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REPORT

Protected areas' role in climate-change mitigation

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Abstract Globally, 15.5 million km^2 of land are currently identified as protected areas, which provide society with many ecosystem services including climate-change mitigation. Combining a global database of protected areas, a reconstruction of global land-use history, and a global biogeochemistry model, we estimate that protected areas currently sequester 0.5 Pg C annually, which is about one fifth of the carbon sequestered by all land ecosystems annually. Using an integrated earth systems model to generate climate and land-use scenarios for the twenty-first century, we project that rapid climate change, similar to high-end projections in IPCC's Fifth Assessment Report, would cause the annual carbon sequestration rate in protected areas to drop to about 0.3 Pg C by 2100. For the scenario with both rapid climate change and extensive land-use change driven by population and economic pressures, 5.6 million km^2 of protected areas would be converted to other uses, and carbon sequestration in the remaining protected areas would drop to near zero by 2100.

Keywords Protected areas · Global carbon cycle · Carbon sequestration · Mitigation · Climate change

INTRODUCTION

Terrestrial protected areas, portions of the global landscape managed to conserve nature, are currently estimated to occupy about 13 % of the Earth's land surface (Campbell et al. 2008; Jenkins and Joppa 2009), and they perform a variety of functions important to people including microclimate control, carbon storage, soil erosion control, pollination, watershed protection and water supply, soil formation, nutrient recycling, and inspiration and a sense of place (Daily and Matson 2008). A recent study has provided a quantitative demonstration of the value of protected areas as an effective strategy for conserving biodiversity (Coetzee et al. 2014), a critical component of the life-support system of the Earth.

The role of protected areas in pulling carbon dioxide (CO_2) out of the atmosphere through plant photosynthesis and storing it as organic matter in vegetation and soil has become a topic of intense interest to the climate-policy community (Reilly et al. 2012). Protected areas, especially forested ones, are being considered as a component of climate-change mitigation strategies that use land to reduce the atmospheric burden of CO_2, a powerful heat-trapping gas (Ricketts et al. 2010).

The importance of forest conservation in mitigating climate change was one of the few points of agreement between developed and developing countries at the UN Climate Change Convention in Copenhagen in 2009. Language from the meeting called for developing countries to reduce emissions from deforestation and degradation (REDD), and for wealthy nations to compensate them for doing so (Kintisch 2009).

Currently, forest ecosystems play an important and dynamic role in the global carbon cycle, both as carbon sources and carbon sinks. During the first decade of the twenty-first century, between 0.9 and 1.3 Pg C per year were released from the land due to deforestation activities, largely in the tropics (Pan et al. 2011; Le Quéré et al. 2014; Ballantyne et al. 2015). Concurrently, an estimated 2.3–2.5 Pg C per year were sequestered in land ecosystems, primarily in actively growing forests across the globe (Pan et al. 2011; Le Quéré et al. 2014; Ballantyne et al. 2015).

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To date, the current annual contribution of protected areas to the land carbon sink has not been quantified, nor have the potential risks to these areas been assessed if protection becomes less effective in the future. While many countries have designated protected areas, these areas may have little present use, and so protection has little opportunity cost and hence may require little enforcement today. As food demand grows with population and income, or the world turns to bioenergy use, and current agricultural lands suffer yield losses due to unabated environmental change, pressure may develop to convert protected lands, either through changes in their legal status or simply as a consequence of ineffective enforcement of land-use conversion.

In this study, we combine databases of global protected areas (IUCN-UNEP 2009), climate (Mitchell et al. 2004), and global land-use history (Hurtt et al. 2006, 2011), with a global terrestrial biogeochemistry model (TEM) (Melillo et al. 1993; McGuire et al. 2001; Tian et al. 2003) and an integrated earth system model (Prinn et al. 1999; Melillo et al. 2009; Reilly et al. 2012) to estimate the role of protected areas as carbon sinks under the current climate and under projected future climate and land-conversion pressures.

MATERIALS AND METHODS

Our strategy in this study is to quantify the dynamic role of protected areas in the global carbon cycle by addressing four questions: What is the current role of protected areas in the global land carbon sink? If protected areas remain intact over the twenty-first century, will they continue to be important components of the global land carbon sink under a changing climate? Are protected areas potentially at risk under pressure from land conversion? If this potential risk is realized, how will this affect the capacity of protected areas to sequester carbon? Here we describe the methods we used to address these questions.

Current carbon sequestration capacity of protected areas

A global version of the Terrestrial Ecosystem Model (TEM) was combined with a reconstruction of global land-use history, a global georeferenced climate database, and a global database of protected areas developed by UNEP and IUCN to estimate the current rate of carbon sequestration in these areas.

The Terrestrial Ecosystem Model (TEM)

The TEM uses spatially referenced environmental information to estimate monthly vegetation and soil carbon fluxes and pools. The model takes into consideration how land carbon dynamics are influenced by multiple environmental factors, both static ones such as soil texture and elevation, and dynamic ones such as CO_2 fertilization, climate change and variability, land-use change, and ozone pollution (Melillo et al. 1993, 2009; McGuire et al. 2001; Tian et al. 2003; Felzer et al. 2005). In this study, carbon dynamics are simulated for a mosaic of land-cover cohorts contained within each 0.5° latitude by 0.5° longitude grid cell.

Carbon-cycle simulation by TEM is initiated by first estimating the uptake of atmospheric CO_2 by vegetation, known as gross primary productivity (GPP). For natural terrestrial ecosystems, carbon is lost from the land to the atmosphere by autotrophic (plant) respiration (R_A) and heterotrophic (microbe) respiration (R_H). The ecosystem-level carbon increment, known as net ecosystem production (NEP), is the difference between carbon gained by GPP and carbon lost by R_A and R_H. Net ecosystem production is also equivalent to the change in the vegetation's carbon stock (ΔVeg) plus the change in the soil carbon stock (ΔSoil):

$$\mathrm{NEP} = \mathrm{GPP} - [R_A + R_H] = \Delta\mathrm{Veg} + \Delta\mathrm{Soil}.$$

The carbon balance in terrestrial ecosystems can be affected by a number of human-related activities including carbon emissions associated with burning of slash from timber harvest or from converting land to agriculture or urban areas; carbon emissions associated with the decay of agricultural and woody products; and livestock respiration. When these effects are considered, the carbon stocks in land ecosystems are reduced.

TEM has shown skill in simulating the rate of net carbon storage of land ecosystems under current environmental conditions (Appendix S1). For example, in a number of studies, we have compared TEM estimates of net carbon uptake of land ecosystems to estimates made by eddy flux. The model results were in reasonable agreement with the measurements for the sites, with modeled NEP estimates generally falling within ±20 % of the eddy flux (NEE) measurements.

Climate

Historic climate data used to drive TEM through 2000 are from the Tyndall Centre for Climate Change Research at the University of East Anglia (Mitchell et al. 2004). This dataset was then linked to the climate data simulated by MIT's Earth System Model (MESM, Sokolov et al. 2005), which provided the climate data for the scenarios that span the twenty-first century.

Land-use/land-cover history reconstruction

The global database on land-use history used in this study spans the period 1700–2005 (Hurtt et al. 2006, 2011). It includes globally gridded estimates of annual land-use transition rates, including those associated with wood harvest and the creation and abandonment of pastures and croplands. The legacy of past land-use change is considered in our study by using a disturbance cohort approach (Reilly et al. 2012) to track the effects of land-use change and climate on terrestrial carbon stocks and fluxes from 1700 to 2005. Starting from the potential vegetation map (Melillo et al. 1993), cohorts within each half-degree grid cell are created or modified (divided) from 1700 to 2005 according to the timing and location of land conversions as derived from the annual land-use transition data of Hurtt et al. (2006, 2011).

Protected areas

The World Database on Protected Areas (WDPA) database, a joint activity of UNEP and IUCN, is the largest extant assembly of data on the world's terrestrial protected areas, containing more than 150 000 entries, with records covering 236 countries and territories throughout the world (IUCN-UNEP 2009). While some of the protected areas show no signs of human influence, many have experienced some human use in the past (Leroux et al. 2010).

The WDPA and the land-use datasets were harmonized to 0.5° latitude by 0.5° longitude grid cells for the globe (Appendix S2). First, the extent of protected area was determined for each grid cell from the WDPA dataset. Then, this area was compared to the areas of cohorts in the grid cell of the underlying land-use/land-cover dataset (described above) for the year 2005. Cohorts in a grid cell were assigned protected status based on their disturbance history until the sum of protected cohorts matched the estimate of protected area of the grid cell in the WDPA dataset. Combining the databases on protected areas and their land-use history, we were able to account for how land-use legacies, such as forests growing on abandoned agricultural land, have affected carbon sequestration.

Carbon sequestration

For protected areas, we calculated the current rate of carbon sequestration by summing NEP as simulated by TEM for cohorts in all 0.5° latitude by 0.5° longitude grid cells. These estimated rates of carbon sequestration account for grid cell-specific variations in environmental variables and land-use legacy effects.

Projected carbon sequestration capacity of protected areas at the end of the twenty-first century

To project carbon sequestration capacity of protected areas at the end of the twenty-first century, we used an integrated global system model framework (Prinn et al. 1999) that simulates global economic activity, climate, atmospheric chemistry, as well as the biogeochemistry of terrestrial ecosystems. With this integrated systems approach, we are able to model many interactions and feedbacks among economic activity, climate, climate mitigation policies, land-use change and to examine the implications of multiple land pressures for the climate system, energy production, and food prices (Appendix S3).

Overview of the integrated modeling framework

Simulations using the framework (Fig. 1) begin with an initial set of greenhouse gas emissions generated by a model of the world economy, The Emissions Predictions and Policy Analysis Model, EPPA (Reilly et al. 2012). The greenhouse gas emissions, as projected by EPPA, drive a coupled atmospheric chemistry and climate model (Prinn et al. 1999) to simulate the future climate that then drives TEM. A set of projected changes in crop, pasture, and forest productivity, simulated in TEM due to changing climate, levels of CO_2 and tropospheric ozone, are then fed back to the EPPA model to change yields in the agricultural sectors. Changes in yields, together with changing demand for these products, as driven by population and income growth, lead to reallocations of land among uses, and conversions of land among land types. The regionally aggregated land-use types are downscaled to the 0.5° latitude by 0.5° longitude grid level based on a statistical approach for use in TEM (Wang 2008). The pattern of land use is affected by a number of factors including population and economic growth, changing climate, and atmospheric concentrations of CO_2 and tropospheric ozone as they concurrently affect both overall productivity and the regional pattern of production. In addition, climate policy and energy demand affect land use as they drive demand for biofuels (Melillo et al. 2009; Reilly et al. 2012).

The Economic Projection and Policy Analysis (EPPA) model

The EPPA model, as used here, includes land use, and through use of a statistically estimate downscaling algorithm is dynamically coupled with TEM (Reilly et al. 2012). The EPPA model is a recursive-dynamic multiregional computable general equilibrium model of the world economy. The model is based on economic data from the Global Trade Analysis Project database (Narayanan and Walmsley 2008) and energy data from the International Energy Agency. The underlying sources of the GTAP data are national income and product account data collected by national statistical agencies. These data are national statistics supporting Gross Domestic Product (GDP)

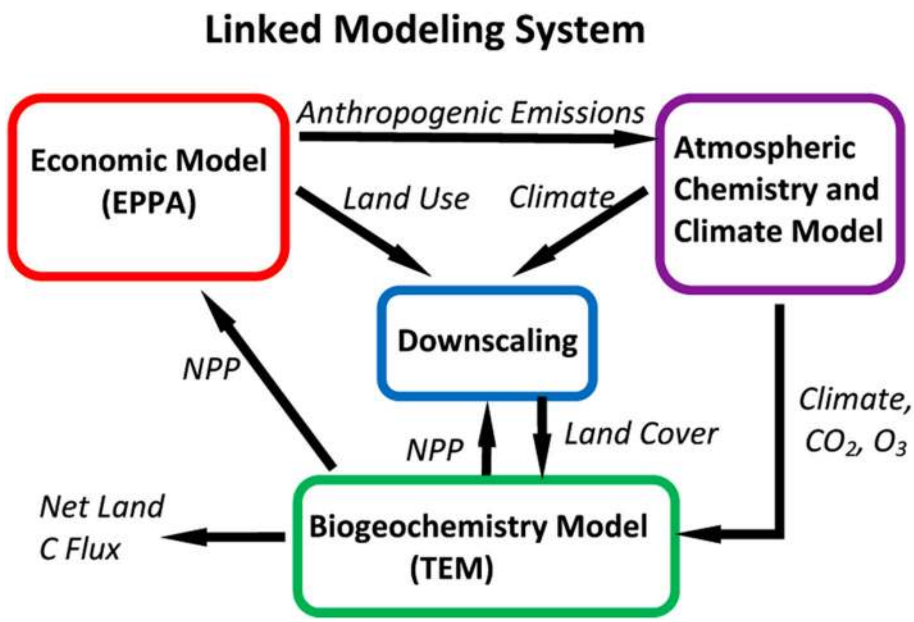

Fig. 1 The dynamically linked modeling system. It consists of an economic model (EPPA), a terrestrial biogeochemistry model (TEM) using climate output from an atmospheric chemistry and climate model (Reilly et al. 2012). The creation of plant biomass, known as net primary production (NPP) is calculated within TEM as the difference between GPP and R_A (see text). Within the modeling system, the combination of TEM and the atmospheric chemistry and climate models are referred to as the MIT Earth Systems Model (MESM)

estimates. There are no well-established measures of the potential error in these data, but they are widely used to monitor the economy. Economic measures of the value of land in the accounts are related to physical accounting of land, based on an effort at Purdue University (Avetisyan et al. 2011). That project documented significant differences in estimates of global land uses among existing datasets—as much as a 20 % difference in cropland, for example, that stems from, among other things, differences in definitions of cropland, forest land, and pasture. A multi-authored volume discusses development of data, errors, and applications in different modeling applications (Hertel et al. 2009).

The base year for the EPPA model is 2004 and it is solved through time for 2005 and in five-year increments thereafter. Production levels of agricultural goods (forest products, livestock, bioenergy, conventional crops) are determined in markets that represent final and intermediate demands and characterization of the production technology, including land requirements. As is the standard in applied general equilibrium models, EPPA is calibrated to reproduce the base year economic and land data. Key uncertainties in projecting forward the economic model, especially as it relates to land-use change, include conversion costs and the representation of willingness to convert land, the ability to substitute other inputs for land, food consumption patterns as they change with income, other demands for land such as for bioenergy or recreation, and exogenous trends in yield growth (Appendix S4).

The MIT Earth System Model (MESM)

The MESM represents the non-EPPA parts of the integrated global modeling framework. As applied here, MESM is a fully coupled, atmosphere–ocean general circulation model (Sokolov et al. 2005). It includes atmospheric dynamics, physics, and chemistry (Sokolov and Stone 1998; Wang et al. 1998), including a sub-model of urban chemistry (Mayer et al. 2000); ocean diffusion of heat and carbon including sea ice (Hansen et al. 1983; Sokolov and Stone 1998); and the land system combining the TEM, a Natural Emissions Model (NEM), and the Community Land Model (CLM) that together describe the global, terrestrial water and energy budgets, and terrestrial ecosystem processes (Schlosser et al. 2007). Latitudinal projections of changes in climate variables over land and oceans are applied to current longitudinal climate data. A significant limitation is the lack of changes in this pattern over time, and likely underestimate of the variability of weather and climate change, especially at regional levels. However, the benefit is computational efficiency. The MESM has been tested in a variety of ways to examine model uncertainties (Appendix S5).

Scenarios

For this study, we used the integrated assessment framework to develop two scenarios to explore the effects of projected changes in climate and land use over the twenty-

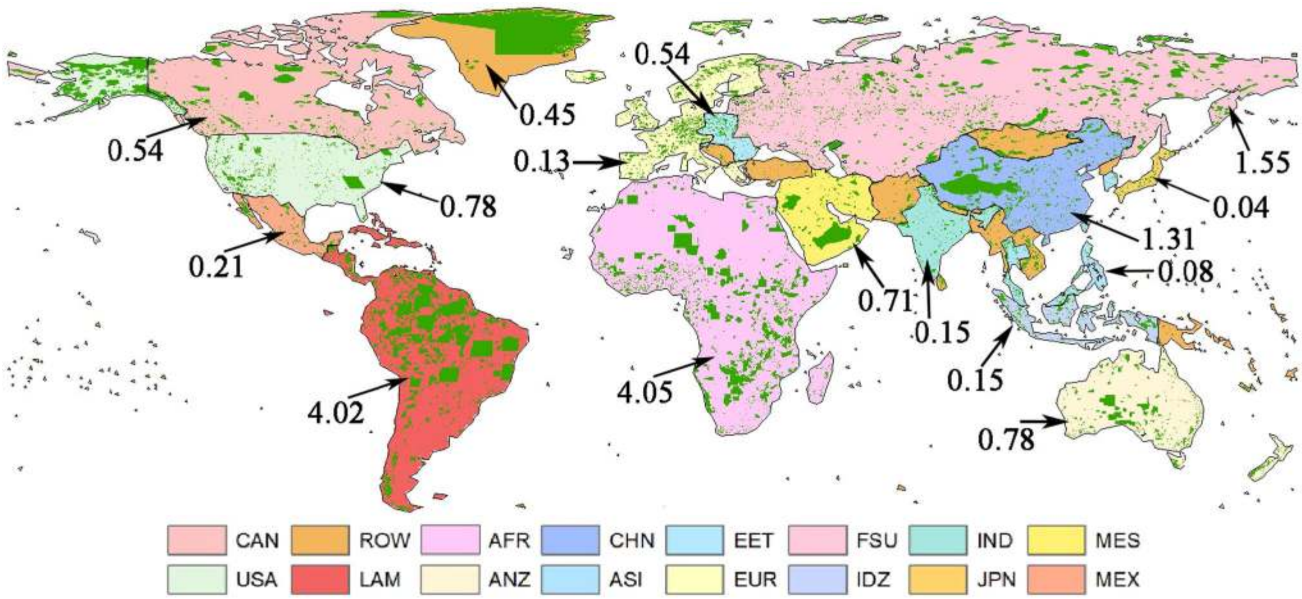

Fig. 2 Current protected areas (*green shade*) in each EPPA region (units are million km^2). *AFR* Africa, *ANZ* Australia and New Zealand, *ASI* Higher Income East Asia, *CAN* Canada, *CHN* China, *EET* Eastern Europe, *EUR* European Union, *FSU* Former Soviet Union, *IDZ* Indonesia, *IND* India, *JPN* Japan, *LAM* Latin America, *MES* Middle East, *MEX* Mexico, *ROW* Rest of the World, *USA* United States of America

first century on carbon sequestration in protected areas. The first scenario, the *Full Protection* (*FP*) scenario, assumes no climate policy into the future (essentially, business as usual), continued economic growth and agricultural productivity growth of 1 % per year, but maintains the integrity of protected areas so that over the twenty-first century the extent of protected areas is constant. The second scenario, the *No Protection* (*NP*) scenario, makes the same assumptions about climate policy, population growth, and agricultural productivity as in *FP*, but allows development in protected areas as projected by the global systems model.

Carbon sequestration

For each scenario, carbon sequestration at the end of the twenty-first century was estimated by summing changes in carbon stocks for the cohorts of all grid cells designated as protected areas at that time (Appendix S6). This approach allowed us to account for changes in carbon sequestration rates associated with changes in the extent of protected areas.

RESULTS

Our resulting contemporary estimates of the global coverage of protected areas are similar to previously reported estimates (Campbell et al. 2008; Jenkins and Joppa 2009). However, our analyses indicate that some croplands and pastures have also been designated as "protected" in addition to land covered by natural vegetation in these areas (Table S2). Our analysis indicates that forests, which cover 6.7 million km^2, are the dominant ecosystems in protected areas, with grazed rangelands/pastures being the second most dominant (3.0 million km^2). In this study, we have excluded the cropland cohorts from consideration of carbon and area dynamics of protected areas in the future, but have included pastures. As the area of lakes and ice do not vary and do not influence our estimates of carbon dynamics, we assumed protected areas currently cover 15.5 million km^2 if pastures are included in area estimates.

Africa and Latin America had the largest reported areas of protected land with 4.1 and 4.0 million km^2, respectively. Other regions that have large areas of protected land include the former Soviet Union and China (Fig. 2; Table S1). Some natural areas currently designated as protected have experienced human use in the past. For example, we estimate that of the 6.7 million km^2 of forests characterized as being in protected areas, 3.6 million km^2 have had wood extracted from them sometime over the past century.

Under current conditions, we estimate that the protected areas store 238 Pg C or about 12 % of land carbon stocks. Of this total, 92 Pg C is in vegetation and 146 Pg C is in soil. Six regions—Latin America, the former Soviet Union, Africa, the United States, Canada and China—store about 85 % of the protected land's organic carbon (Table 1).

Table 1 Distribution of carbon stocks (Pg C) in 2005 and changes in total organic carbon (Pg C year^{-1}) in protected areas among EPPA regions between 2005 and 2010

Region	Vegetation carbon (Pg C)	Soil organic carbon (Pg C)	Total carbon (Pg C)	ΔTotal C (Pg C year^{-1})
AFR	11	20	31	0.06
ANZ	1	4	5	0.01
ASI	1	1	2	0.01
CAN	3	9	12	0.01
CHN	2	11	13	0.01
EET	1	1	2	0.01
EUR	4	7	11	0.05
FSU	7	26	33	0.03
IDZ	3	2	5	0.01
IND	1	1	2	0.01
JPN	0	1	1	0.00
LAM	51	48	99	0.25
MES	0	1	1	0.00
MEX	0	1	1	0.01
ROW	2	3	5	0.01
USA	5	10	15	0.03
Globe	92	146	238	0.51

Carbon is being captured from the atmosphere by these land ecosystems annually across the globe through photosynthesis. While most of this carbon is returned to the atmosphere as a result of plant and microbial respiration, a fraction of the total amount of carbon captured in photosynthesis is sequestered in these protected areas as organic matter in plants and soil. We estimate that these areas are currently accumulating 0.5 Pg C annually, and much of this carbon is being stored in woody vegetation (Table 2).

We estimate that protected areas in four regions currently account for about 77 % of the total amount of carbon sequestered in all terrestrial protected areas annually (Table 1). Latin America accounts for the largest share (49 %) followed by Africa (12 %), Europe (10 %), and the United States (6 %).

In a world with climate change, we project a reduction of the carbon sequestration rate in protected areas with both the *FP* and *NP* scenarios (Table 2). Under the *FP* scenario with climate change, but no change in the extent of protected areas, we project that by the end of the twenty-first century, there will be about a 40 % reduction in the carbon sequestration rate in protected areas; down to 0.3 Pg C per year relative to the present rate of 0.5 Pg C per year (Table 2).

In the second simulation, the *NP* simulation, we explore the carbon-cycle consequence of allowing pressures from a growing and wealthier world population to reduce the extent of protected areas. Economic pressures across the globe, as simulated by the EPPA model, result in a loss of 5.6 million km^2 over the twenty-first century such that the residual global protected area is only 9.9 million km^2 by 2100 (Table 3). Over 60 % of this loss is projected to occur in sub-Saharan Africa and Latin America (Fig. 3). The reduction in protected areas, combined with the net effects of climate change over the century, lowers the annual carbon sequestration rate in the remaining protected areas to zero; a rate much below the current rate of 0.5 Pg C per year sequestered in protected areas across the globe (Table 2).

The simulated geographic patterns of carbon sequestration rates vary across regions and between the two simulations, *FP* and *NP*. Comparing the current carbon sequestration pattern (Fig. 4a) to the ones we project with the two scenarios, we see an increase in carbon sequestration rates in protected areas across the high latitudes by century's end. For the rest of the world in the FP scenario, the picture is more complex, with a mix of increases and decreases in carbon sequestration rates in the temperate and tropical zones in response to changes in climate (Fig. 4b). In contrast, in the *NP* simulation for the temperate and trophic region, carbon sequestration rates in protected areas are projected to decrease by century's end with wide spread decreases in Africa and Latin America (Fig. 4c).

DISCUSSION

In this study, we have estimated that terrestrial protected areas currently function as carbon sinks that sequester about 0.5 Pg C each year. We consider this a first-order

Table 2 Projected changes in natural vegetation cover in designated protected areas and associated carbon sequestration (averaged over 5 years) over the twenty-first century under a BAU future climate scenario and two land-use scenarios—*FP* and *NP*. In the *FP* scenario, the extent of protected areas is constant over the twenty-first century; in the *NP* scenario, the extent of protected areas is reduced in response to land-use pressures from a growing and wealthier world population

Variable	Current	Year 2100	
		FP scenario	*NP* scenario
Area (10^6 km^2)	15.5	15.5	9.9
ΔVegetation carbon (Pg C year^{-1})	0.6	0.3	0.1
ΔSoil organic carbon (Pg C year^{-1})	−0.1	0.0	−0.1
ΔTotal land carbon (Pg C year^{-1})	0.5	0.3	0.0

Table 3 Potential loss of protected areas by the end of the twenty-first century in the *NP* scenario, in which the extent of protected areas is reduced in response to land-use pressures from a growing and wealthier world population

Region	Current (10^6 km^2)	Future (10^6 km^2)	Change (10^6 km^2)	% of Global change
Africa	4.1	2.1	−2.0	35.7
Latin America	4.0	2.5	−1.5	26.8
Former Soviet Union	1.5	1.1	−0.4	7.1
Australia/New Zealand	0.8	0.4	−0.4	7.1
United States of America	0.8	0.6	−0.2	3.6
Eastern Europe	0.5	0.3	−0.2	3.6
China	1.3	1.1	−0.2	3.6
Other Parts of the Globe	2.5	1.8	−0.7	12.5
Globe	15.5	9.9	−5.6	100.0

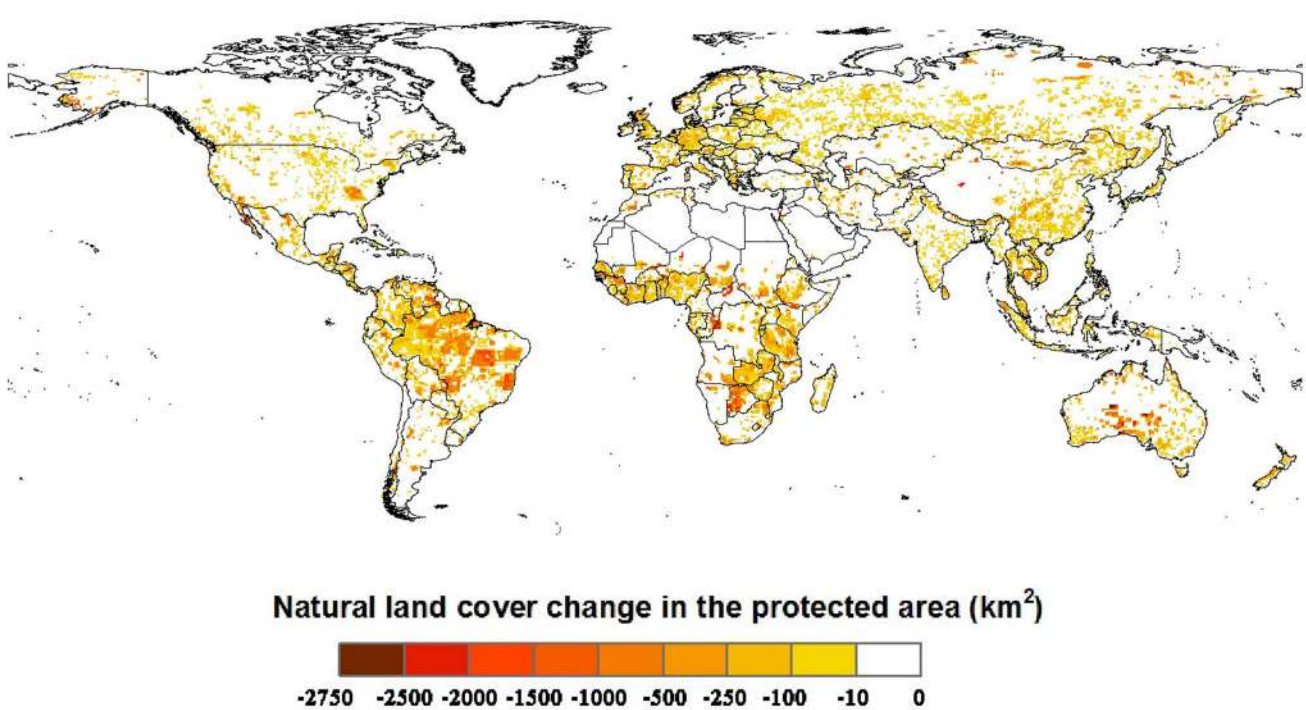

Fig. 3 Projected changes by the end of the century in the extent of protected areas in the *NP* simulation, which includes allowing pressures from a growing and wealthier world population to reduce the extent of protected areas

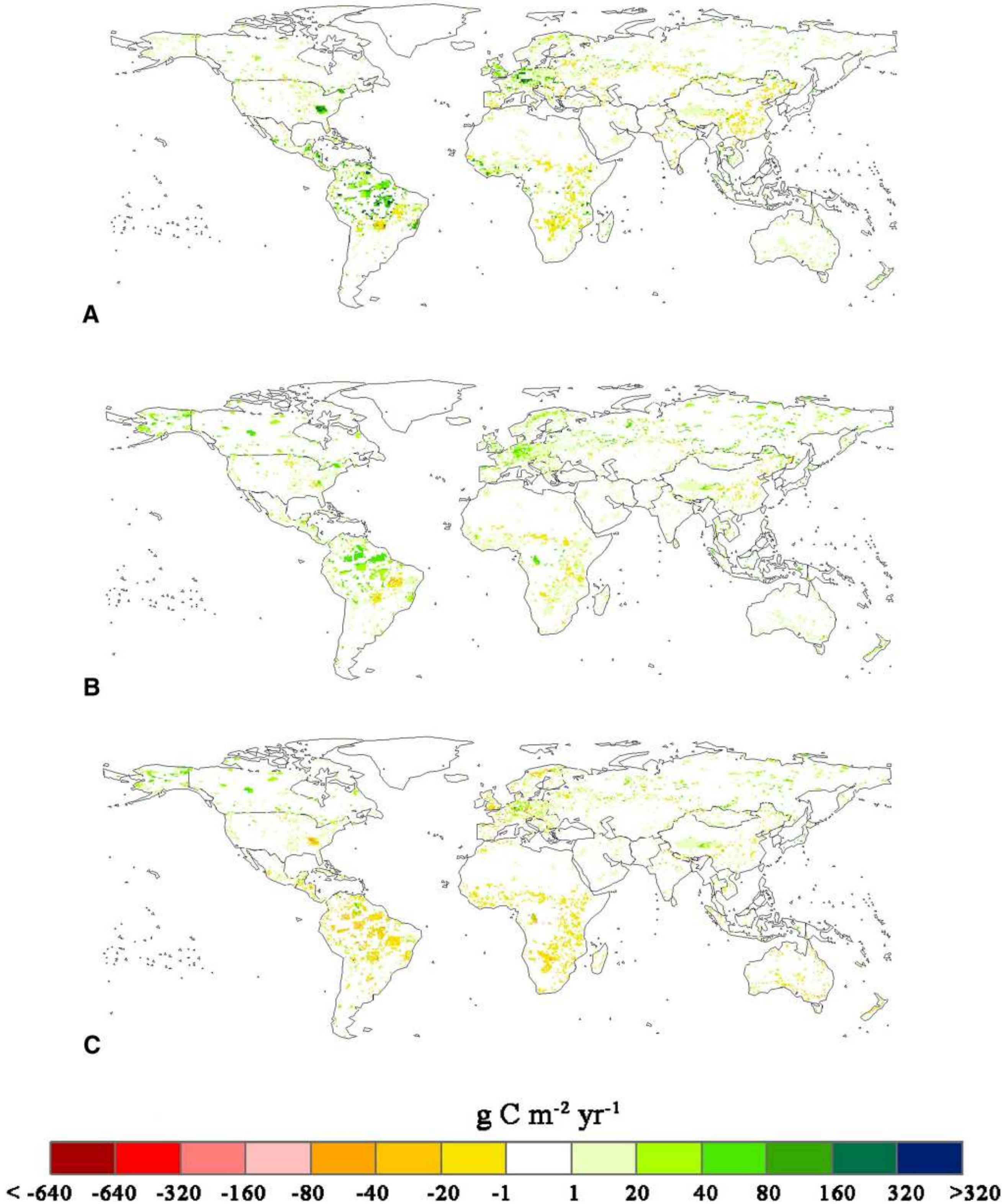

Fig. 4 Carbon sequestration rates by land ecosystems for current conditions (2005–2010) and under two future scenarios at the end of the twenty-first century (2095–2100): **A** current conditions; **B** the *FP* scenario; and **C** the *NP* scenario. In the *FP* scenario, the extent of protected areas is constant over the twenty-first century, while in the *NP* scenario, the extent of protected areas is reduced in response to land-use pressures from a growing and wealthier world population

Table 4 Estimates of major carbon fluxes between the terrestrial biosphere and the atmosphere during the first decade of the twenty-first century. Global carbon budgets traditionally recognize two major fluxes between the terrestrial biosphere and the atmosphere—fluxes from the land (E_L) associated with land-use changes such as deforestation and fluxes to the land (N_L), including protected areas (N_{Lpro}), associated with a variety of factors including forest regrowth after disturbance and enhanced plant growth from fertilization with increases in atmospheric CO_2 and N deposition in precipitation (Melillo et al. 1996). The sum of E_L and N_L yields the net exchange of carbon between the land and the atmosphere, which we refer to as Δ_L in Table 4

Approach	N_L	E_L	Δ_L	N_{Lpro}	Period	Reference
Inventory (all land ecosystems)	2.4	1.0	1.4	–	2000–2009	Le Quéré et al. (2014)
Inventory (forests only)	2.3	1.1	1.2	–	2000–2007	Pan et al. (2011)
Models (9 process-based)	2.5	1.3	1.2	–	2000–2009	Le Quéré et al. (2014)
Residual calculation[a]	2.5	0.9	1.6	–	2000s	Ballantyne et al. (2015)
TEM	2.5	1.2	1.3	0.5	2000s	This study

[a] Land uptake (N_L) is the unknown term in a mass balance equation of the global carbon budget where estimates of other terms in the equation (fossil fuel emissions, net land-use emissions, ocean uptake, changes in atmospheric carbon concentration) are considered known

estimate that can be improved with more accurate determinations of the extent of protected areas (Vistconte et al. 2013) and improved model parameterizations of key ecosystem processes such as photosynthetic responses to elevated CO_2, especially for tropical forests (Schimel et al. 2015).

While, to our knowledge, there are no other estimates of the annual carbon sequestration rate in the globe's terrestrial protected areas for the first decade of the twenty-first century, there are several estimates of the rate of carbon sequestration by forests and all land ecosystems including protected areas for this period (Table 4). Using the same modeling approach that we used for protected areas, we ran TEM for all land ecosystems at the global scale for current environmental and land-use conditions. The TEM estimates for the major global scale land–atmosphere carbon fluxes, including N_L, land sink strength, agree well with the mean annual values of the other estimates for the 2000s (Table 4). Some of the estimates are made with process-based models, while others are primarily inventory based (Pan et al. 2011; summarized by Le Quéré et al. 2014). TEM's global land sink estimate is 2.5 Pg C year^{-1} for the early 2000s. The mean estimate from the process models is also 2.5 ± 0.8 Pg C year^{-1} for this period, with the uncertainty representing ± 1 standard deviation of results from the nine individual models. The bookkeeping method gives a mean of 2.4 Pg C year^{-1} for the 2000s. In addition, the estimate of the land sink, N_L, as calculated as the residual term in a in global carbon budget equation (Ballantyne et al. 2015) for the 2000s is 2.5 ± 1.0 Pg C year^{-1}, with the uncertainty representing ± 1 standard deviation of decadal mean. This set of comparisons provides one test of TEM's skill in estimating key components of the contemporary land carbon cycle including the land sink, N_L, at large spatial scales and increases our confidence in TEM's first-order estimate of the current carbon sink in terrestrial protected areas.

The changes in carbon sequestration rates over the twenty-first century that we simulated with the two scenarios, *FP* and *NP*, are due to several factors. At least two mechanisms are interacting to result in the decline in carbon sequestration in the *FP* scenario. The first is related to the effects of climate change on key ecosystem processes and the second is related to changes in carbon-cycle dynamics as forests in protected areas mature over the twenty-first century.

The terrestrial carbon cycle responds to a combination of climate and associated environmental changes including an increase in atmospheric CO_2 concentration (Melillo et al. 2009). By 2100 in the *FP* and *NP* scenarios, fossil fuel carbon emissions are in the range of 22 Pg C annually, the atmospheric CO_2 concentration reaches about 930 part per million, and the mean global temperature rises by 5.5 °C (Fig. 5). While the increase in CO_2 concentration has the potential to increase carbon sequestration in ecosystems not limited by shortages of water or key nutrients such as nitrogen, the projected global temperature rise dominates the carbon sequestration response by increasing both plant and soil respiration, which results in a reduction in the rate of carbon storage in most land ecosystems including protected areas. As noted earlier, high latitude forests are an exception to this general response in both the *FP* and *NP* scenarios (Fig. 4A). This exception reflects an increase in N availability to vegetation associated with an increase in soil organic matter decay in a warmer world (Sokolov et al. 2008; Melillo et al. 2011).

The age structure of forests also affects the rate of carbon storage, with young forests generally sequestering carbon faster than old forests (Pregitzer and Euskirchen 2004). In the TEM model, we represent this pattern with an asymptotic function of GPP with standing stock of vegetation carbon (Tian et al. 2003), where the slope and the duration of the period of rapid carbon accumulation vary

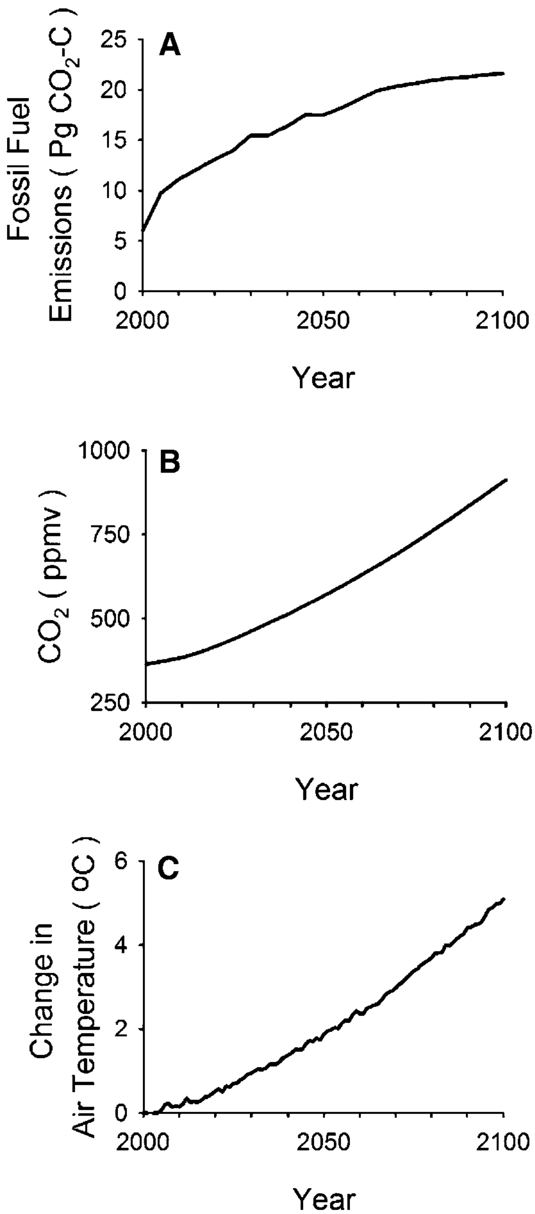

Fig. 5 Changes in global fossil fuel emissions (**a**), atmospheric carbon dioxide (CO_2) concentrations (**b**) and changes in global mean air temperatures from year 2000 (**c**) for the BAU climate scenario

with major forest type. In our integration of the land-use and protected areas databases, we identified protected areas across the globe that had complex land-use histories. For example, some of the protected areas that are now forested were once croplands. The timing of the transition from agriculture to forest determines stand age at the end of the twenty-first century and also the rate of carbon sequestration.

As we consider the future of terrestrial protected areas, we must recognize that they are already under development pressure (Watson et al. 2014). A recent study reported high rates of deforestation in Indonesia over the period 2000–2012 (Margono et al. 2014). By 2012, annual primary forest loss in Indonesia was estimated to be higher than in Brazil (0.84 and 0.46 Mha, respectively). Using high-resolution remote sensing, the study estimated that 16 % of the deforestation in Indonesia occurred within conservation and protection forests that prohibit clearing.

Looking to the future, projections that protected areas in Africa and Latin America will come under increasing development pressures are consistent with the expectations that these regions will experience rapid population growth and extensive development of their natural resources over the twenty-first century (Watson et al. 2014). A recent United Nations report (UN 2015) projects (the medium variant projection) that the population of Africa could almost quadruple over the century, increasing from 1.1 billion today to 4.2 billion by 2100. Much of the population growth in Africa is expected to occur in six countries—Nigeria, Tanzania, the Democratic Republic of Congo, Niger, Uganda, and Ethiopia—each with millions of hectares of protected areas.

An analysis of conservation options for the Brazilian Amazon suggests that the protected areas of the region could also come under heavy development pressure (Soares-Filho et al. 2006, 2010). The Amazon has entered a new era as the growing profitability of cattle ranching and soy production could increase deforestation rates. In an extremely aggressive development scenario used in the analysis, as much as 40 % of the forests inside of protected areas are subject to deforestation for agriculture.

The loss of protected areas to agricultural development will have two consequences for the global carbon cycle. First, the process of site preparation (clearing and burning) will release carbon to the atmosphere as CO_2, thus accelerating climate change. Second, the loss of perennial vegetation such as forests translates into a loss of future carbon sequestration capacity, further diminishing the ability of land ecosystems to slow the rate of climate change.

In this study, we assume that there is no land-use "leakage" associated with protected areas. Leakage, also called "slippage," occurs when the carbon sequestration benefits of a protected area are entirely or partially negated by increased carbon emissions from another area to meet the demand for land that cannot be satisfied by converting protected areas to other uses (Brown et al. 1997; Costa et al. 2000). In the worst case, leakage could totally negate any carbon sequestration benefits we project for the globe's protected areas over the century.

The relative importance of protected areas in the global carbon budget depends not only on their absolute sequestration rate, but also on the magnitude of fossil fuel carbon emissions globally. With the combination of shrinking rates of carbon sequestration in protected areas over the century and growing fossil fuel emissions over this period that reach about 25 Pg C in 2100 in the *NP* scenario, protected areas become a very minor term in the annual global carbon budget. Despite a possible diminished role in the global carbon cycle, the protected areas that remain will have a number of important functions, including a critical role in conserving biodiversity on our planet. On a planet predicted to be home of 10.9 billion people (UN 2015), the importance of protected areas as a repository of biodiversity is expected to grow.

CONCLUSION

We estimate that terrestrial protected areas sequester about 0.5 Pg C annually in the present. Our analysis indicates that maintaining the current capacity of protected areas to sequester carbon over the twenty-first century will require that the present protected areas remain unaltered by development pressures and that the global extent of protected areas on land grow over the century. This growth in terrestrial protected areas will be needed to compensate for the loss of the carbon sink capacity of extant protected areas in response to climate change. Expansion and effective management of protected areas as called for in the Convention on Biological Diversity's Strategic Plan for Biodiversity (CBD 2012) would yield a double win—a win in the fight against climate change and a win in the battle to protect our planet's biodiversity.

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