model run. The first simulation (S1) was driven by interannually non-varying climate and atmospheric data sets (with each year represented by mean monthly data calculated from the 1901–1930 time period), where land cover is assumed to be potential vegetation throughout the model run (i.e., no disturbance or land use), and with the global annual atmospheric CO_2 level being the only transient data set. The transient climate and atmospheric chemistry data sets (O_3 pollution and N deposition) were added to varying CO_2 level to drive all subsequent simulations, with the second (S2) based on undisturbed potential vegetation. In each successive model run, a new disturbance data set was imposed on potential

Table 6.1 The framework for the multiple TEM simulations conducted and data sets used to analyze different LCLUC and non-LCLUC controlling factors on C balance over the study area. The input data sets are added sequentially in each successive simulation, so that the S5 simulation includes all effects (total), and each effect is isolated by subtracting the results from the previous simulation

Simulation	Effects	Variables and data sets
Non-LCLUC Factors		
S1	Vegetation type	Potential vegetation (Loveland et al. 2000)
	+ CO_2	Global annual CO_2 (Keeling and Whorf 2005)
S2	+ Climate variability	TAIR, PREC, NIRR (CRU and NCEP data sets)
	+ Atmospheric chemistry	O_3 (Felzer et al. 2005), N dep (Van Drecht et al. 2003)
LCLUC Factors		
S3	+ Fire	Area Burned (Sukhinin et al. 2004; Balshi et al. 2007; Randerson et al. 2006b)
S4	+ Agriculture	Crop/pasture establishment and abandonment (Hurtt et al. 2006)
S5	+ Forest harvest (Total effect)	Area harvested (Hurtt et al. 2006)

vegetation and, along with transient CO_2 and climate, was used to drive the S3 (area burned), S4 (land use) and S5 (forest harvest) simulations. To distinguish the effects of wildfire, agriculture and timber harvest, essentially three unique LCLUC data sets were developed for this study: one that includes only the occurrence of wildfire, a second that prescribes fire and agricultural (crops and pastures) establishment and abandonment, and a third that incorporates fire, agriculture and timber harvest.

Since the transient data sets were individually added in each successive run, the effects of each on C stocks and change were determined by subtracting the results of a simulation from those of the subsequent run. Specifically, climate and atmospheric chemistry effects were determined by subtracting S1 results from the S2, fire by S2 from S3, agriculture by S3 from S4 and forest harvest by S4 from S5. In addition, we report the effect of CO_2 fertilization from the S1 results, the combined disturbance and land use effect (LCLUC effect) as S5 minus S2, and the total effect of all controlling factors considered here as the S5 results. Note that with this simulation framework being built in an "additive" fashion, as opposed to a full factorial analysis, any effects reported contain both the direct effects of the factor being considered plus any interactions with the factors included in the preceding simulations.

6.2.5 Data Analysis

The model produces monthly estimates of C stocks from vegetation, reactive SOM, non-reactive SOM, DOC, and three harvest product pools (1-, 10- and 100-year; see McGuire et al. 2001) for each cohort over the length of the simulation. We report the sum of these C stocks as annual total ecosystem C. Annual changes in C stocks are calculated as the difference of the December standing stocks of successive years. Total changes in C stocks for our analysis period are determined as the difference in standing stocks between December 1996 and December 2006 and are reported as an average annual change in teragrams (Tg) of C year^{-1} (10^{12} g C year^{-1}). This average annual change in C stocks reported here represents the net ecosystem C balance (NECB) of the system (see Chapin et al. 2006), the sum of all fluxes into and out of the terrestrial system (Fig. 6.1):

$$\mathrm{NECB} = \mathrm{NPP} - (\mathrm{R_H} + \mathrm{TCE} + \mathrm{PDF} + \mathrm{DOC_{EX}}) \tag{6.1}$$

where NPP is net primary production, R_H is heterotrophic respiration, TCE represents the total C emissions due to disturbance and land use conversion, PDF corresponds to the combined flux from the decay of the three post-disturbance product pools, and DOC_{EX} is DOC export from the terrestrial system. The vertical flux, or net C exchange between the terrestrial system and the atmosphere (NCE), is determined by the difference between NPP input and the sum of C emissions from R_H, TCE and PDF. As such, NECB does not equate exactly to NCE, because it also includes the lateral leaching flux of DOC via stream export.

We compared the modeled C balance responses to climate, disturbance and land use effects with temporally- and spatially-explicit climatology and LCLUC data for the Northern Eurasia study area over the 1997–2006 analysis period. In this analysis, we report the cohort-level results aggregated to broad vegetation categories, as well as for the total study area, to illustrate the differences in C balance responses among the major ecological zones ("ecozones") of the region. These ecozones, based on the input potential vegetation layer, include arctic tundra (prostrate and shrub vegetation), boreal forest (needleleaf evergreen and deciduous and broadleaf), temperate forest (evergreen and deciduous) and other non-forest types (xeric wood and shrub lands, grasslands, croplands and pastures). LCLUC effects on C balance within and across ecozones were compared with area burned, forest area harvested, and the area in crops and pastures.

Climate effects were compared with trends in average annual surface air temperature (TAIR, °C) and total annual precipitation (PREC, mm) over the time period, with the trend defined as the slope of the regression relationship of the climate variable on year. The overall trends for the 1997–2006 time period are reported as the annual trends aggregated to the 10-year time period (decade^{-1}). Anomalies in the climate variables for each year in the analysis period were calculated as the deviation from long-term means for TAIR and PREC from a previous 30-year time period, 1961–1990. To report climate trends and anomalies separately for an individual ecozone, we used in the calculation only those grid cells that had a majority area coverage (>50%) by that ecozone.

6.3 Results

6.3.1 General Trends

Overall, our study suggests that the Northern Eurasia region as a whole is losing C from terrestrial ecosystems on average of 44.5 Tg C year^{-1} from 1997 to 2006 (Table 6.2). Both climate and LCLUC variability had negative (source) effects on

Table 6.2 The quantitative effects, of the controlling factors considered amongst the various simulations in this study, on total ecosystem C balance (Tg C year^{-1}) for the major ecozones of the study area, for the 1997 to 2006 analysis period

	Ecozones				
Effects	Tundra	Boreal forest	Temperate forest	Other	Total study area
CO_2 (S1)	13.0	44.0	3.02	0.40	60.5
Climate (S2−S1)	13.0	−32.2	3.06	−0.92	−17.1
Non-LCLUC (S2)	26.0	11.8	6.08	−0.52	43.4
Fire (S3–S2)	4.25	−80.0	1.0	−1.0	−75.8
Agriculture (S4–S3)	−3.64	−1.04	−0.27	1.17	−3.78
Harvest (S5–S4)	0.00	−8.97	0.64	0.00	−8.33
LCLUC (S5–S2)	0.61	−90.0	1.40	0.12	−87.9
Total (S5)	26.7	−78.2	7.48	−0.40	−44.5

regional C balance, with disturbance and land use having the largest magnitude effect on the total study area of the controlling factors considered here. The combined negative (source) effect of about 105 Tg C year^{-1} on the regional C balance from climate, atmospheric chemistry and disturbance responses is partially offset by a nearly 61 Tg C year^{-1} positive effect (sink) from CO_2 fertilization. The study area as a whole lost an estimated 17 Tg C year^{-1} from the terrestrial ecosystems in response to variability in climate and atmospheric chemistry (S2−S1 simulation results). The model simulations estimate that the region all together lost 88 Tg C year^{-1} over the time period in response to the combined effect of disturbance, forest management and land use (S5−S2 simulations). Fire, agriculture and forest harvest each individually produced negative (source) effects on the C balance for the study area, with fire by far contributing the majority of the LCLUC-driven source (76 Tg C year^{-1}).

While the study area as a whole was estimated to be acting as a source of C during the time period of analysis, closer inspection of the broad ecozone categories demonstrates that these ecosystems have considerable variation in C balance with respect to the effects of the controlling factors of the simulations (Table 6.2). In terms of the total effects (S5 simulation), the majority of the C source across the study area was found in the boreal forest ecozone. The 78 Tg C year^{-1} loss of total ecosystem C from the boreal zone was partially offset, however, by net C accumulation in the other ecozones, primarily corresponding with the nearly 27 Tg C year^{-1} net sink in the arctic tundra ecozone. The C accumulation over the 10-year period in the tundra and temperate forest ecosystems was largely driven by the positive (sink) effects of CO_2, atmospheric chemistry and climate (S1 and S2 simulations), while the majority of the C release (source) from the boreal forest ecozone was due to the LCLUC effect (S5−S2 simulation results).

6.3.2 Non-LCLUC Effects

The global annual CO_2 concentration in the atmosphere increased by 14.9 ppm over the 10-year period, up to 378.7 ppm in 2006. The 60.5 Tg C year^{-1} sink estimate from the S1 simulation (Table 6.2) equates to an overall effect of 6.4 g C m^{-2} year^{-1} across the study area from CO_2 fertilization. Comparing the per-area effects of the different major ecozones illustrates the variability in the strength of this effect across the region. Among ecozones, the effect of CO_2 on total ecosystem C stocks was strongest in the boreal forest, at 10.6 g C m^{-2} year^{-1} averaged over the 1997–2006 time period. A substantially smaller sink effect of 3.2 g C m^{-2} year^{-1} was estimated for the tundra ecozone. Within each ecozone, the positive CO_2 effect was generally of similar magnitude to the climate effect. While CO_2 fertilization enhanced the climate sink in arctic tundra and temperate forests, the negative climate effects observed for the boreal forest and non-forest ecozones mostly or completely offset the positive CO_2 effect.

The study area as a whole was warmer and wetter during the analysis period (1997–2006) relative to the reference period (1961–1990), with an overall average TAIR anomaly of 0.7°C year^{-1} and PREC anomaly of 10 mm year^{-1}. An examination of the variation in C balance of the individual ecozones in the study area suggests that they may be responding differently to changes in climate and atmospheric chemistry over the time period (Table 6.2). The climate-driven sink (positive effect) of 13 Tg C year^{-1} in the arctic tundra ecozone was in response to increases in TAIR and PREC during the analysis period (1997–2006) of 0.7°C year^{-1} and 1.4 mm year^{-1}, respectively, relative to the reference period (1961–1990), while the boreal zone, in contrast, showed a negative (source) climate effect of about 32 Tg C year^{-1} over the 10-year period with a similar increase in TAIR (0.7°C year^{-1}) and a larger average PREC anomaly (13 mm year^{-1}). Similarly, but to a lesser degree, warmer and wetter climate changes produced a slight positive effect in the temperate zone and a small negative effect in the non-forest zone. The net result was an overall negative climate effect on the study area as a whole in response to general increases in TAIR and PREC during the analysis period, which could be mostly attributed to the climate-driven C source corresponding to the boreal forest.

Arctic tundra and boreal forest comprise the two major ecozones in the region in terms of area coverage and ecosystem C stocks (Chapter 5, this volume), and this analysis indicates that these ecozones have experienced markedly different overall trends in climate during the 1996–2006 time period. The temporal patterns in the climate data suggests that C stocks among the individual ecozones may not necessarily be responding to observed differences in climate relative to the reference period, but rather to variation in TAIR and PREC trends during the analysis period. Figure 6.2 illustrates the responses of vegetation and soil C stocks for each of these ecozones to trends in TAIR and PREC over this time period. The climate effects (S2−S1 simulation results) on the cumulative change in total ecosystem C stocks follow the general climate trends, with tundra C stocks accumulating in response to strong, increasing trends in both TAIR and PREC, and C loss from the boreal zone corresponding to a strong decreasing PREC trend (with a relatively weak trend in TAIR). In the tundra ecozone, C was accumulated in both the vegetation and soil pools at rates of similar magnitude (7.1 and 5.9 Tg C year^{-1}, respectively), contributing more-or-less equally to the overall climate-driven sink in tundra ecosystems over the analysis period. While vegetation C stocks increased in the boreal ecozone over this time period (19.7 Tg C year^{-1}), this accumulation was overwhelmed by a substantial loss of soil C in response to climate effects (−51.9 Tg C year^{-1}).

6.3.3 LCLUC Effects

The large, negative effect of LCLUC on the total ecosystem C balance of the region was almost entirely a consequence of the −90 Tg C year^{-1} effect in the boreal forest ecozone, which was the largest magnitude effect of any of the controlling factors considered in this study (Table 6.2). The boreal ecozone had the largest area

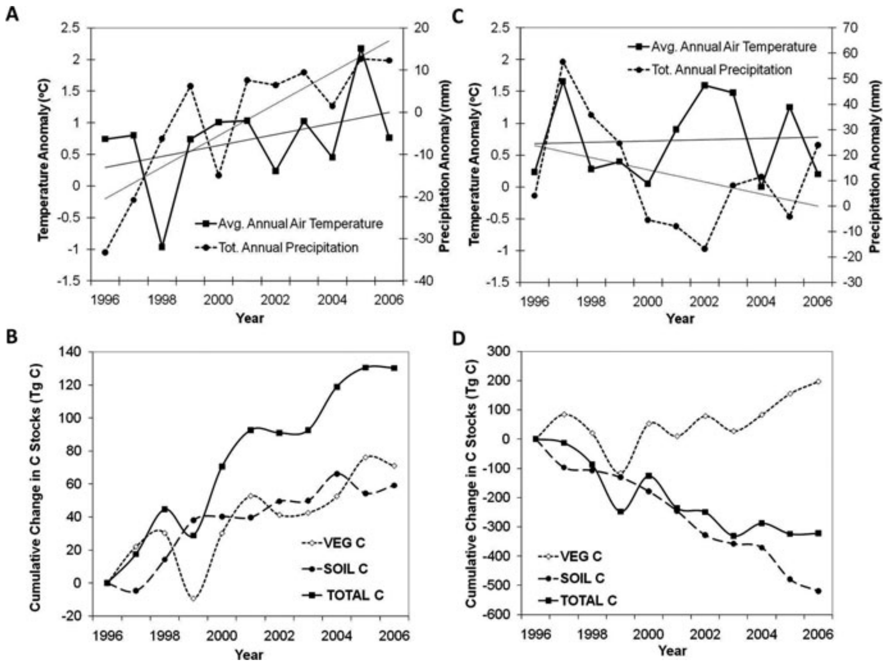

Fig. 6.2 The temporal trends in air temperature and precipitation data and the climate effects on C stocks in vegetation and soil of arctic tundra and boreal forest ecosystems. **Panel A** plots the annual anomalies (as compared to the 1961–1990 reference period) in average annual surface air temperature and total annual precipitation over the tundra ecozone for the analysis period, with the trend lines for each variable superimposed on the annual data. Climate data points from 1996 are also shown for comparison with the C stock plots (cumulative since December 1996) below. **Panel B** shows the response of tundra C stocks according to the climate effects (S2–S1 simulation results), with cumulative change in vegetation, soil stocks and total ecosystem C stocks since December 1996 shown for the analysis period. The same climate anomalies and changes in C stocks are shown for the boreal forest ecozone in **panels C** and **D**, respectively

affected by fire and forest harvest, with 52% of the forest harvest and 86% of the area burned in the total study area contained in this ecozone. Relative to the area of each ecozone, the temperate forest had the highest percentage of area affected by LCLUC, with 10% harvested over the 10-year period. Combined with low levels of fire, this resulted in a small positive (sink) LCLUC effect in the temperate forest ecozone. The non-forest ecozone also had a small positive LCLUC effect, with an area burned that, although less in total, was a slightly greater percentage of its area than that of the boreal zone (3.9–3.5%, respectively). In addition to area burned, this ecozone includes agricultural areas (crop and pasture lands) in its results. There was also a small positive LCLUC effect for the arctic tundra ecozone, which had less than 0.2% of its area burned over the time period. The combined positive LCLUC effect of less than 4 Tg C year^{-1} from the three other ecozones did little toward offsetting the large negative effect in the boreal zone.

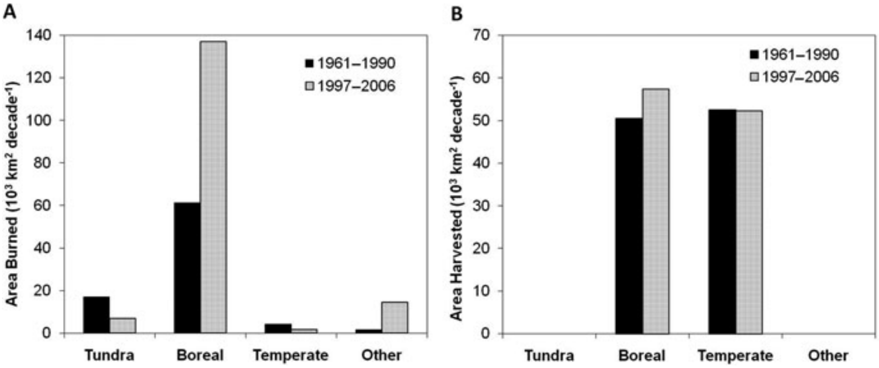

Fig. 6.3 (**panel A**) Comparison of the area burned and (**panel B**) area harvested by ecozone during the analysis period (1997–2006) relative to the average per decade area affected during the reference period (1961–1990)

To understand the role that LCLUC processes play in the contemporary C budget of Northern Eurasian terrestrial ecosystems, the magnitudes of fire and forest harvest during the 1997 to 2006 analysis period, for each of the major ecozones, are reported and compared to the longer-term average data from the 1961–1990 reference period (Fig. 6.3). Nearly 160×10^3 km^2 were burned over this decade (about 2% of the total study area), the majority of which occurred in the boreal forest ecozone (Fig. 6.3a). The total area burned during the analysis period represented a 76×10^3 km^2 increase over the per-decade average area burned estimated by the fire return interval backcasting approach (Balshi et al. 2007) for the 1961–1990 reference period. Approximately 110×10^3 km^2 of forest were harvested during the analysis period (~2.5% of the combined boreal and temperate forest area), a 6% increase in area according to the modeled data (Hurtt et al. 2006) from the reference period (Fig. 6.3b). The total area of forest harvested was more-or-less evenly distributed between boreal and temperate forests in both the analysis period (57×10^3 km^2 and 52×10^3 km^2, respectively) and the reference period (51×10^3 km^2 and 53×10^3 km^2, respectively). The methodology used in this study whereby the coarse resolution ($1°\times1°$) modeled forest-harvest transition data (Hurtt et al. 2006) was allocated to individual cohorts in our LCLUC data sets based on a priority toward forest types resulted in no harvest area simulated in non-forest ecosystems during either the analysis or reference periods.

The transitions to and from agricultural use over the full study area, including row-crop agriculture and pasture land uses, were also compared between the analysis period and the per decade area averages for the reference period (Fig. 6.4). Approximately 62×10^3 km^2 (less than 1% of the total area) was in agricultural land use, of which 32×10^3 km^2 was represented by row-crop agriculture and 32×10^3 km^2 by pastures. This actually represents a net loss of total agricultural area (from about 71×10^3 km^2 in 1997), as the modeled land use upon which we based our LCLUC data set (Hurtt et al. 2006) suggests that the rates of agricultural abandonment outpaced those of establishment over the analysis period for this study area.

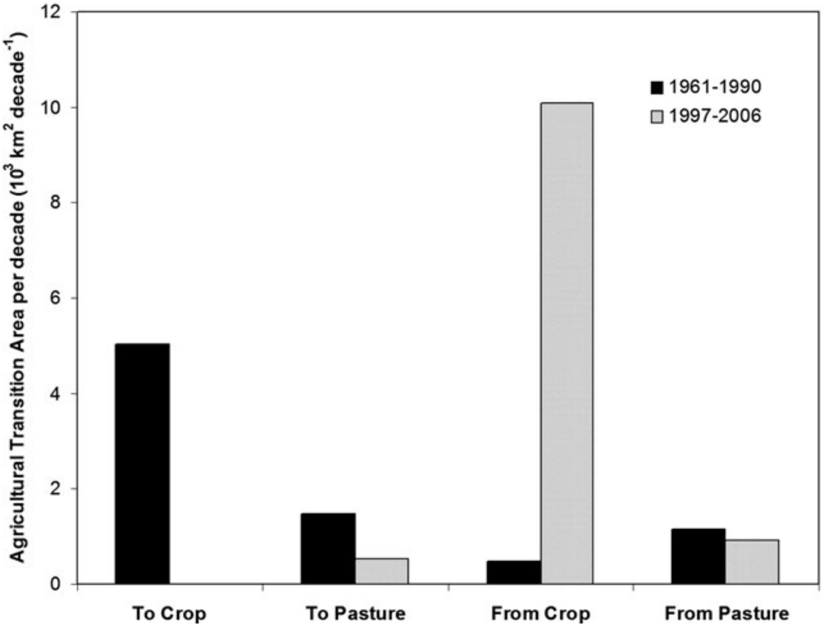

Fig. 6.4 A comparison of the area converted to and from agricultural use over the full study area, including row-crop agriculture and pasture land uses, during the analysis period (1997–2006) relative to the average per decade area affected during the reference period (1961–1990)

Between 1997 and 2006, there was only a slight reduction in the area in pasture land use (0.4×10^3 km^2), while vast majority (96%) of the abandonment was from row-crop agriculture. This 10.5×10^3-km^2 net loss of agricultural area during the analysis period was a reversal in trend from an average net gain in agricultural area of 1.6×10^3 km^2 per decade over the reference period.

The interannual variability in disturbance and land-use change over the region as a whole was analyzed to get a sense for the trends in LCLUC within the analysis period, which was then compared with annual dynamics in C balance during this time period (Fig. 6.5). The areas affected by forest harvest and pasture land use were estimated to remain steady over the analysis period, while the decline in modeled row-crop agricultural use, described above, is apparent (Fig. 6.5a). The largest variability in LCLUC during this time period is found with the fire data set, with area burned increasing to great heights in years 2001–2003 from the relatively low levels of the other years. The average of 33.5×10^3 km^2 year^{-1} burned in years 2001–2003 is almost 400% higher than the average area burned during the other years in the analysis period. The vast majority of area burned during the 10-year period was located in the boreal forest (Fig. 6.3a), and the large fire years from 2001 to 2003 correspond to comparatively warm and dry conditions in this ecozone (Fig. 6.2c).

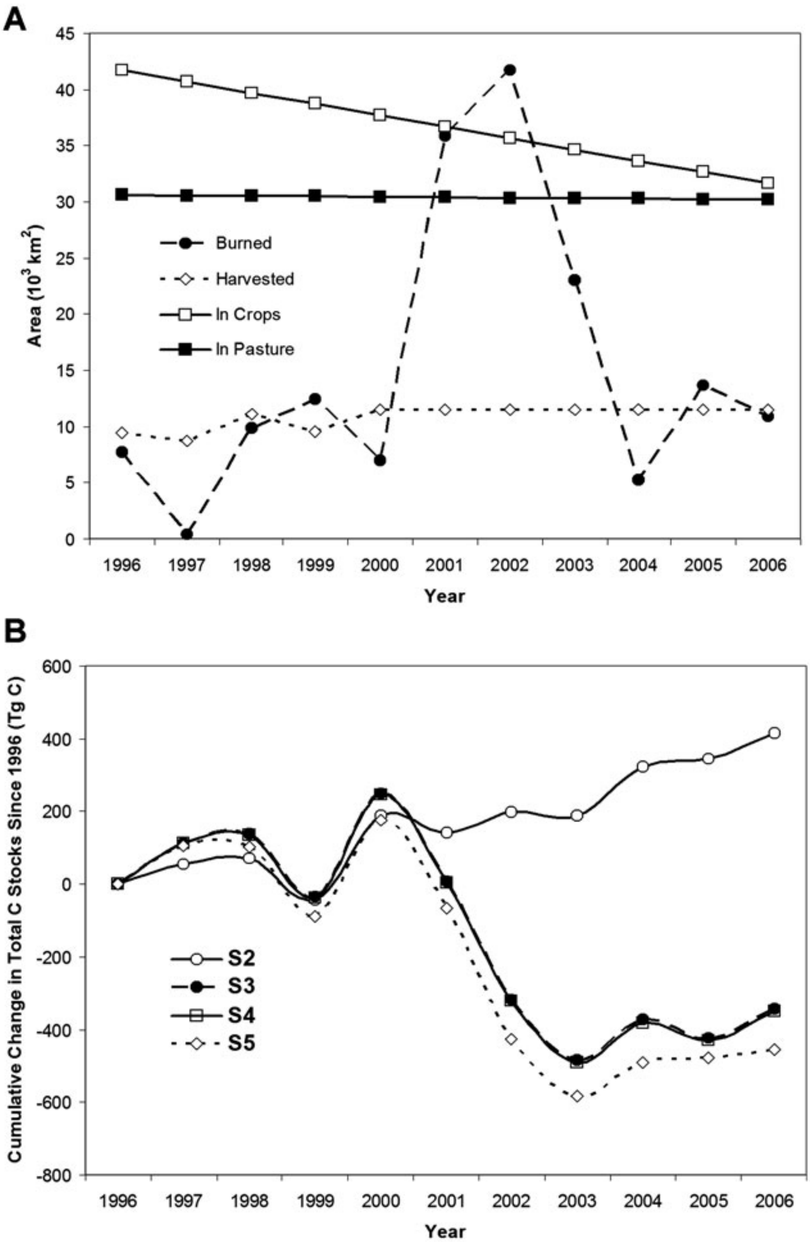

Fig. 6.5 The annual variability in area burned, harvested and in agricultural use over the study area as a whole from 1996 to 2006 (**panel A**) in relation to the trends in the cumulative change in total ecosystem C stocks since 1996 for the full study area (**panel B**), according to the results of the different simulations analyzed in this study (see Section 6.2.3)

The effects of these recent trends in LCLUC on C dynamics are reflected in the change in total ecosystem C stocks across each year in the analysis period (Fig. 6.5b). The cumulative change in C stocks for the LCLUC simulations (S3, S4 and S5) follows that of the simulated CO_2 and climate effects (S2) for the first 4 years in the analysis period. This suggests that only small LCLUC effects were found at low levels of fire and forest harvest. At low levels of area burned in 1997, 1998 and 2000, the simulations resulted in small positive fire effects (S3−S2). Beginning in 2001, however, the added fire effects on CO_2 and climate (S3 simulation) launch a divergence in C stocks toward a large negative effect corresponding to the large area burned from 2001 through 2003. By December 2003, the study area had lost approximately 730 Tg C as a result of the fire effect since December 2000, just prior to the onset of the large fire years. After 2003, the C stocks began to recover according to the pattern of the CO_2 and climate effects but retained the large deficit in cumulative C stocks as a legacy of the large fire years. By the end of the analysis period (2006), the fire effect on total C stocks was cumulatively about −760 Tg C.

The cumulative loss of total ecosystem C from the fire effect (S3−S2 simulation results) constituted about 87% of the overall LCLUC effect for the study area over the 10-year period (S5−S2). The simulation results in which area burned was added to CO_2 and climate effects (S3) resulted in a large negative effect on total C stocks after 2001, as compared to the simulation without fire (S2). Adding land use (crops and pastures) to the fire, CO_2 and climate simulation (S4) had little effect on total C stocks over the time period. Adding forest harvest in the simulations resulted in a cumulative loss of 108 Tg C over the 10-year period, all of which was accounted for in the boreal and temperate ecozones. The magnitude of this negative harvest effect accounted for 12% of the overall LCLUC source effect.

6.3.4 Landscape Analysis

Figure 6.6 presents the spatial patterns of C balance across the study area from 1996 to 2006 in relation to those of some of the controlling factors (i.e., vegetation, climate and LCLUC) considered in this analysis. The map of the base-line potential vegetation data set (Panel A) depicts the distribution of arctic tundra, boreal forest and temperate and non-forest types across the study area. The input potential vegetation map portrays upland vegetation community type mosaics and their transitions across spatial gradients by describing the area represented by each vegetation type within a half-degree cell as individual cohorts. The resulting map captures the transition zones between vegetation types, including boreal forest and tundra in central Siberia, and the boreal and temperate/other zones in Northern Europe.

Average air temperature anomalies (Panel B) show that increases in TAIR relative to the reference period were nearly ubiquitous in grid cells across the region during the analysis period, with stronger warming observed over Scandinavia and other, localized areas in the artic tundra and boreal forest regions. While the region as

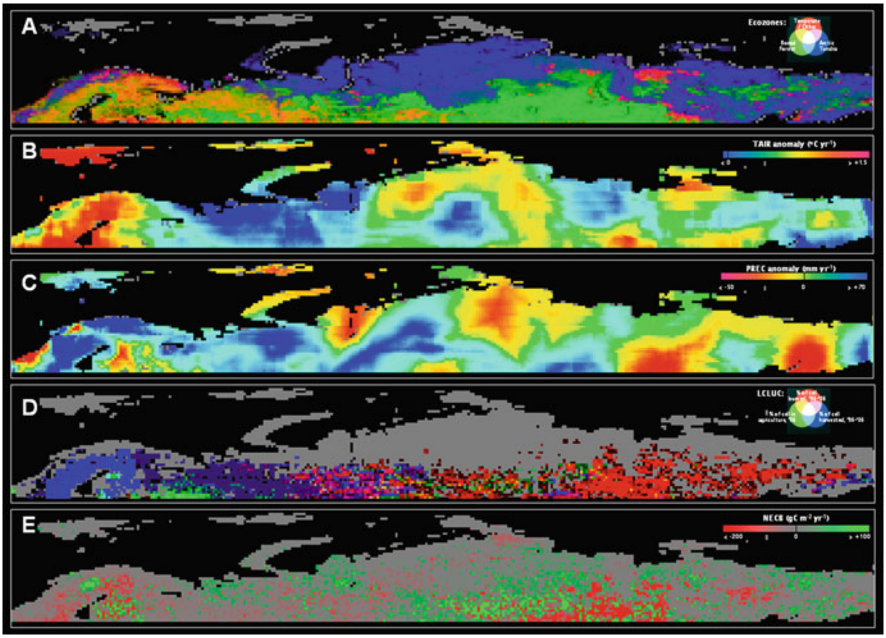

Fig. 6.6 The spatial patterns of the ecozone mosaics according to the input vegetation map (**panel A**), the anomalies in average annual surface air temperature (**panel B**) and total annual precipitation (**panel C**), and the disturbance data sets (area burned, harvested and in agriculture) (**panel D**), in relation to the net ecosystem C balance of the study area (**panel E**). Each map shows the variable summarized for each 0.5° grid cell over the 1997–2006 analysis period

a whole was generally wetter during the analysis period than during the reference period, the spatial pattern of PREC anomalies illustrates high variability across the region (Panel C). The strongest increases in precipitation were located in the mixed ecozones of Scandinavia and western Russia, while large areas of the tundra and boreal forest zones in central Siberia and the Far East show substantial negative PREC anomalies during the analysis period.

The majority of disturbance and land use activity (Panel D) was located outside of the arctic tundra ecozone, but covered much of the southern and inland portions of the study area. A large band of burned area during this time period stretched across the boreal forest of Siberia, and included a portion of the tundra/boreal transition zone in the Far East. Most of the harvest area, on the other hand, was concentrated in the mixed boreal and temperate forests further to the west, especially in Scandinavia. Agricultural land use was found primarily toward the southern extent of the study area, in eastern Europe and central Siberia. A subset of the region in western and central Siberia represented a mixed mosaic of fire, forest harvest and agricultural land use.

The spatial patterns of vegetation types, climate anomalies, and LCLUC combine in part to produce the variation observed in C balance across the region (Panel E).

The strongest fluxes both into and out of the terrestrial system during the analysis period occurred in central and eastern Siberia, as well as over northern Scandinavia. These fluxes correspond to areas of high LCLUC activity in the boreal and temperate forest ecozones. The large C source (negative NECB) in eastern Siberia clearly matches the area of high fire activity in the boreal forest during this time period. This large area burned was mostly linked to the patterns of increased TAIR and decreased PREC, according to the climate anomaly maps. A mix of both source and sink activity was found in the boreal/temperate forest mosaic of the Scandinavian region, where the highest rates of forest harvest activity were found. The results of the simulations also suggest a strong C sink in the boreal forest of central Siberia, where the data sets show mixed LCLUC activity and a mostly warmer, wetter climate compared to the reference period. Much of the arctic tundra ecozone was represented by a lesser, dispersed positive C balance, particularly in areas where TAIR anomalies were not as strongly positive.

6.4 Discussion

A large amount of political, social and scientific attention over the last decade has been directed to the measured increases of CO_2 concentrations in the atmosphere, and attempts to balance the global C budget have consistently shown that accumulation in the atmosphere is proceeding at a slower pace than suggested by the overall rate of emissions from anthropogenic sources (i.e., cement production and the burning of fossil fuels). This 'drawdown' of atmospheric CO_2 levels has long been of interest to global change scientists, and studies have produced convincing evidence that global ocean and land ecosystems have been approximately equally responsible for the uptake of this residual C (Prentice at el. 2001; Sabine et al. 2004). Recent estimates place the residual terrestrial sink at about 2.6 Pg C year^{-1} from 2000 to 2005 (IPCC, 2007), or roughly one-third of the 7.2 ± 0.3 Pg C year^{-1} from anthropogenic emissions (Marland et al. 2006). Studies using *top–down* approaches (i.e. atmospheric inversion models) for estimating global C budgets have shown that the majority of this land-based sink can be attributed to northern extratropical regions, with a generally accepted flux estimate of about 2 Pg C year^{-1} into the terrestrial ecosystems over these regions (Tans et al. 1990; Kaminiski et al. 1999; Myneni et al. 2001; Gurney et al. 2002).

6.4.1 The High-Latitude Terrestrial Sink

While inverse modeling calculations are poorly constrained at continental and regional scales, other estimates based on *bottom-up* approaches (process-based modeling and inventory methods) suggest that high latitude terrestrial ecosystems have been responsible for a significant portion of the extratropical land-based sink.

Inventory-based studies on the C balance of boreal forest and arctic tundra ecosystems suggests a net uptake of CO_2 on the order of 0.3–0.6 Pg C year^{-1} over the late twentieth Century in these regions (McGuire et al. 2009). More specific to the region analyzed in this study, estimates from both *top–down* and *bottom–up* studies suggest that the terrestrial ecosystems of Eurasia have been responsible for a majority of this sink activity. Gurney et al. (2004) estimated a 0.36 ± 0.56 Pg C year^{-1} net sink over boreal Asia from 1992 to 1996 using inverse modeling calculations. Inventory-based methods have estimated the terrestrial CO_2 sink in recent decades at 0.32 Pg C year^{-1} for Russian forests (Shvidenko and Nilsson 2003) and 0.47 Pg C year^{-1} over Eurasia (Myneni et al., 2001). Process-based model estimates from Balshi et al. (2007), which include the effects of CO_2 fertilization and fire on C dynamics, are reported as 0.22 Pg C year^{-1} for Russia and 0.31 Pg C year^{-1} for the larger Eurasia region. Taking the range of these estimates, the high latitude terrestrial ecosystems of Eurasia have been responsible for somewhere between 16 and 24% of the overall northern extratropical 2 Pg C year^{-1} land-based sink.

Given the role of this region as a significant terrestrial CO_2 sink in recent decades, any changes to the strength of this sink will have important consequences for the global C cycle. The current and future directions of the C balance in high latitudes remain uncertain, but are critical for understanding the role of these ecosystems with respect to feedbacks to future changes in climate. While models generally estimate that boreal regions were a sink in the late twentieth Century, several studies have suggested that the sink strength is decreasing, and possibly changing to a source, as a result of increased disturbance and changes in climate (Kurz and Apps 1999; Goetz et al. 2005; Balshi et al. 2007; Kurz et al. 2008). At the global scale, Canadell et al. (2007) offer a discussion on the potential for 'sink saturation', in which they review evidence that the balance between C uptake by biological processes and the emission of CO_2 from terrestrial ecosystems may be changing in such a way as to cause a decrease, or even disappearance, of the terrestrial sink.

6.4.2 Saturation of the Sink in Northern Eurasia Ecosystems

The results from our retrospective analysis of the C balance of Northern Eurasian terrestrial ecosystems over a recent 10-year period lend credence to further consideration of the near-term prospect of terrestrial sink saturation, at least in the context of high latitude ecosystems. While the studies mentioned above show the larger Eurasia region, and the pan-Arctic as a whole, acting as a C sink in earlier time periods, our analysis of the terrestrial Eurasian ecosystems north of 60°N shows a net source of nearly 45 Tg C year^{-1} from 1997 to 2006. The results from the model simulations reported in this study, when viewed in a longer-term historical perspective of total effects on C balance, show that indeed the terrestrial C source in recent years marked a switch in C balance from a sink in earlier decades (Fig. 6.7). Our simulations show the total effect of all controlling factors considered as a net C sink of

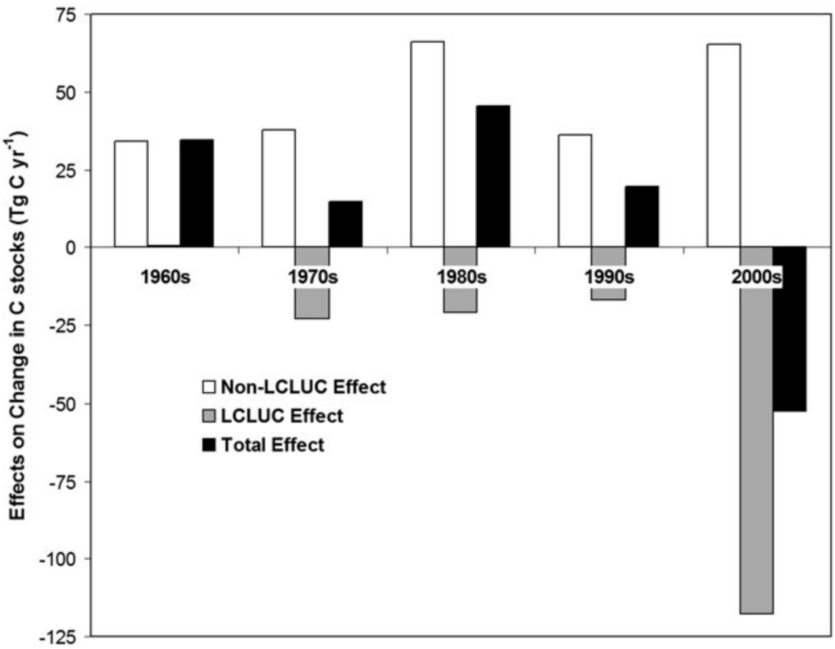

Fig. 6.7 The non-LCLUC (CO_2 concentration, atmospheric chemistry and climate variability), LCLUC (fire, forest harvest, and agricultural land use), and combined total effects on the simulated net ecosystem carbon balance for the Northern Eurasia study area during each decade from the 1960s through the 2000s. The change in carbon stocks is given as the annual average over each 10-year period, except for the 2000s decade, which is the 7-year average from 2000 to 2006.

28.5 Tg C year^{-1} from the 1960s through the 1990s, with a dramatic shift to a 52.5 Tg C year^{-1} source from 2000 to 2006. It should be noted that the latter estimate is nearly an order of magnitude lower than those from the studies mentioned earlier (although within the range of uncertainty of some of these studies), but for various reasons it is problematic to directly compare these different results. The smaller spatial extent of our analysis may be responsible in part for the lower estimate, along with the different controlling factors considered in this study. For example, most previous studies do not include the full effects of atmospheric chemistry changes, which can have a significant effect on C balance estimates (Felzer et al. 2005). Additionally, the version of TEM employed here more explicitly considers the effect of increasing active layer depth on the decomposition of SOM than previous versions (see Section 6.2.2). The effect of recent climate trends on the melting of near-surface permafrost remains a source of uncertainty and debate in the scientific literature (Yi et al. 2007; Euskirchen et al. 2006; Burn and Nelson 2006; Lawerence and Slater 2005). A better understanding of this issue will be required for current and future C balance estimates of arctic regions (see also Chapter 7, this volume).

6.4.3 Mechanisms Leading to the Shift in C Balance

Canadell et al. (2007) describe several mechanisms that control the dynamics of the terrestrial C sink and could contribute to its saturation, including both non-LCLUC (CO_2 fertilization, atmospheric chemistry effects, and climate variability) and LCLUC (disturbances and land use change and management) controlling factors. The framework of simulations used to produce the analyses reported in this study allow for consideration of the relative contribution of these different effects toward creating the net source of C observed in our results. The longer-term effects of these controlling factors on the simulation results (Fig. 6.7) suggest that the regional C balance during the 1960s though the 1990s was driven primarily by the positive effects of CO_2 fertilization and atmospheric chemistry and climate responses. Any negative effects from the LCLUC factors were small (−15.1 Tg C year^{-1}) relative to the non-LCLUC response (43.6 Tg C year^{-1}), and did not substantially impact the overall sink activity of the region. The nature of this balance between negative LCLUC and positive non-LCLUC effects has been shifted substantially in the current decade, however, according to our simulations. While the non-LCLUC effect remains positive in this decade (65.2 Tg C year^{-1}), this response has been overwhelmed by a much larger negative LCLUC effect from 2000 to 2006 (−118 Tg C year^{-1}) than was found in earlier decades.

Of the non-LCLUC factors considered in this study, they combine to produce a 43.4 Tg C year^{-1} net sink effect on the C balance of the total study area for the 10-year analysis period (1997–2006). However, the atmospheric chemistry and climate effects alone (without the CO_2 effect) were estimated to be a net source of 17.1 Tg C year^{-1} for the study area. While we did not explicitly separate the effects of atmospheric chemistry from climate variability for this study, past results with TEM simulations that considered these factors have shown that the positive effects of CO_2 fertlization are mostly cancelled out by the negative effects of atmospheric pollution (i.e. O_3) on overall C balance (Felzer et al. 2004). Felzer et al. (2005) noted that consideration of ozone pollution caused the carbon balance of some regions to change from a positive balance to a negative balance, including eastern Europe, which is a “hot spot” of ozone pollution according to that analysis.

Amongst the major ecozones in the study area, our results suggest that arctic tundra has been responding differently to climate effects than the boreal forest ecozone (Table 6.2). The positive C balance (sink) in tundra ecosystems may be explained in part by observations, described in several other studies, of enhanced productivity in the Arctic due to increased CO_2 uptake, longer-growing seasons, increasing active layer depth and the expansion of woody vegetation (see Goetz et al. 2005). The overall negative climate effect, however, is largely driven by that of the boreal forest ecozone. Subsequent analysis showed that the loss of C from the boreal forest due to the climate effect generally followed the trend toward decreasing annual precipitation in this ecozone (Fig. 6.2). This result is consistent with growing evidence of a declining trend in productivity in undisturbed boreal forests, both in North America and Asia, which has been attributed to increasing drought stress in these ecosystems (Bunn et al. 2007; Zhang et al. 2007; Goetz et al. 2005).

Changes in land cover and land use are known to play an important, but uncertain, role in the operation of the terrestrial C sink, globally and within high latitude ecosystems (McGuire et al. 2001; Houghton 2003). In addition to the drought-induced reduction of productivity in boreal forests, other studies have discussed the potential for shifts in disturbance and land use regimes to alter the strength of the C sink in these ecosystems (Randerson et al. 2006a; Goetz et al. 2007). Despite only small effects in earlier decades (Fig. 6.7), LCLUC processes combined to produce a large, negative (source) effect on the C balance of Northern Eurasia during the last decade, an effect that overwhelmed all other factors considered in this study and was primarily responsible for the overall loss of C during this time period. Our results show that the negative effect of fire in the boreal forest ecozone was responsible for most of this C loss simulated for the analysis period. Over the longer-term, the data used in these model simulations indicate that harvest levels have remained constant since the 1960s, and the simulations suggest that agricultural land use has had only small effects on C balance. On the other hand, the data show a large increase in area burned across the study area in recent years, which coincides with the shift from an overall net C sink to a net source for this region.

6.5 Conclusions

An ecosystem biogeochemistry model driven by spatially- and temporally-explicit data sets on vegetation, climate, fire, forest management and land use was used to simulate a retrospective C budget analysis for the past decade (1997–2006) over the Northern Eurasia terrestrial region. The results of the simulations indicate the study area as a whole was losing C on the order of 45 Tg year^{-1} from terrestrial ecosystems over this recent time period in response to the total effect of the controlling factors included in this study. The overall C source during the past decade, according to this analysis, marks a shift in direction of the net flux from the terrestrial sink of earlier decades that has been identified in this and other studies of Northern Eurasian ecosystems. The simulation framework and subsequent analyses presented in this study allow for attribution of mechanisms responsible for the shift in C balance for this region over the recent 10-year analysis period. Our results show that the estimated positive effect on regional C balance from CO_2 fertilization was offset by negative responses to climate, disturbance and land use change. The current trend toward a warmer and wetter climate over arctic tundra regions appears to be enhancing C storage in this ecozone, while the loss of C stocks due to climate effects in the boreal forest follows the strong decreasing trend in precipitation over this ecozone. The current trend toward warmer, drier conditions in the boreal forest may also be leading to increased area burned and therefore a large, additional negative LCLUC effect. Indeed, our analysis shows this correlated climate and fire effect in boreal forests to be the largest signal in the negative C balance response of the Northern Eurasian region during the 10-year time period.

Our model simulations suggest that a shift in terrestrial ecosystem C balance from a sink to source may be occurring in the boreal forests of Northern Eurasia as a result of changes in climate and an increase in fire activity in recent years over the region. These results do include several important sources of uncertainty, however, as well as bring to light other issues to prioritize for future research. Overall, it will be important to compare these results to other studies of regional C balance, particularly those using other methods (e.g., inversion models and inventory-based estimates). While our simulations agree with previous studies demonstrating that the high latitude regions of Eurasia acted as a C sink during earlier decades (through the 1990s), we are not aware of any studies that have made more current estimates of C balance, especially considering the recent large fire years in this region.

The results presented here, which suggest that LCLUC plays a key role in this shift in C balance, are also based on modeled data that could be corroborated and/or improved with more detailed, regional-level data on forest harvest statistics and agricultural land use data sets. The ability of the model to estimate C dynamics in earlier time periods, and to simulate the stand age distribution of the boreal forest landscape, is limited primarily by the length of the historical fire record. It is also important to note that the LCLUC data sets used to drive the model simulations presented here do not include any data on insect disturbance, which has been suggested to emit C in peak outbreak years on a magnitude comparable to that of fires (Kurz et al. 2008). Finally, while it is difficult to reduce the uncertainty of estimates of contemporary C dynamics, especially with respect to the effects of LCLUC, it is even more of a challenge to produce projections of C balance according to future scenarios. All of these issues are important to consider in lieu of a potential weakening, or disappearance, of the terrestrial C sink in high latitude ecosystems having serious consequences for the global C budget, creating a positive feedback to climate change by effectively accelerating the build-up of CO_2 in the atmosphere.

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