Potential Direct and Indirect Effects of Global Cellulosic Biofuel Production on Greenhouse Gas Fluxes from Future Land-use Change

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

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Abstract

The production of cellulosic biofuels may have a large influence on future land emissions of greenhouse gases. These effects will vary across space and time depending on land-use policies, trade, and variations in environmental conditions. We link an economic model with a terrestrial biogeochemistry model to explore how projections of cellulosic biofuels production may influence future land emissions of carbon and nitrous oxide. Tropical regions, particularly Africa and Latin America, are projected to become major producers of biofuels. Most biofuels production is projected to occur on lands that would otherwise be used to produce crops, livestock and timber. Biofuels production leads to displacement and a redistribution of global food and timber production along with a reduction in the trade of food products. Overall, biofuels production and the displacement of other managed lands increase emissions of greenhouse gases primarily as a result of carbon emissions from deforestation and nitrous oxide emissions from fertilizer applications to maximize biofuel crop production in tropical regions. With optimal application of nitrogen fertilizers, cellulosic biofuels production may enhance carbon sequestration in soils of some regions. As a result, the relative importance of carbon emissions versus nitrous oxide emissions varies among regions. Reductions in carbon sequestration by natural ecosystems caused by the expansion of biofuels have minor effects on the global greenhouse gas budget and are more than compensated by concurrent biofuel-induced reductions in nitrous oxide emissions from natural ecosystems. Land policies that avoid deforestation and fertilizer applications, particularly in tropical regions, will have the largest impact on minimizing land emissions of greenhouse gas from cellulosic biofuels production.

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1. INTRODUCTION

Biofuels are being promoted as an important part of the global energy mix in the coming decades to meet the climate change challenge (Pacala and Socolow, 2004; Farrell *et al*., 2006). Recent research on biofuels has determined that how and where biofuels are produced affect their usefulness in mitigating climate change. A core focus in research to determine the mitigation potential of biofuels is the issue of land use. While much of the focus of previous research has been on carbon emissions, land-use change also influences emissions of nitrous oxide (N_2O), a very powerful greenhouse gas. The amount of biofuels produced, the regional pattern of its production, and the consequences of its production on land use and greenhouse gas (GHG) emissions depend on a host of economic and environmental feedbacks, including the growth in food demand, the potential for more intense use of existing managed lands (e.g., grazing lands to row-crop agriculture), the willingness to convert natural forests and grasslands to agriculture in different regions, and the differential regional impacts of climate and air quality (e.g., atmospheric carbon dioxide concentrations, ozone pollution) on crop and natural ecosystem productivity. In this study, we apply a modeling system that takes these factors into account and find that the production and trade of biofuels causes a complex pattern of changes in land use and food trade across the globe. These changes lead to carbon sequestration or reductions in carbon or N_2O emissions in some regions, but may increase these land-use GHG emissions in other regions.

The conversion of land to biofuel production can release a large amount of carbon from land ecosystems to the atmosphere (Fargione *et al*., 2008) and this results in greenhouse gas effects that may be larger than the displaced fossil fuels. One way to avoid future carbon emissions associated with land conversion is to intensify the use of existing managed lands or recently abandoned lands to biofuel production. Intensification, however, often requires use of additional amounts of nitrogen fertilizers, which increases N_2O emissions (Crutzen *et al*., 2008, Davidson, 2009). In addition to nutrient availability, biofuels production also depends on other local environmental conditions such as climate and air quality (e.g. atmospheric carbon dioxide and ozone concentrations). The productivity of biofuel crops will ultimately determine the land requirements and the location of production activities (Wang, 2008).

A growing world population will create increasing demand for food and fiber in addition to energy in the future. To satisfy these demands, there will be increasing pressure on the land for competing land uses. Thus, changing the use of cropland from food production to biofuel production in one region may create pressure for land conversion of natural areas in another region to compensate for the loss of food production. While the carbon emissions resulting directly from devoting croplands to biofuel production may not be large, the indirect carbon emissions from land conversion of displaced land uses may be substantial (Searchinger *et al*., 2008; Melillo *et al*., 2009). Furthermore, several programs have already been started to protect natural areas or establish plantations specifically to sequester atmospheric carbon dioxide to offset carbon footprints of current and future energy use (van Minnen *et al*., 2008). Land conversion for biofuels, food or fiber may reduce the capacity of the land to sequester carbon in many regions (Searchinger *et al*., 2008). Thus, changes in carbon sequestration capacity caused either directly or indirectly by biofuels production also need to be considered in any assessment of potential impacts of a global biofuels program.

In addition to sequestering carbon, many natural ecosystems, particularly tropical forests, emit N_2O even without the subsidy of nitrogen fertilizer applications, (e.g., Goodroad and Keeney, 1984; Matson *et al*., 1991; Serca *et al*., 1994; Bowden *et al*., 2000; Kiese and Butterbach-Bahl, 2002; Melillo *et al.* 2001; Garcia-Montiel *et al*., 2004; Pihlatie *et al*., 2007; Xu *et al*., 2008; Koehler *et al*., 2009). At the global scale, these natural N_2O emissions contribute a similar amount of N_2O to the atmosphere as anthropogenic sources (Denman *et al*., 2007). Furthermore, disturbances and land conversions alter the rate of N_2O emissions from these ecosystems (Luizão *et al*., 1989; Melillo *et al*., 2001; Garcia-Montiel *et al*., 2001; Keller *et al*., 2005; Neill *et al*., 2005). As N_2O has a global warming potential (GWP) that is about 298 times that of carbon dioxide over a 100-year time horizon (Forster *et al*., 2007), changes in natural N_2O emissions either directly or indirectly by biofuels production should also be considered in any assessment of the potential impacts of a global biofuels program.

To address most of these concerns, Melillo *et al*. (2009) have evaluated the potential effects (both direct and indirect) of a global cellulosic biofuels program on future global greenhouse gas emissions using a modeling framework that linked models of the global economy, terrestrial biogeochemistry, atmospheric chemistry and climate. In that study, they find that more land is devoted to biofuel production than food production by the end of the 21st century. They also note that cellulosic biofuels production can lead either to a loss or a gain of carbon within terrestrial ecosystems based on the carbon stocks of the former land cover, the effects of local environmental conditions on the simulated plant productivity of the biofuel or food crop and the former vegetation cover, and the time period examined. The conversion of forested lands (vegetation with high carbon density) to biofuels, food crops or pastures (vegetation with low carbon density) leads to a loss of carbon from terrestrial ecosystems. In contrast, the application of nitrogen fertilizer to biofuels and food crops alleviates the nitrogen limitation often found in natural vegetation leading to higher plant productivity, and faster accumulation of biomass and soil organic matter in these fertilized agro-ecosystems than found in unfertilized, low carbon density ecosystems such as pastures, grasslands or shrublands. An ecosystem may initially lose carbon as natural vegetation is converted to cellulosic biofuels production, but then later gain carbon as soil organic matter accumulates with the production of fertilized biofuel crops. As a result of this temporal dynamic, relatively little carbon may be lost when managed lands are co-opted for cellulosic biofuels production because the conversion losses of carbon have already occurred with the establishment of the previous land use. Indeed, the ecosystem may gain carbon by devoting the land to biofuels production especially if the previous land management, such as pastures, did not include nitrogen fertilizer applications. Melillo *et al*. (2009) also find that the indirect effects of a global cellulosic biofuels production are larger than the direct effects on land-use carbon emissions, but the relative importance of these effects will vary over time and depend upon the land-use policy being implemented. Further, they find that N_2O emissions from fertilizer applications to biofuel crops continually increase over the 21st century until they have a larger effect on greenhouse gas forcing than the associated carbon emissions. The greenhouse gas costs of land carbon and N_2O emissions associated with biofuels production are predicted to overwhelm the abatement benefits of avoiding fossil fuels over the next 30 to 50 years, but in the latter part of the 21st century, these land emission costs become less than the associated abatement benefits.

Although Melillo *et al*. (2009) note that changes in these net land greenhouse gas fluxes are associated with how land is allocated for biofuels production across the globe, they do not examine these allocation patterns and their associated effects on land-use emissions in regional detail. In addition, while the effects of biofuels production on carbon sequestration capacity are considered implicitly in the Melillo *et al.* (2009) study, the effects on natural N_2O emissions are not considered at all. Here, we take a closer look at the spatially explicit results underlying the Melillo *et al*. (2009) study including the projected global distribution of cellulosic biofuel production, its relationship to the displacement of other managed lands, and how land-cover characteristics of the ecosystems being converted to biofuels or displaced agricultural land influence the distribution of land carbon and N_2O emissions. We also assess the importance of losses in the carbon sequestration capacity of natural ecosystems and alteration of N_2O emissions from these ecosystems. We then examine the consequences on regional greenhouse gas budgets of assigning carbon emissions from biofuels use along with associated fossil fuel abatement benefits to regions that produce biofuels versus regions that consume biofuels.

2. METHODS

We examine how an aggressive global biofuels program with advanced technologies using cellulosic feedstocks may influence future terrestrial carbon dynamics and N_2O emissions by linking a full computable general equilibrium (CGE) model of the economy, the MIT Emissions Prediction and Policy Analysis (EPPA) model, with a model of terrestrial biogeochemistry, the Terrestrial Ecosystem Model (TEM) and an atmospheric chemistry/climate model (**Figure 1**). The approach is unique in that it considers complete inter-sectoral input-output relationships of the global economy within the context of the structure and function of the terrestrial biosphere.

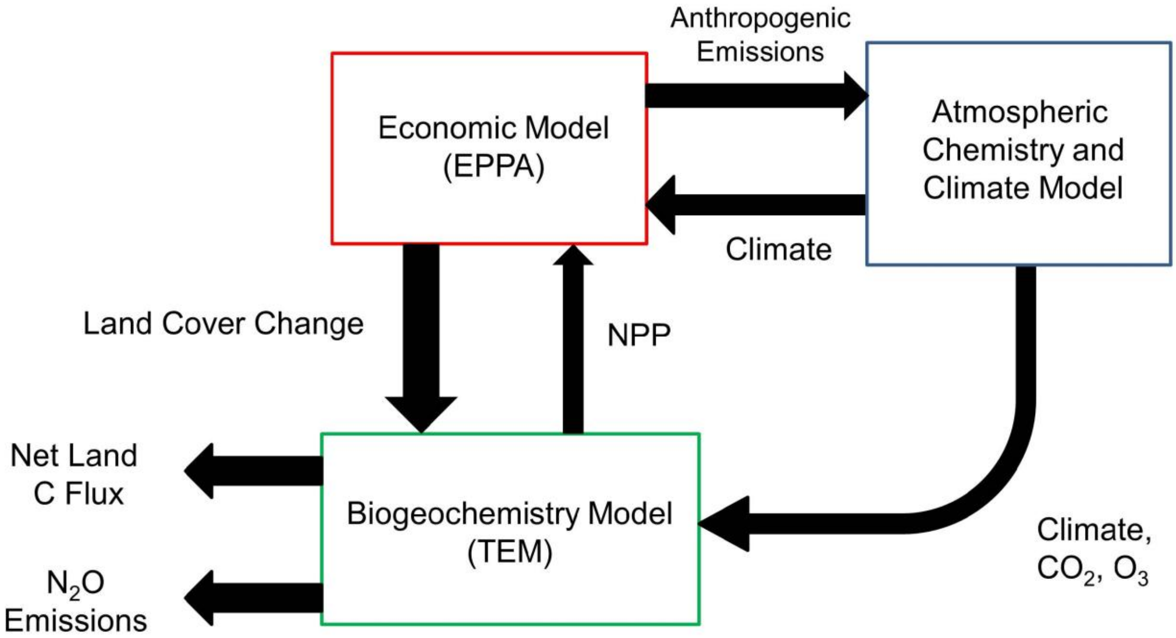

Figure 1. General approach to project future land use (including cellulosic biofuels) and their effects on terrestrial carbon fluxes and nitrous oxide (N_2O) emissions associated with production of cellulosic biofuels. The approach links an economic model (Emissions Prediction and Policy Analysis or EPPA, Babiker *et al*., 2001; Paltsev *et al*., 2005) with a terrestrial biogeochemistry model (the Terrestrial Ecosystem Model or TEM, Melillo *et al*., 1993; Tian *et al*., 1999, 2003; McGuire *et al*., 2001; Felzer *et al*., 2004) and an atmospheric chemistry and climate model (Sokolov *et al*., 2009). The EPPA model uses climate variables from the atmospheric chemistry and climate model and net primary production (NPP) estimates from TEM to predict changes in the land share in each of 67,420 grid cells (spatial resolution: 0.5^o latitude x 0.5^o longitude). The TEM then uses the land-use changes projected by EPPA along with atmospheric carbon dioxide (CO_2) and ozone (O_3) concentrations and climate variables from the atmospheric chemistry model to predict net land carbon fluxes and N_2O emissions.

Thus, the approach captures both the effects of changes in climate and atmospheric composition and the effects of potential land-use changes resulting from various market and international trade policies on terrestrial carbon dynamics and N_2O emissions. In addition, environmental impacts are represented in the economy fully within the theoretical construct of a neoclassical general equilibrium model by identifying specific primary factors and goods and service demands affected by environmental change, and adaptation to it. Further details of the models and their linkages may be found in Melillo *et al*. (2009).

Below, we first describe how we estimate land carbon fluxes and N_2O emissions using the Terrestrial Ecosystem Model. We then describe how we track land-use change through time and the projection of land-use change in the future through the development of two land-use scenarios. Finally, we describe how we assess the impact of cellulosic biofuels production on land-use change and associated greenhouse gas emissions and explore the consequences of different regional attributions of emissions from biofuels use and associated fossil fuel abatement.

2.1 Estimation of Land Carbon Fluxes

To determine the influence of land-use change on terrestrial carbon dynamics, we calculate the net carbon exchange (NCE) between terrestrial ecosystems and the atmosphere from: 1) the carbon gained or lost through ecosystem metabolism, as represented by net ecosystem production (NEP, Chapin *et al*., 2006); 2) the carbon lost during the conversion of natural ecosystems to agriculture (E_C); and 3) the carbon lost during the decomposition of agricultural and wood products (E_P) as described in previous publications (McGuire *et al*., 2001; Tian *et al*., 2003; Felzer *et al*., 2004). Thus, we assume:

$$NCE = NEP - E_C - E_P \tag{1}$$

Any carbon emissions associated with the consumptive use of biofuels would be included as part of the E_P flux.

To represent a generic cellulosic biofuel crop, we use the extant grassland parameterization of TEM in a manner similar to that used by Felzer *et al*. (2004, 2005) for row-crop agriculture. In these simulations, we assume that both biofuels and food crops are optimally fertilized so that the productivity of these crops does not experience any nitrogen limitations.

2.2 Estimation of Land N_2O Emissions

We use different approaches to estimate N_2O emissions from fertilized agroecosystems versus other ecosystems. For food and biofuel crops, we assume that all N_2O emissions from these ecosystems are associated with the application of nitrogen fertilizers. For pastures and natural ecosystems, we assume that N_2O emissions can be determined from TEM estimates of soil respiration (Garcia-Montiel *et al*., 2004; Galford *et al*., 2010).

2.2.1 N_2O Emissions from Fertilizer Applications in Agroecosystems

To estimate nitrous oxide fluxes associated with fertilizer applications, we determine the amount of nitrogen fertilizer required by crop plants by estimating the amount of nitrogen that crops would take up under both nitrogen-limiting and non-limiting conditions with TEM. We then subtract the estimate of nitrogen uptake under N-limiting conditions from the corresponding estimate under non-limiting conditions to determine optimum nitrogen fertilizer requirements. All crops are assumed to be fertilized. Our approach likely underestimates fertilizer applications in regions where fertilizers are widely used. Because it is not possible to time applications and amounts exactly to plant needs and the yield penalty of too little nitrogen is fairly substantial relative to the cost of fertilizer, rates of fertilizer application are generally in excess of that actually used by the plant. On the other hand, many crops in poor regions, such as Africa or Latin America, receive little fertilizer so we may overestimate application rates in these regions. Even with these caveats, we believe the approach provides a reasonable estimate of the relative importance of N_2O emissions compared to carbon emissions, highlighting the area for further research.

We assume that an additional 3% of the amount of fertilizer applied is lost as N_2O (Crutzen *et al.*, 2008; Davidson, 2009). This loss includes both direct N_2O emissions from croplands and indirect N_2O emissions associated with the deposition of volatilized fertilizer nitrogen on adjacent natural ecosystems and the runoff of excess fertilizer to wetlands and river networks.

2.2.2 Natural N_2O Emissions

In natural ecosystems, N_2O is produced primarily from the microbial processes of nitrification and denitrification (Davidson *et al*., 2000). A large field study of N_2O fluxes from forests of the Brazilian Amazon reported a linear correlation between soil N_2O emissions and CO_2 fluxes resulting from decomposition of soil detritus and root respiration, collectively known as soil respiration (Garcia-Montiel *et al.* 2004). It is thought to be a result of the dependency of denitrification on the availability of labile carbon and the fact that decomposition can create anaerobic microsites that are needed for denitrification (Garcia-Montiel *et al*., 2003). Xu *et al.* (2008) found the relationship between soil respiration and N_2O emissions to apply to a number of studies conducted in different ecosystems.

For this study, we adapt the relationships between hourly N_2O emissions and soil respiration rates developed by Xu *et al*. (2008) for eight different ecosystems to estimate annual N_2O emissions based on annual estimates of soil respiration determined by TEM as follows:

$$N_2Oflx = aR_S + b \tag{2a}$$

$$R_S = \alpha R_A + R_H \tag{2b}$$

Table 1. Relationships between nitrous oxide (N_2Oflx, Tg N/yr), soil respiration (R_S, Pg C/yr) and nitrogen fertilizer application (NFERT, Tg N/yr) used to estimate nitrous oxide emissions from different land covers.

Description of Vegetation	Calculation of N_2O Emissions	Source
Needle-leaf Evergreen Tree (NET) temperate	$N_2Oflx = 0.1979\ R_S + 0.0052$	Based on Xu et al. (2008)
Needle-leaf Evergreen Tree (NET) boreal	$N_2Oflx = 0.1979\ R_S + 0.0052$	Based on Xu et al. (2008)
Needle-leaf Deciduous Tree (NDT) boreal	$N_2Oflx = 0.1979\ R_S + 0.0052$	Based on Xu et al. (2008)
Broadleaved Evergreen Tree (BET) tropical	$N_2Oflx = 0.1817\ R_S + 0.1714$	Based on Xu et al. (2008)
Broadleaved Evergreen Tree (BET) temperate	$N_2Oflx = 0.1979\ R_S + 0.0052$	Based on Xu et al. (2008)
Broadleaved Deciduous Tree (BDT) temperate	$N_2Oflx = 0.1979\ R_S + 0.0052$	Based on Xu et al. (2008)
Broadleaved Deciduous Tree (BDT) boreal	$N_2Oflx = 0.1979\ R_S + 0.0052$	Based on Xu et al. (2008)
Broadleaved Deciduous Shrub (BDS) boreal	$N_2Oflx = 0.2181\ R_S – 0.0330$	Based on Xu et al. (2008)
C3 grass arctic	$N_2Oflx = 0.2181\ R_S – 0.0330$	Based on Xu et al. (2008)
C3 grass	$N_2Oflx = 0.0172\ R_S + 0.0075$	Based on Xu et al. (2008)
C4 grass	$N_2Oflx = 0.0713\ R_S + 0.0100$	Based on Xu et al. (2008)
Food Crops	$N_2Oflx = 0.03\ NFERT$	Based on Crutzen et al. (2008)
Biofuel Crops	$N_2Oflx = 0.03\ NFERT$	Based on Crutzen et al. (2008)
Wetlands (Tree tropical)	$N_2Oflx = 0.0688\ R_S + 0.0575$	Based on Xu et al. (2008)
Wetlands (No-tree tropical)	$N_2Oflx = 0.0713\ R_S + 0.0100$	Based on Xu et al. (2008)
Wetlands (Tree temperate)	$N_2Oflx = 0.1979\ R_S + 0.0052$	Based on Xu et al. (2008)
Wetlands (No-tree temperate)	$N_2Oflx = 0.0172\ R_S + 0.0075$	Based on Xu et al. (2008)
Wetlands (Tree boreal)	$N_2Oflx = 0.2181\ R_S – 0.0330$	Based on Xu et al. (2008)
Wetlands (No-tree boreal)	$N_2Oflx = 0.2181\ R_S – 0.0330$	Based on Xu et al. (2008)
Floodplains (Tree tropical)	$N_2Oflx = 0.0688\ R_S + 0.0575$	Based on Xu et al. (2008)
Floodplains (No-tree tropical)	$N_2Oflx = 0.0713\ R_S + 0.0100$	Based on Xu et al. (2008)
Floodplains (Tree temperate)	$N_2Oflx = 0.1979\ R_S + 0.0052$	Based on Xu et al. (2008)
Floodplains (No-tree temperate)	$N_2Oflx = 0.0172\ R_S + 0.0075$	Based on Xu et al. (2008)
Pastures	$N_2Oflx = 0.0172\ R_S + 0.0075$	Based on Xu et al. (2008)

where N_2Oflx is the emission of nitrous oxide, *a* and *b* are linear regression coefficients that are stratified by biome type (**Table 1**), R_S is soil respiration, α (0.35, Garcia-Montiel *et al.*, 2004) is the fraction of autotrophic respiration (R_A) of plants assumed to be root respiration. In TEM, R_A is dependent upon the amount of vegetation biomass, air temperature and photosynthesis (Tian *et al*., 1999). Heterotrophic respiration (R_H) is associated with the decomposition of organic matter and is influenced by the amount and quality (as represented by the C:N ratio) of soil organic matter, air temperature and soil moisture (McGuire *et al*., 1997; Tian *et al*., 1999). In this study, we estimate the N_2O emissions for pastures based on the relationship between N_2O and soil respiration for temperate grasslands described by Xu *et al*. (2008). We also assume that no N_2O emissions occur from bare ground, temperate shrublands, xeromorphic forests, salt marshes and mangroves due to lack of information on the relationships between N_2O emissions and soil respiration for these ecosystems.

2.3 Tracking Land-use Change

To represent land-use change, we use a dynamic cohort approach (Schlosser *et al*., 2007; Melillo *et al*., 2009; Hayes *et al*., 2011). In this approach, cohorts are used to track the recovery of terrestrial carbon dynamics from a disturbance within a 0.5^o x 0.5^o grid cell. A new cohort is created for every unique disturbance so that it is possible to simultaneously track the recovery of terrestrial ecosystems from many different disturbances that vary either in time or cause. The TEM is then used to simulate the recovery of terrestrial carbon dynamics after a disturbance within the context of local environmental conditions for the new disturbed cohort. Disturbances are prescribed either by spatially-explicit time-series data sets (McGuire *et al*., 2010; Hayes *et al*. 2011) or by output from a land-use change model (Melillo *et al*., 2009; Reilly *et al*., 2011).

2.4 Development of Land-use Change Scenarios

To generate the land-use change data sets for this study, we focus on a climate policy scenario that uses biofuels to help control GHG emissions. It starts with the Kyoto Protocol, and intensifies emissions reductions in succeeding years. The climate policy makes the use of fossil fuels more expensive and speeds up the introduction of biofuels, and ultimately increases the size of the biofuel industry, with additional effects on land use, land prices, and food and forestry production and prices. The GHG policy scenario follows Paltsev *et al*. (2008) and reflects a path whereby developed countries would gradually phase in a 50% reduction in emissions by 2050. Developing countries delay their mitigation action until 2025, and intensify reductions in 2035. The cumulative level of GHG emissions from fossil energy and other industrial activities is consistent with a frequently discussed 550 ppmv CO_2 stabilization goal. Similar to the provisions of existing climate policies, fossil fuel emissions of CO_2 (including those resulting from the production of biofuels) are controlled, but land-use emissions are not. As a result, the climate policy scenario used here does not provide incentives to avoid land-use emissions resulting from land clearing to produce biofuels.

A key issue in terms of the implications of expanded biofuels crop production on land conversion is whether the additional land use will have repercussions on the intensive margin (causing land owners to use existing land more intensively—increasing yields or moving from extensive pasture and grazing toward more confined livestock operations) or on the extensive margin (converting land). Such market responses depend on the willingness of land owners to convert natural areas or the effectiveness of measures designed to protect these areas as well as the prospects for intensification, which is captured in our modeling system as estimated abilities to substitute other inputs for land. We consider two cases to illustrate this point. Case 1 allows conversion of natural areas to meet increased demand for land, as long as conversion is profitable; i.e., conversion costs are covered by returns. Case 2 allow less conversion by incorporating regional land-conversion-response elasticities that reflect the observed rate of land conversion over the past decade, and as a result, economic forces drive more intensification of existing managed lands.

2.5 Assessment of Biofuels Production Impacts

To assess the impact of cellulosic biofuels production on greenhouse gas emissions, we first examine how biofuels production moderates the evolution of land use in the future and how these changes vary among the sixteen EPPA regions (**Table 2**). We then determine direct and indirect effects of biofuels on regional land carbon fluxes and N_2O emissions, both separately and together, and the resulting impacts on regional net greenhouse gas budgets.

2.5.1 Land-use Change

To determine the influence of land-use policy on the conversion of other managed lands to cellulosic biofuels production and the displacement of these other managed lands by cellulosic biofuels production, we compare the losses and gains in area of each managed ecosystem (food crops, pasture, managed forests) within each 0.5^o x 0.5^o grid cell across the globe between a pair of biofuels/no-biofuels scenarios for each of the two land-use cases (i.e., Case 1 and Case 2). Losses in area of a particular managed ecosystem may occur when this ecosystem has been converted to production of cellulosic biofuels or to another managed ecosystem (e.g., loss of

Table 2. Association of EPPA4 regions to countries and territories across the globe.

EPPA Region	Countries and Territories
AFR	**Africa** - Algeria, Angola, Benin, Botswana, Burkino Faso, Burundi, Cameroon, Canary Islands, Cape Verde, Central African Republic, Chad, Comoros, Democratic Republic of Congo, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Europa Island, Gabon, Gambia, Ghana, Glorioso Islands, Guinea, Guinea-Bissau, Ivory Coast, Juan De Nova Island, Kenya, Lesotho, Liberia, Libya, Madagascar, Madeira, Malawi, Mali, Mauritania, Mauritius, Mayotte, Morocco, Mozambique, Namibia, Niger, Nigeria, Republic of Congo, Reunion, Rwanda, Saint Helena, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Tromelin Island, Tunisia, Uganda, Western Sahara, Zambia, Zimbabwe
ANZ	**Australia**, Cook Islands, **New Zealand**, Niue, Norfolk Island, Tokelau
ASI	**Higher Income East Asia** - Malaysia, Philippines, Singapore, South Korea, Taiwan, Thailand
CAN	**Canada**
CHN	**China**, Hong Kong, Paracel Islands
EET	**Eastern Europe** - Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia
EUR	**European Union** - Austria, Belgium, Denmark, Faroe Islands, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, The Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom
FSU	**Former Soviet Union** - Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
IDZ	**Indonesia**, Timor Leste
IND	**India**
JPN	**Japan**
LAM	**Latin America** - Anguilla, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands, French Guiana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti. Honduras, Jamaica, Martinique, Montserrat, Netherland Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela, Virgin Islands
MES	**Middle East** - Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestinian Territories, Qatar, Saudi Arabia, Syria, United Arab Emirates, Yemen
MEX	**Mexico**

Table 2 (continued). Association of EPPA4 regions to countries and territories across the globe.

ROW	**Rest of the World -** Afghanistan, Albania, American Samoa, Bangladesh, Bhutan, Bosnia-Herzegovina, British Indian Ocean Territory, Brunei, Cambodia, Croatia, Cyprus, Fiji, French Polynesia, French Southern and Antarctic Lands, Futuna Island, Greenland, Guam, Kiribati, Laos, Macedonia, Maldives, Marshall Islands, Micronesia, Mongolia, Montenegro, Myanmar, Nauru, Nepal, New Caledonia, Northern Mariana Islands, North Korea, Pakistan, Palau, Papua New Guinea, Pitcairn Islands, Samoa, Serbia, Solomon Islands, Sri Lanka, South Georgia Island, Tonga, Turkey, Tuvalu, Vanuatu, Vietnam, Wallis Island
USA	**United States of America**

pasture to food crops with intensification), or if this managed ecosystem has been abandoned to natural ecosystems. Gains in area of a particular managed ecosystem may occur when natural ecosystems or other managed ecosystems are converted to this particular managed ecosystem. In this study, we assume that all losses represent areas of a particular managed ecosystem that has been “co-opted” directly for cellulosic biofuels production or indirectly by the displacement of other managed ecosystems as a result of biofuels production, and that all area gains represent conversion of natural or other managed lands to a particular managed ecosystem due to displacement by biofuel production. Similarly, losses in the areas of natural ecosystems are assumed to occur from land being “co-opted” either directly for cellulosic biofuels production or by displacement of managed lands from biofuels production. Losses and gains in area of managed and natural ecosystems are then summed for each EPPA region in each case to evaluate how cellulosic biofuels production may influence the distribution of future land-use change across the globe.

2.5.2 Impacts on Land Carbon Fluxes

To separate the direct from the indirect effects of biofuels, the experimental scenario design matches each simulation of the above land-use cases (i.e. Case 1 and Case 2) with a simulation of a comparable scenario where the biofuel option is not available. We then examine carbon emissions between each scenario pair of each case to identify the total land-use effects of the expansion of cellulosic biofuels production over the 21st century. In the scenarios with biofuels, we evaluate the direct effects of biofuels production on carbon emissions by estimating the NCE on only those areas devoted to biofuels production. The total effects of biofuels production on carbon emissions are calculated by the difference in NCE estimates between biofuels/no-biofuels pair of scenarios for all land covers. Indirect effects are the difference between the total effects and the direct effects. This approach includes the effects of biofuel production on carbon stored in both vegetation and soil organic matter along with the effects on carbon stored in agricultural and wood products in our estimates. To evaluate GHG forcing of land carbon fluxes, the carbon estimates are converted to carbon dioxide equivalence (CO_2-eq) by multiplying these estimates by the factor (44 g CO_2 / 12 g C).

With our approach, our estimates of land carbon fluxes account for the carbon emissions associated with land conversion for both cellulosic biofuels production and displaced managed lands, and any changes in natural carbon sequestration capacity associated with vegetation regrowth after disturbance. Carbon sequestration may occur on land devoted to biofuels production or displaced managed lands (i.e. “additionality”, Searchinger *et al*., 2008), but this sequestration is considered along with carbon losses due to land conversion when developing our NCE estimates from these managed lands. In addition, natural ecosystems may also sequester carbon, especially with changing environmental conditions in the future (e.g., Friedlingstein *et al*., 2006; Plattner *et al*., 2008; Sokolov *et al*., 2008), but land-use change may diminish the capacity of these natural ecosystems to perform this ecosystem service. To evaluate changes in carbon sequestration capacity of natural terrestrial ecosystems, we subtract the NCE estimates of natural land cover of the no-biofuel simulations from the comparable estimates of the biofuel simulations for each land-use case.

2.5.3 Impacts on N_2O Emissions

Similar to the assessment of biofuel production impacts on land carbon fluxes, we calculate the difference in N_2O emissions between the biofuels/no-biofuels pairs of land-use cases to deduce the total N_2O emissions associated with biofuels production. Direct effects are then determined as the N_2O emissions associated with application of nitrogen fertilizers to biofuel crops and indirect effects are determined as the difference between total effects and direct effects. Indirect effects include biofuel-induced changes in N_2O emissions associated with fertilizer application to displaced food crops along with biofuel-induced changes in N_2O emissions from natural ecosystems, managed forests and pastures. The biofuel-related N_2O emission estimates are then converted to CO_2-eq units by multiplying the estimates first by the factor (44 g N_2O/ 28 g N), to convert from molecular units of nitrogen to molecular units of N_2O, and then by 298, the 100-year global warming potential of nitrous oxide (Forster *et al*., 2007).

After examining the direct and indirect effects of biofuels on land carbon fluxes and N_2O emissions separately, we combine the direct effects of biofuels on GHG forcing of land carbon fluxes to the direct effects of biofuels on GHG forcing of N_2O emissions and also combine the comparable indirect effects to determine the relative importance of direct and indirect effects of biofuels on greenhouse gas emissions.

2.5.4 Impacts on Regional Greenhouse Gas Budgets

To determine if the GHG costs of cellulosic biofuels production outweighed the GHG benefits of this technology, we compare the avoided fossil emissions due to biofuels use to the land carbon fluxes and N_2O emissions determined above. The avoided fossil emissions are based on the carbon content of the displaced gasoline/diesel fuel. Because biofuels production is assumed in our model to be zero-emissions (a fraction of harvested biomass is used to fuel processing, etc.), the avoided emissions by using biofuels instead of refined oil is simply the total emissions that would result from combusting an energy-equivalent amount of refined oil. Emissions abatement is thus determined by multiplying EPPA biofuels production in a given year (EJ) by the carbon emission coefficient for refined oil used in EPPA, 18.4 Tg C EJ^{-1} (California EPA, 2009). Carbon emissions are then converted to CO_2-eq units by multiplying the carbon estimates by the factor (44 g CO_2 / 12 g C).

The method used to assign fossil fuel abatement benefits may have a large influence on a region’s GHG cost/benefit analysis because biofuels may be mostly produced in one region, but mostly consumed in another. Should the abatement benefits be credited to the region that produces the biofuel to offset the GHG costs of land emissions associated with producing the biofuels? Or, should the abatement benefits be credited to the region that actually consumes the biofuels instead of consuming fossil fuels? We apply both approaches to examine how this discrepancy may influence the potential assignment of future GHG credits.

To determine regional fossil fuel abatement benefits that are based on the consumption rather than the production of biofuels, we use EPPA to determine the amount of energy used in each region that is assumed to be derived from biofuels (i.e. energy demand) in addition to the amount of energy produced from biofuels (energy supply) in each region. The difference between energy demand and energy supply determines if a region imports biofuels to satisfy its energy needs or exports biofuels. Because the global consumption of biofuel energy is assumed to equal the global production of biofuel energy, the amount of carbon associated with the imports and exports of biofuels is determined by multiplying the global estimate of fossil fuel emissions abatement (described above) by the proportion of this global energy determined to be either imported or exported into a region.

Because biofuels may also alter food production and the trade of food products among regions, we also determine biofuel-induced changes in the horizontal transfer of carbon in food products among regions. For both the future land-use cases with and without biofuels, we calculate the carbon in food imports and exports by multiplying the global food crop yield estimated by TEM by the proportion of the value of global food production represented by food imported or exported into a region, as estimated by EPPA. To determine the influence of biofuels on the horizontal transfer of carbon among regions, we first add the regional estimates of biofuel exports to the appropriate regional estimates of food exports from the land-use case scenario with biofuels and then subtract the appropriate regional estimates of food exports from the land-use case scenario without biofuels. The carbon exports and imports are then converted to CO_2-eq units by multiplying the carbon estimates by the factor (44 g CO_2 / 12 g C). In all of these analyses, the carbon emissions associated with land conversions for biofuels and displaced agriculture are always attributed to the producer regions where they occur.

3. RESULTS

3.1 Biofuel Production Effects on Land-use Change

3.1.1 Future Land-use Change without Biofuels

Our analysis indicates that land-use pressures will increase over the 21st century, even without the production of cellulosic biofuels, to help satisfy the basic food and fiber needs of a growing world population (**Figure 2**). Areas devoted to food production will increase from 16.1 million km^2 at the beginning of the 21st century to 23.3 million km^2 in Case 1 and 20.8 million km^2 in Case 2 by the end of the 21st century. Pastures will initially increase from 25.8 million km^2 to 31.6 million km^2 in Case 1 and 28.7 million km^2 in Case 2 over the first half of the 21st century, but then decrease to 29.9 and 26.9 million km^2, respectively, as these areas are used more intensively for food crops during the latter half of the 21st century. The temporal trends in managed forest area depend on the land-use policy being invoked. In Case 1, managed forests increase from 7.3 million km^2 in 2000 to 11.8 million km^2 in 2050 and 12.9 million km^2 in 2100. In contrast, managed forests in Case 2 initially decrease during the first few decades of the 21st century, but then increase in areal extent so that they cover 7.1 million km^2 in 2050 and 8.9

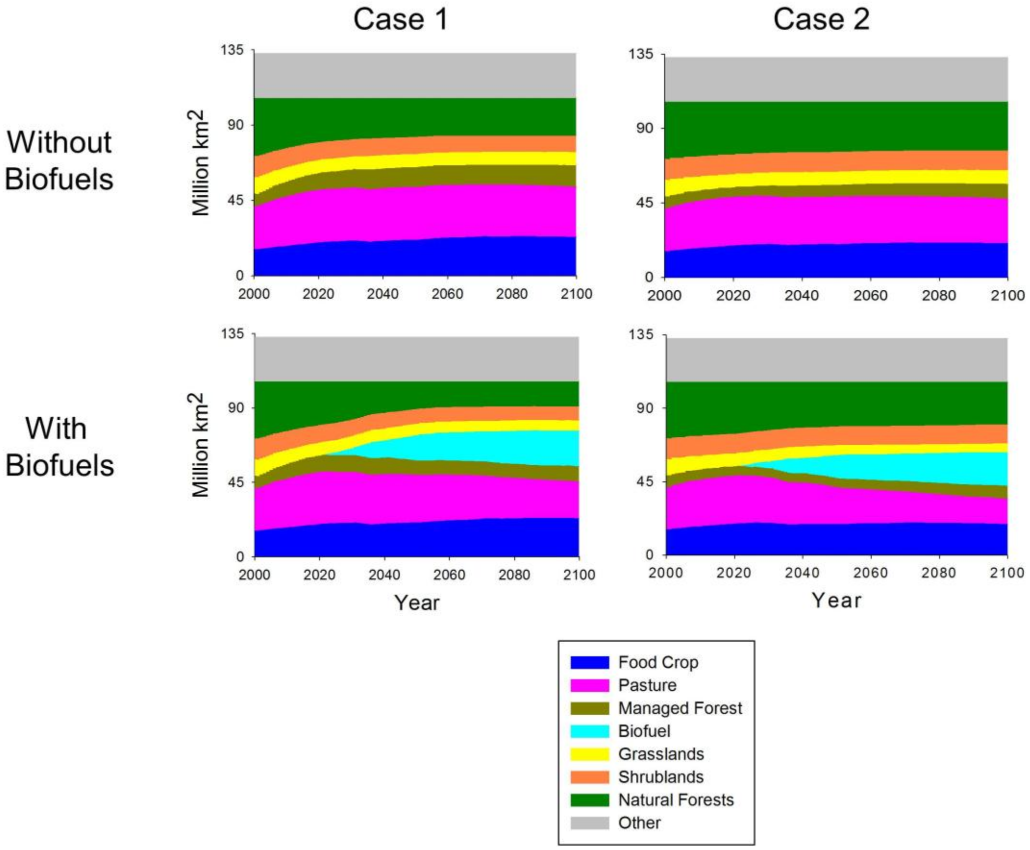

Figure 2. Future distribution of managed and natural land cover as projected by land-use scenarios Case 1 and Case 2 with and without consideration of cellulosic biofuels.

million km^2 in 2100. As a result of these land-use changes, most of the estimated future losses of natural ecosystems occur during the first half of the 21st century even without biofuels production (Figure 2).

3.1.2 Intensification of Managed Lands versus Conversion of Natural Lands

The production of cellulosic biofuels enhances these land-use pressures leading to more intense use of managed lands and additional land conversions over the 21st century. In our analysis, cellulosic biofuels production does not begin until 2022, but expands rapidly so that 15.3 million km^2 are devoted to biofuels production by 2050 in Case 1 and 14.1 million km^2 in Case 2. During the latter half of the 21st century, the expansion of biofuels production slows down such that 21.6 million km^2 in Case 1 and 20.6 million km^2 in Case 2 are devoted to biofuels production by 2100.

While biofuels production does lead to additional land conversions from natural ecosystems, we estimate that most of the area used for biofuels production has been co-opted from other land uses (**Figure 3a,b**). In the year 2050, we estimate that 74% of the area devoted to biofuels production in Case 1 would have otherwise been used for food production, pastures or managed forests with the most area co-opted from managed forests. For Case 2, we estimate that 80% of the area devoted to biofuels production in 2050 has been co-opted from other managed lands with the most area co-opted from pastures. By 2100, the proportion of land devoted to biofuels production that has been co-opted from other managed lands increases to 85% in Case 1 and 84% in Case 2 with the most area co-opted from pastures in both cases, which indicates an intensification of the use of managed lands in both cases.

Because the changes in managed lands are not enough to compensate for the area required for biofuels production, some natural lands will be converted directly to cellulosic biofuels ("Residual Biofuel" in Figure 3a,b). In addition, more natural lands will be converted to support food production or managed forests displaced by biofuels production to help satisfy the food and fiber needs of a growing global population. For Case 1, we estimate that biofuels production caused an additional 4.0 million km^2 of natural land to be converted by 2050, but this requirement decreased to 3.2 million km^2 by 2100. In contrast, displaced managed lands caused an additional 5.0 million km^2 of natural land to be converted by 2050 and 7.5 million km^2 by 2100. For Case 2, biofuels production caused less natural lands (2.9 million km^2) to be converted by 2050 than Case 1, but slightly more (3.3 million km^2) to be converted by 2100. Less managed land is displaced in Case 2 with an additional 2.8 million km^2 of natural land converted by 2050 and 3.6 million km^2 by 2100. In both cases, food crop production accounts for most of the displaced managed land whereas pastures account for the least.

Overall, the area of displaced managed land is only a fraction of the area co-opted for biofuels production with relatively more area displaced by mid-century (44% in Case 1, 25% in Case 2) than at the end of the 21st century (41% in Case 1, 21% in Case 2). An exception, however, is that the area of displaced food crops in 2100 is greater than the area co-opted in Case 1. Intensified land use in both cases has diminished the need for additional land such that the area of displaced managed lands is only a fraction of the area of managed lands co-opted for cellulosic biofuels production. This intensification has also diminished the importance of the relatively inefficient pastures for providing food in the future and enhanced the reliance on food

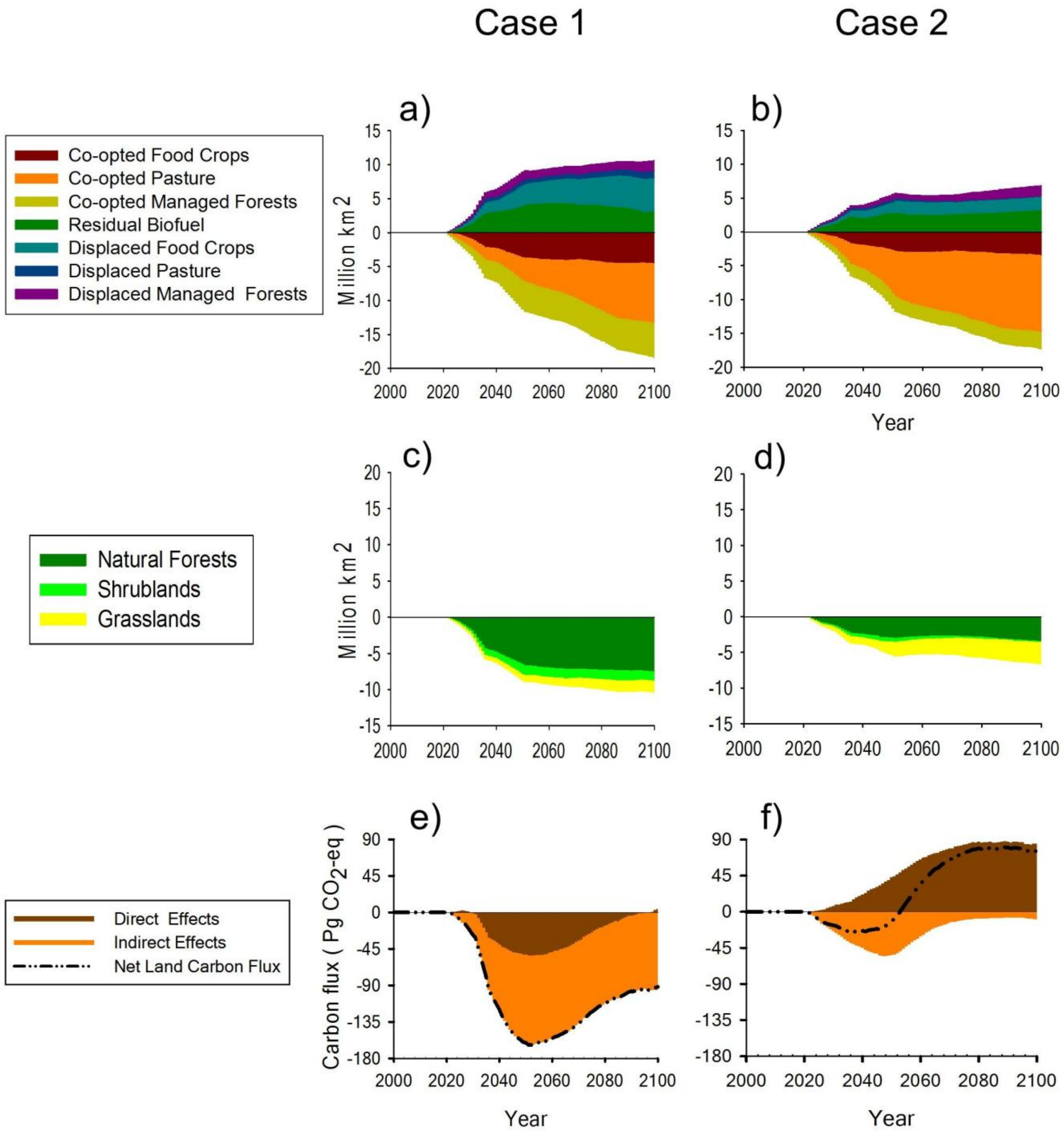

Figure 3. Projected changes in managed land co-opted or displaced by biofuels production for Case 1 (a) and Case 2 (b) land-use scenarios along with the types of natural lands converted by biofuels production or displaced managed lands (c and d), and the associated changes in land carbon fluxes resulting from direct and indirect effects of cellulosic biofuels production (e and f). The total area of natural lands converted by biofuels production in (c) and (d) corresponds to the combined area of Residual Biofuel, Displaced Food Crops, Displaced Pasture, Displaced Managed Forests in (a) and (b) respectively.

crop production subsidized with the application of nitrogen fertilizers. Thus, the larger area of displaced food crops compared to co-opted food crops is a result of this shift in the relative importance of pastures to row-crop agriculture in providing food in the future. As a result of these land-use dynamics, the additional land converted from natural ecosystems for biofuels production and displaced managed lands is only about one-half of the area devoted to biofuels in Case 1 and about one-third of the biofuels area in Case 2.

The impact of biofuels production on concurrent food production varies with the land-use policy implemented over the 21st century. The area devoted to food crop production increases by 0.38 million km^2 (a 2% increase over the scenario without biofuels) in Case 1, but decreased by 1.53 million km^2 (a 7% decrease) in Case 2 as a result of these land-use changes associated with biofuels production. Large decreases in the area devoted to pastures, however, occur for both land-use scenarios as a result of biofuels production with larger reductions occurring in Case 2 (11.25 million km^2 or a 42% decrease) than in Case 1 (7.73 million km^2 or a 26% decrease).

3.1.3 Regional Variations in Land-use Change

Differential regional effects on land-use change result from many complex interactions. Our economic model includes the possibility of trade in all goods, including food and biofuels. For food, the predisposition of countries to produce food domestically and trade with existing trade partners is reflected in Armington elasticity assumptions. In contrast, we assume biofuels are a homogeneous good where the origin of the biofuel does not matter to consumers other then as it affects cost of production and transportation. Relative demand for both biofuel and food, and differential demand growth due to population and income over time interacts with this representation of trade. Because biofuels are a homogeneous good, we expect significant biofuel imports in regions with high energy demands, especially if expansion of biofuel production is limited in the region. Environmental conditions also vary among regions along with future changes in these conditions. For example, higher ozone levels exist in the northern temperate regions and reduce crop productivity, while warming allows cropping to extend poleward. As a result, the expansion of biofuels production causes a loss of areas devoted to food crops, pastures and managed forests in some regions, but gains in other regions as additional natural lands are converted to replace those managed lands co-opted by biofuels production. Over the 21st century, most of the expansion of cellulosic biofuels production occurs in Africa and Latin America for both of the land-use cases (**Figure 4**). These regions are attractive areas for growing biofuels in our economic analyses because the land is relatively inexpensive (Gurgel *et al.*, 2007) and simple management interventions, such as fertilizer additions, can dramatically increase crop productivity (Sanchez, 2002). By 2100, Africa accounts for 46% of the global area devoted to biofuels in Case 1 (**Table 3**) and 48% in Case 2 (**Table 4**). Most of this production occurs in sub-Saharan Africa outside of the tropical forests of the Congo Basin (**Figures 5** and **6**). Latin America accounts for an additional 31% of the global area devoted to biofuels in Case 1 and 30% in Case 2 by 2100 with most of the production occurring in Brazil, including the formerly forested areas of the Amazon Basin. Other important regions for cellulosic biofuels production in both of the land-use scenario cases include Australia and New Zealand (6%), Cambodia, Laos, Myanmar, Sri Lanka and Vietnam (lumped together in EPPA with other countries throughout the globe in a region known as the "Rest of the World", 6%) and Mexico (3%).

For some regions, the production of cellulosic biofuels depends on the assumed land-use policy. For Case 1, Canada (5%) and Indonesia (1%) are also relatively important regions for cellulosic biofuels production, but these regions become less important in Case 2 where Canada accounts for only 1% of the land devoted to cellulosic biofuels and no land is devoted in Indonesia. In contrast, cellulosic biofuels production is relatively unimportant in the United States of America in Case 1 (1%), but becomes more important in Case 2 (6%). There are also many regions where no land is ever devoted to cellulosic biofuels production such as China, Japan, Eastern Europe, the European Union and the former Soviet Union.

While areas devoted to biofuels production expand continuously throughout the 21st century in Africa and Latin America, an initial expansion of biofuels production in many other regions is followed by abandonment as other management options become more important or more profitable (Figure 4, see also **Figures A1** to **A16** in the **Appendix**). In Canada and the United States of America, some of the land devoted to cellulosic biofuels production during the first half of the 21st century is then later co-opted for managed forests. Similarly, in India, there is an initial expansion of land devoted to cellulosic biofuels production, but all of this land is then later co-opted for food crop production. As a result, the spatial distribution of cellulosic biofuels production during the middle of the 21st century is different and more widespread from that found at the end of the 21st century (Figures 5 and 6).

The displacement of food crops from biofuels production also varies across the globe and

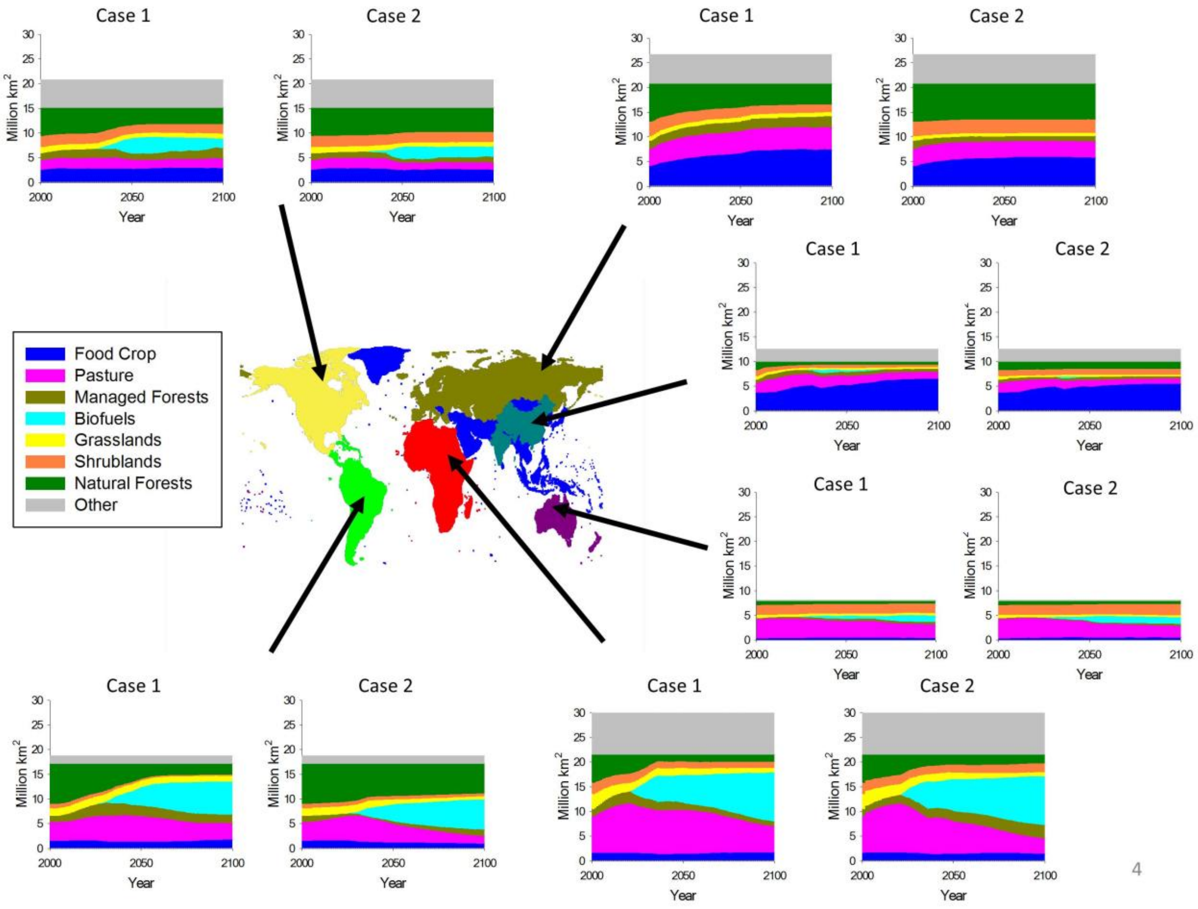

Figure 4. Future distribution of managed and natural land cover as projected by land-use scenarios Case 1 and Case 2 in select regions: Africa (reddish brown), Latin America (green), North America (yellow), Europe-Russia (gold), China-India (teal), and Australia-New Zealand (purple). North America contains the EPPA regions of Canada, Mexico and the United States of America. Europe-Russia contains the EPPA regions of the European Union, Eastern Europe and the Former Soviet Union.

differs between the two land-use scenarios. By 2100, Africa accounts for about 31% of the displaced food crops in both land-use scenarios (Tables 3 and 4). Latin America accounts for about 28% of the displaced food crops in Case 1, but only 3% of the displaced food crops in Case 2. In contrast, Australia and New Zealand account for about 25% of the displaced food crops in Case 2, but only 8% of the displaced food crops in Case 1. In several regions (e.g. Australia/New Zealand, the European Union, the former Soviet Union), the area of displaced food crops is greater than the area co-opted by biofuels indicating that biofuels production is forcing a redistribution of food production.

Table 3. Distribution of land devoted to cellulosic biofuels production in Case 1 over the 21st century and associated changes in areas of food crops, pastures and managed forests co-opted or displaced by biofuel production. Units are million km^2.

EPPA Region	Year	Biofuels	Co-opted Food Crops	Displaced Food Crops	Co-opted Pastures	Displaced Pastures	Co-opted Managed Forests	Displaced Managed Forests	Co-opted Natural Forests	Co-opted Natural Shrub	Co-opted Natural Grass
AFR	2030	3.44	-0.45	+0.41	-0.96	+0.15	-0.92	+0.20	-1.28	-0.29	-0.30
	2050	5.59	-1.18	+1.04	-1.11	+0.45	-1.77	+0.28	-2.36	-0.68	-0.26
	2100	9.89	-1.61	+1.52	-4.66	+0.67	-2.03	+0.15	-2.32	-0.79	-0.82
LAM	2030	0.21	-0.20	0.00	-0.01	+0.01	-0.02	+0.03	-0.01	0.00	-0.01
	2050	3.69	-0.70	+0.39	-0.57	+0.01	-1.09	+0.46	-1.68	-0.31	-0.20
	2100	6.69	-1.32	+1.39	-1.76	+0.29	-2.03	+0.30	-2.65	-0.51	-0.40
ROW	2030	0.14	-0.03	+0.03	-0.04	0.00	-0.02	0.00	-0.07	0.00	-0.01
	2050	1.22	-0.35	+0.22	-0.41	0.00	-0.20	+0.03	-0.30	-0.12	-0.09
	2100	1.40	-0.33	+0.18	-0.43	0.00	-0.26	+0.02	-0.31	-0.15	-0.12
ANZ	2030	0.25	-0.02	+0.02	-0.16	+0.04	-0.04	+0.02	-0.03	-0.04	-0.04
	2050	0.69	-0.05	+0.12	-0.58	+0.01	-0.09	+0.10	-0.09	-0.01	-0.10
	2100	1.33	-0.34	+0.41	-1.15	0.00	-0.15	+0.14	-0.15	+0.03	-0.12
MEX	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.65	-0.23	+0.22	-0.25	+0.08	-0.09	+0.02	-0.23	-0.12	-0.05
	2100	0.69	-0.25	+0.23	-0.33	+0.03	-0.06	+0.03	-0.17	-0.11	-0.06
CAN	2030	0.05	-0.04	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
	2050	1.14	-0.48	+0.49	-0.05	0.00	-0.23	+0.20	-0.98	-0.04	-0.05
	2100	1.06	-0.43	+0.41	-0.05	0.00	-0.25	+0.30	-0.97	-0.04	-0.03
USA	2030	0.00	-0.01	+0.01	0.00	+0.01	0.00	0.00	0.00	-0.01	0.00
	2050	1.26	-0.34	+0.19	-0.24	+0.03	-0.47	+0.01	-0.16	-0.17	-0.11
	2100	0.22	-0.15	0.00	-0.09	0.00	-0.01	+0.36	-0.33	+0.01	-0.01
IDZ	2030	0.03	0.00	0.00	0.00	0.00	0.00	0.00	-0.03	0.00	0.00
	2050	0.47	-0.04	+0.01	-0.01	0.00	-0.07	+0.01	-0.37	0.00	0.00
	2100	0.28	-0.05	0.00	-0.01	0.00	-0.02	+0.05	-0.25	0.00	0.00

Table 3 (continued). Distribution of land devoted to cellulosic biofuels production in Case 1 over the 21st century and associated changes in areas of food crops, pastures and managed forests co-opted or displaced by biofuel production. Units are million km^2.

EPPA Region	Year	Biofuels	Co-opted Food Crops	Displaced Food Crops	Co-opted Pastures	Displaced Pastures	Co-opted Managed Forests	Displaced Managed Forests	Co-opted Natural Forests	Co-opted Natural Shrub	Co-opted Natural Grass
IND	2030	0.19	-0.06	0.00	0.00	0.00	-0.05	0.00	-0.06	-0.01	-0.01
	2050	0.36	-0.20	0.00	-0.01	0.00	-0.10	+0.01	-0.05	0.00	-0.01
	2100	0.00	0.00	+0.03	-0.01	0.00	-0.01	+0.01	-0.02	0.00	0.00
CHN	2030	0.00	0.00	+0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.00	0.00	+0.04	-0.03	0.00	-0.01	0.00	0.00	0.00	0.00
	2100	0.00	-0.01	+0.01	-0.01	0.00	0.00	+0.01	0.00	0.00	0.00
EUR	2030	0.00	0.00	+0.01	0.00	0.00	0.00	0.00	-0.01	0.00	0.00
	2050	0.00	0.00	+0.13	-0.01	+0.01	-0.05	+0.01	-0.09	0.00	0.00
	2100	0.00	0.00	+0.20	0.00	+0.06	-0.17	+0.01	-0.09	-0.01	0.00
FSU	2030	0.00	0.00	+0.07	-0.02	0.00	0.00	+0.04	-0.07	-0.01	-0.01
	2050	0.00	0.00	+0.16	-0.08	+0.01	-0.01	+0.10	-0.15	-0.01	-0.02
	2100	0.00	0.00	+0.43	-0.22	0.00	-0.06	+0.10	-0.18	-0.07	0.00
EET	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.00	0.00	+0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00
	2100	0.00	-0.01	0.00	-0.01	0.00	0.00	+0.01	+0.01	0.00	0.00
MES	2030	0.00	0.00	0.00	0.00	+0.01	0.00	0.00	0.00	0.00	-0.01
	2050	0.15	-0.01	+0.01	-0.05	+0.05	-0.05	+0.01	-0.05	-0.06	0.00
	2100	0.00	0.00	+0.09	-0.05	0.00	0.00	+0.06	-0.04	-0.02	-0.04
ASI	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.03	-0.05	0.00	0.00	0.00	-0.01	+0.01	+0.02	0.00	0.00
	2100	0.00	-0.02	0.00	0.00	0.00	-0.02	+0.01	+0.03	0.00	0.00
JPN	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.00	0.00	0.00	0.00	0.00	0.00	+0.02	-0.02	0.00	0.00
	2100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Globe	2030	4.31	-0.81	+0.56	-1.20	+0.22	-1.06	+0.29	-1.56	-0.36	-0.39
	2050	15.25	-3.63	+3.03	-3.41	+0.65	-4.24	+1.27	-6.51	-1.52	-0.89
	2100	21.56	-4.52	+4.90	-8.78	+1.05	-5.07	+1.56	-7.44	-1.66	-1.60

Table 4. Distribution of land devoted to cellulosic biofuels production in Case 2 over the 21st century and associated changes in areas of food crops, pastures and managed forests co-opted or displaced by biofuel production. Units are million km^2.

EPPA Region	Year	Biofuels	Co-opted Food Crops	Displaced Food Crops	Co-opted Pastures	Displaced Pastures	Co-opted Managed Forests	Displaced Managed Forests	Co-opted Natural Forests	Co-opted Natural Shrub	Co-opted Natural Grass
AFR	2030	3.53	-0.35	+0.26	-1.21	+0.12	-0.77	+0.17	-1.05	-0.23	-0.47
	2050	6.38	-0.75	+0.55	-2.46	+0.23	-1.39	+0.36	-1.61	-0.55	-0.76
	2100	9.89	-1.06	+0.61	-5.47	+0.01	-1.26	+0.67	-1.59	-0.26	-1.54
LAM	2030	0.36	-0.23	0.00	-0.01	+0.03	-0.06	+0.02	-0.08	-0.01	-0.02
	2050	3.41	-0.74	+0.28	-1.85	+0.04	-0.09	+0.24	-0.65	-0.07	-0.57
	2100	6.11	-0.77	+0.06	-2.85	+0.01	-0.77	+0.32	-0.90	-0.27	-0.94
ROW	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.68	-0.26	+0.14	-0.29	0.00	-0.10	+0.01	-0.06	-0.06	-0.06
	2100	1.18	-0.46	+0.15	-0.43	0.00	-0.09	+0.03	-0.14	-0.10	-0.14
ANZ	2030	0.25	-0.01	+0.02	-0.20	+0.01	-0.02	+0.02	-0.02	+0.01	-0.06
	2050	0.96	-0.20	+0.25	-0.85	+0.02	-0.04	+0.08	-0.11	+0.05	-0.16
	2100	1.33	-0.38	+0.49	-1.58	0.00	-0.06	+0.28	-0.17	+0.27	-0.18
MEX	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.65	-0.18	+0.14	-0.32	+0.05	-0.03	+0.02	-0.16	-0.10	-0.07
	2100	0.70	-0.27	+0.20	-0.33	+0.02	-0.05	+0.03	-0.15	-0.09	-0.06
CAN	2030	0.06	-0.06	0.00	0.00	0.00	-0.01	+0.01	0.00	0.00	0.00
	2050	0.27	-0.11	0.00	-0.04	0.00	-0.09	0.00	-0.02	+0.01	-0.02
	2100	0.16	-0.04	+0.02	-0.04	0.00	-0.08	0.00	-0.02	+0.01	-0.01
USA	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	1.52	-0.33	+0.03	-0.39	+0.03	-0.33	0.00	-0.27	-0.03	-0.23
	2100	1.23	-0.40	+0.02	-0.37	+0.02	-0.09	+0.09	-0.39	-0.01	-0.10
IDZ	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.00	-0.01	+0.01	0.00	0.00	0.00	+0.02	-0.02	0.00	0.00
	2100	0.00	-0.02	+0.01	0.00	0.00	0.00	+0.06	-0.05	0.00	0.00

Table 4 (continued). Distribution of land devoted to cellulosic biofuels production in Case 2 over the 21st century and associated changes in areas of food crops, pastures and managed forests co-opted or displaced by biofuel production. Units are million km^2.

EPPA Region	Year	Biofuels	Co-opted Food Crops	Displaced Food Crops	Co-opted Pastures	Displaced Pastures	Co-opted Managed Forests	Displaced Managed Forests	Co-opted Natural Forests	Co-opted Natural Shrub	Co-opted Natural Grass
IND	2030	0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.09	-0.05	0.00	0.00	0.00	-0.01	+0.03	-0.06	0.00	0.00
	2100	0.00	-0.01	+0.01	-0.01	0.00	0.00	+0.01	0.00	0.00	0.00
CHN	2030	0.00	0.00	+0.01	-0.01	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.00	0.00	+0.03	-0.03	0.00	0.00	0.00	0.00	0.00	0.00
	2100	0.00	-0.02	+0.01	-0.02	0.00	0.00	+0.01	+0.02	0.00	0.00
EUR	2030	0.00	0.00	+0.01	0.00	0.00	-0.01	0.00	0.00	0.00	0.00
	2050	0.00	0.00	+0.11	-0.02	0.00	-0.07	0.00	-0.02	0.00	0.00
	2100	0.00	0.00	+0.12	-0.01	+0.01	-0.10	0.00	-0.02	0.00	0.00
FSU	2030	0.00	-0.01	+0.04	-0.03	0.00	0.00	+0.01	0.00	0.00	-0.01
	2050	0.00	-0.02	+0.08	-0.07	0.00	0.00	+0.03	0.00	0.00	-0.02
	2100	0.00	-0.03	+0.16	-0.15	0.00	0.00	+0.02	+0.01	+0.01	-0.02
EET	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.00	0.00	0.00	-0.01	0.00	0.00	+0.01	0.00	0.00	0.00
	2100	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	+0.01	0.00	0.00
MES	2030	0.00	0.00	0.00	0.00	+0.01	0.00	0.00	0.00	0.00	-0.01
	2050	0.08	0.00	+0.01	-0.05	0.00	-0.01	+0.01	0.00	-0.01	-0.03
	2100	0.00	0.00	+0.10	-0.06	0.00	-0.01	+0.02	0.00	-0.01	-0.04
ASI	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.03	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2100	0.00	-0.02	0.00	0.00	0.00	0.00	+0.02	0.00	0.00	0.00
JPN	2030	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2050	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Globe	2030	4.21	-0.67	+0.34	-1.46	+0.17	-0.87	+0.23	-1.15	-0.23	-0.57
	2050	14.07	-2.68	+1.63	-6.38	+0.37	-2.16	+0.81	-2.98	-0.76	-1.92
	2100	20.60	-3.49	+1.96	-11.32	+0.07	-2.51	+1.56	-3.39	-0.45	-3.03

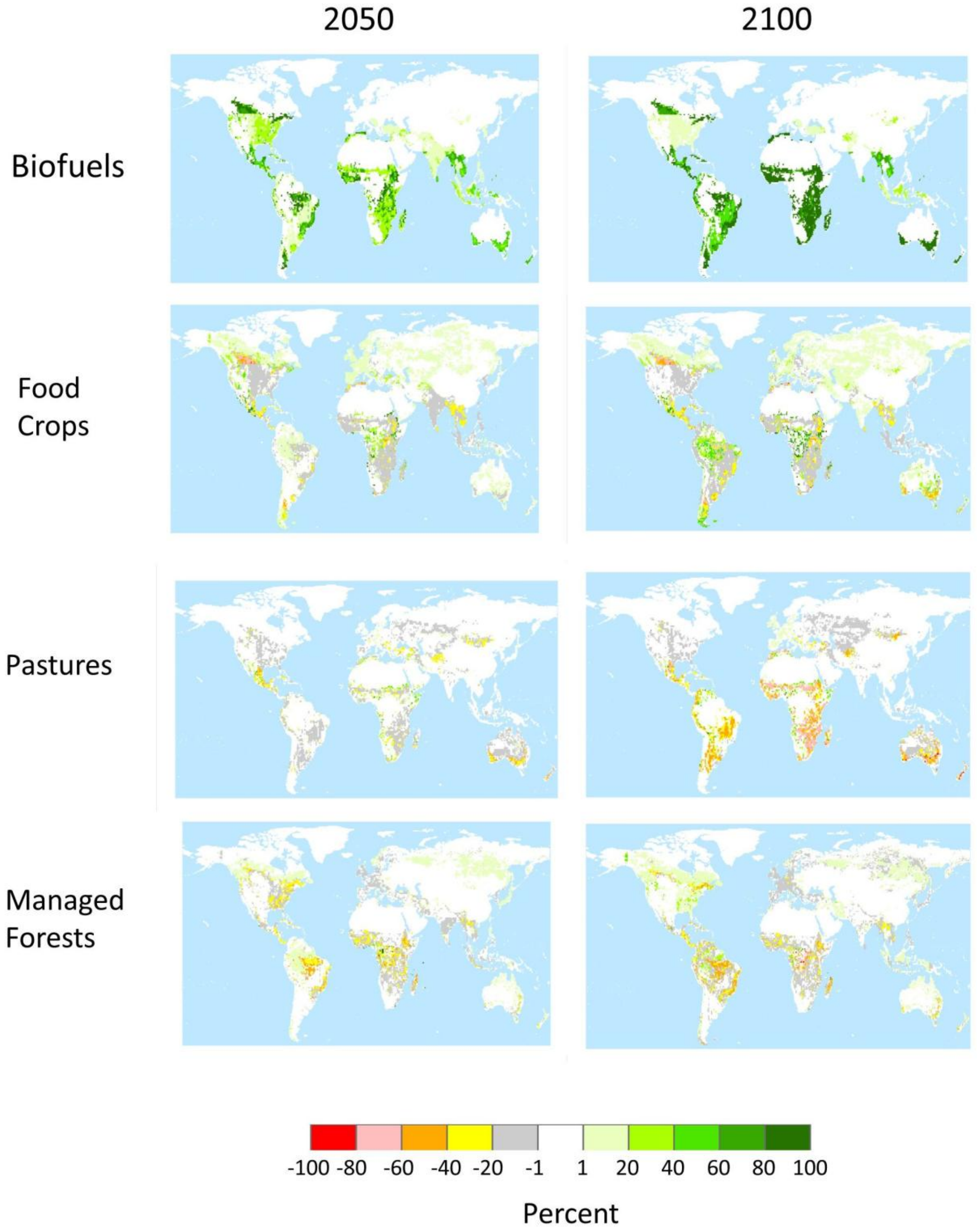

Figure 5. Projected distribution of cellulosic biofuels and the biofuel-induced changes in the distribution of food crops, pastures and managed forests for the Case 1 land-use scenario during 2050 and 2100.

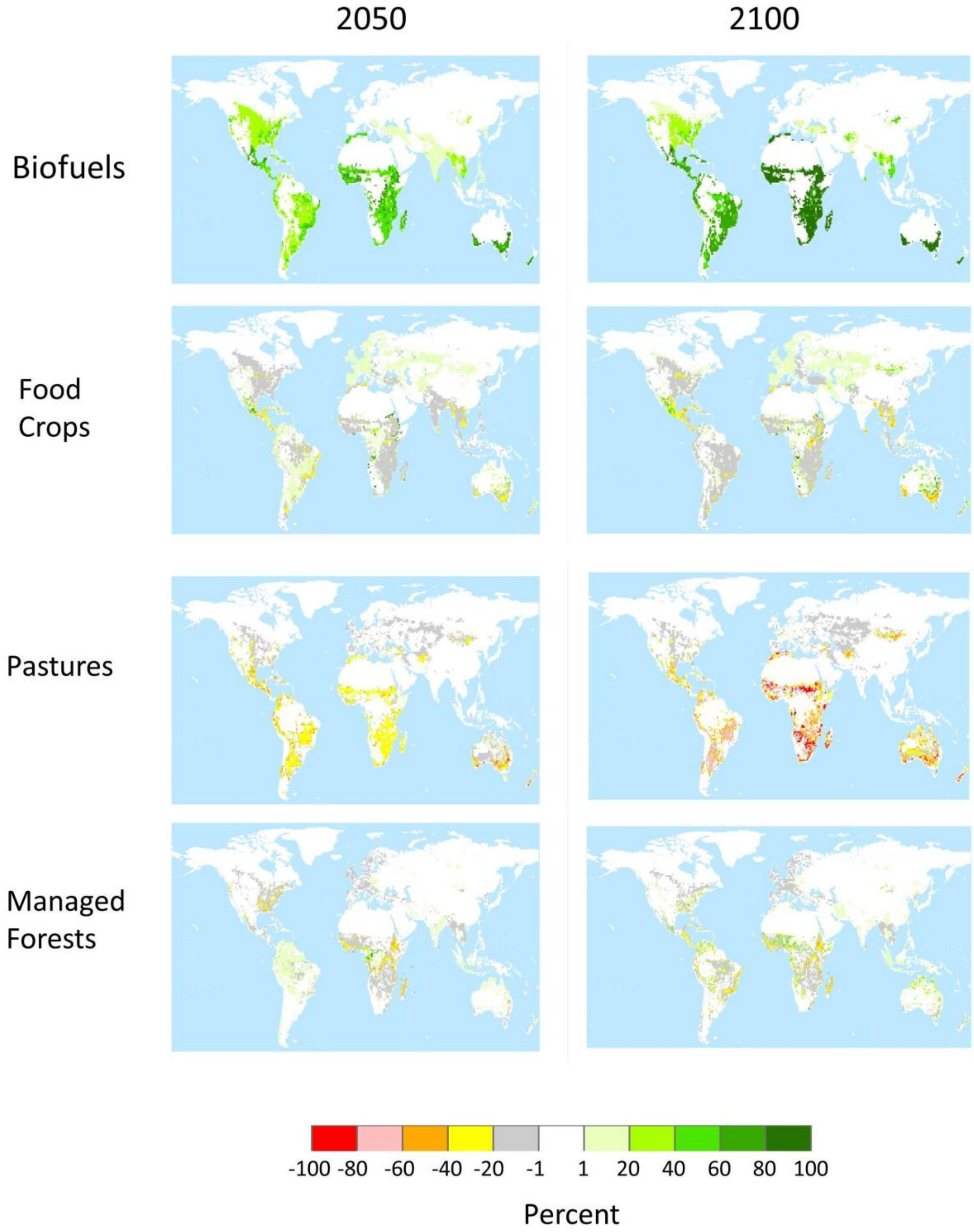

Figure 6. Projected distribution of cellulosic biofuels and the biofuel-induced changes in the distribution of food crops, pastures and managed forests for the Case 2 land-use scenario during 2050 and 2100.

3.1.4 Redistribution of Global Food Production

The use and displacement of pastures and food croplands for cellulosic biofuels production has modified the pattern of food production across the globe (Figures 5 and 6) including regions in which no cellulosic biofuels production occurs. Overall, biofuels production leads to a decrease in the area used as pastures in both scenarios with larger losses occurring in Case 2 (6.0 million km^2 lost in 2050, 11.3 million km^2 lost in 2100) than in Case 1 (2.8 million km^2 lost in 2050, 7.7 million km^2 lost in 2100). Most of the losses occur within Africa which accounts for 24-37% of the losses in 2050 and 49-52% of the losses in 2100. Large losses in pasture area also occur in Latin America (20-30% of the losses in 2050, 19-25% of the losses in 2100) and Australia and New Zealand (14-21% of the losses in 2050, 14-15% of the losses in 2100). Cellulosic biofuels production does eventually lead to an increase of less than 0.1 million km^2 in pastures within the European Union by 2100 in Case 1, but this is the only instance where an increase in pasture area has been noted in our analysis.

Unlike pastures, cellulosic biofuels production leads to both increases in the area of food crops in some regions and losses in other regions. These land-use dynamics lead to an overall decrease in the area of food crops by 2050 with larger losses occurring in Case 2 (1.1 million km^2) than in Case 1 (0.6 million km^2). Most of these losses for both land-use cases occur in Latin America (0.3 million km^2 for Case 1, 0.5 million km^2 for Case 2), but large losses also occur in the United States of America (0.2 million km^2 for Case 1, 0.3 million km^2 for Case 2), Africa (0.1 million km^2 in Case 1, 0.2 million km^2 for Case 2), India (0.2 million km^2 in Case 1, 0.1 million km^2 in Case 2) and the Rest of the World (0.1 million km^2 for both Cases 1 and 2). In contrast, cellulosic biofuels production leads to relatively large increases in the areal extent of food crop production in the Former Soviet Union (0.2 million km^2 in Case 1, 0.1 million km^2 in Case 2), the European Union (0.1 million km^2 in both Cases 1 and 2) and Australia and New Zealand (0.1 million km^2 in both Cases 1 and 2).

By 2100, the effect of cellulosic biofuels production on the distribution of food crops has changed. There is still an overall decrease in the area of food crops of 1.5 million km^2 in Case 2, but there is an overall increase of 0.4 million km^2 in food crops in Case 1 as a result of cellulosic biofuels production. In Case 2, most of the losses in food-crop area occurs in Latin America (0.7 million km^2) with additional large losses in Africa (0.5 million km^2), the United States of America (0.4 million km^2), and the Rest of the World (0.3 million km^2). In contrast, most of the losses of food-crop area in Case 1 occur in the United States of America (0.2 million km^2) and the Rest of the World (0.2 million km^2) with additional large losses in Africa (0.1 million km^2) and Indonesia (0.1 million km^2). In Latin America, global cellulosic biofuels production has increased the area of food crops by 0.1 million km^2 in Case 1 due to displacement. Similar to the results for 2050, cellulosic biofuels production leads to relatively large increases in the areal extent of food production for 2100 in the Former Soviet Union (0.4 million km^2 in Case 1, 0.1 million km^2 in Case 2), the European Union (0.2 million km^2 in Case 1, 0.1 million km^2 in Case 2) and Australia and New Zealand (0.1 million km^2 in both Cases 1 and 2). However, large increases in food crop area (0.1 million km^2 in both Cases 1 and 2) now also occur in the Middle East.

3.2 Biofuels Production Effects on Land Carbon Fluxes

As noted in Melillo *et al*. (2009), cellulosic biofuels production can lead either to a loss or a gain of carbon within terrestrial ecosystems in our simulations. In both of the land-use scenario cases, cellulosic biofuels production causes deforestation to be more rapid during the early part of the 21st century (Figure 3c,d) and result in large carbon losses from the terrestrial biosphere by 2050 (Figure 3e,f). As this deforestation is more extensive and lasts longer in Case 1, more carbon is lost in Case 1 (44 Pg C or 161 Pg CO_2-eq) by mid-century than in Case 2 (3 Pg C or 11 CO_2-eq). For Case 1, the carbon losses associated with indirect effects (30 Pg C or 109 Pg CO_2-eq) are more than twice that associated with direct effects (14 Pg C or 52 Pg CO_2-eq) even though displaced managed lands caused only 1.25 times more natural lands (mostly forests) to be converted than biofuels production. Fertilization of co-opted pastures allows some of the areas devoted to cellulosic biofuels production to sequester carbon in soils and thus compensate for some of the losses of carbon due to biofuels production in formerly forested areas so that the direct effects of biofuels production contribute a smaller proportion to the overall carbon loss than the indirect effects. For Case 2, the carbon losses associated with indirect effects (15 Pg C or 54 Pg CO_2-eq) are mostly compensated by carbon sequestration (12 Pg C or 43 Pg CO_2-eq) in areas devoted to cellulosic biofuels production. Again, fertilization of the relatively large area of co-opted pastures along with the area of converted natural grasslands and shrublands during cellulosic biofuels production has already allowed the soils in these ecosystems to accumulate more than enough carbon to compensate for any losses associated with forest conversion to biofuels production in other areas in Case 2. In addition, there are fewer natural forests converted and fewer managed forests co-opted by biofuels production in Case 2 than Case 1, so that the carbon penalty associated with forest conversion is substantially less. As a result, the direct effects of biofuels in Case 2 allow these fertilized ecosystems to sequester carbon. In contrast, the forested land converted by displacement of food crops and managed forests results in the carbon losses associated with the indirect effects.

During the second half of the century, deforestation rates decreased dramatically in both land-use cases so there is a net accumulation of carbon in response to the use of nitrogen fertilizers on lands devoted to biofuels and displaced food crops. This later carbon accumulation is not enough to compensate for the earlier deforestation losses of carbon in Case 1 so that cellulosic biofuels production still lead to a net loss of 25 Pg C (92 Pg CO_2-eq) by the end of the 21st century with the losses of carbon associated with indirect effects of biofuels (26 Pg C or 96 Pg CO_2-eq) being slightly compensated by the gains in carbon associated with the direct effects (1 Pg C or 4 Pg CO_2-eq). In contrast, this later accumulation of carbon by terrestrial ecosystems in Case 2 is more than enough to compensate for land conversion losses so that cellulosic biofuels production enhances terrestrial carbon sequestration by 21 Pg C (76 Pg CO_2-eq) with the gains from the direct effects of biofuels (23 Pg C or 85 Pg CO_2-eq) being slightly offset by carbon losses associated with indirect effects (2.5 Pg C or 9 Pg CO_2-eq).

3.2.1 Regional Variations in Land Carbon Fluxes

Besides the distribution of cellulosic biofuels production, the response of terrestrial ecosystems to this additional land-use pressure also varies across the globe (**Figures 7** and **8**). In addition to vegetation stature (low carbon density versus high carbon density) and land management described earlier, spatial and temporal variations in growing season, air temperatures, precipitation, and atmospheric chemistry will influence whether or not cellulosic biofuels production enhances carbon sequestration or losses from an ecosystem. As tropical ecosystems have longer growing seasons and warmer temperatures, these ecosystems tend to have higher productivity rates than temperate and boreal ecosystems leading to higher carbon sequestration rates by fertilized biofuels production in formerly unfertilized low carbon density ecosystems. The warmer temperatures in tropical regions, however, also causes higher decomposition rates leading to higher losses of carbon from formerly tropical forested

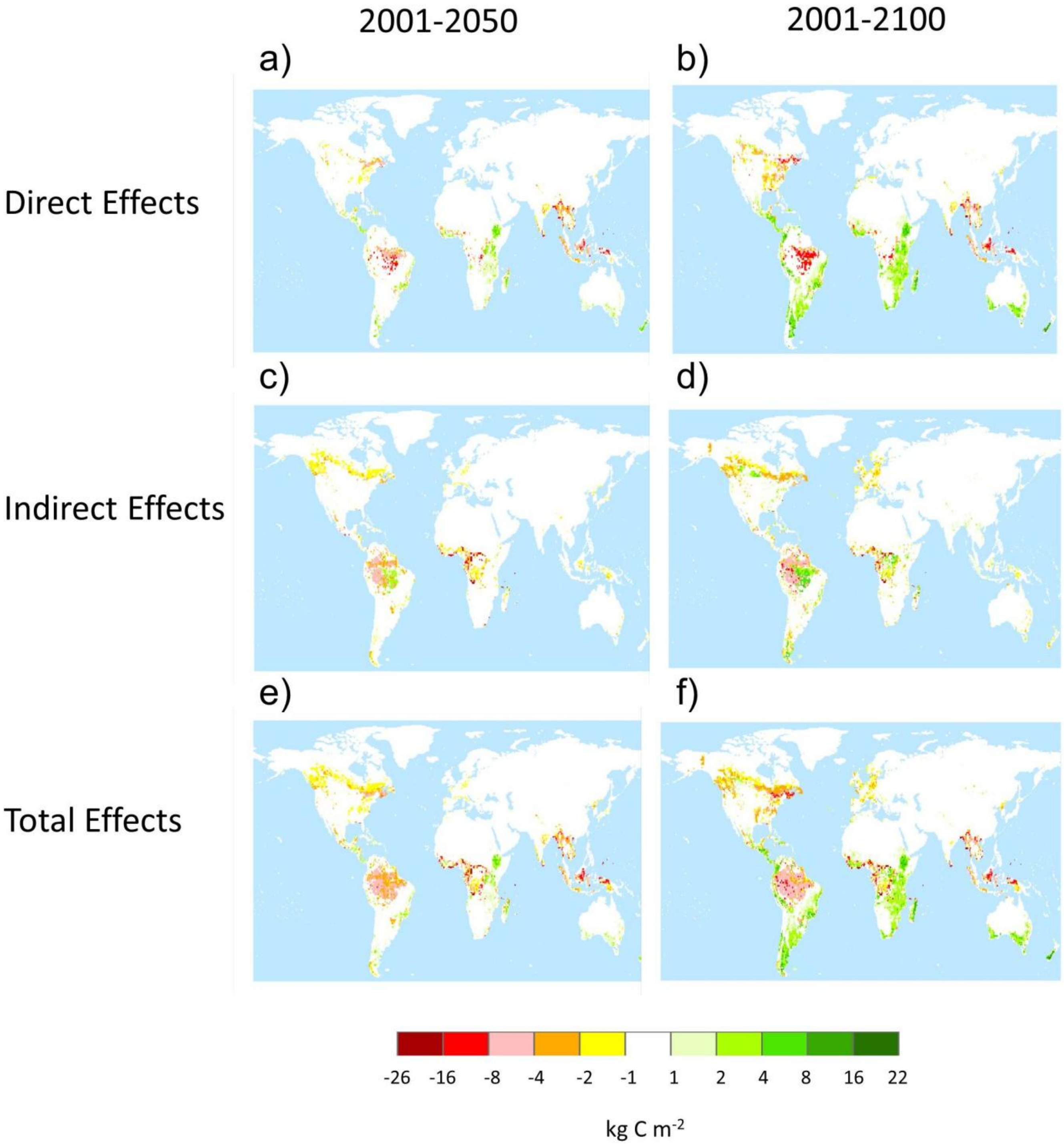

Figure 7. Distribution of the direct, indirect and total (direct+indirect) effects of cellulosic biofuels on the projected cumulative land carbon flux from 2001 to years 2050 (a, c, e) and 2100 (b, d, f) for the Case 1 land-use scenario.

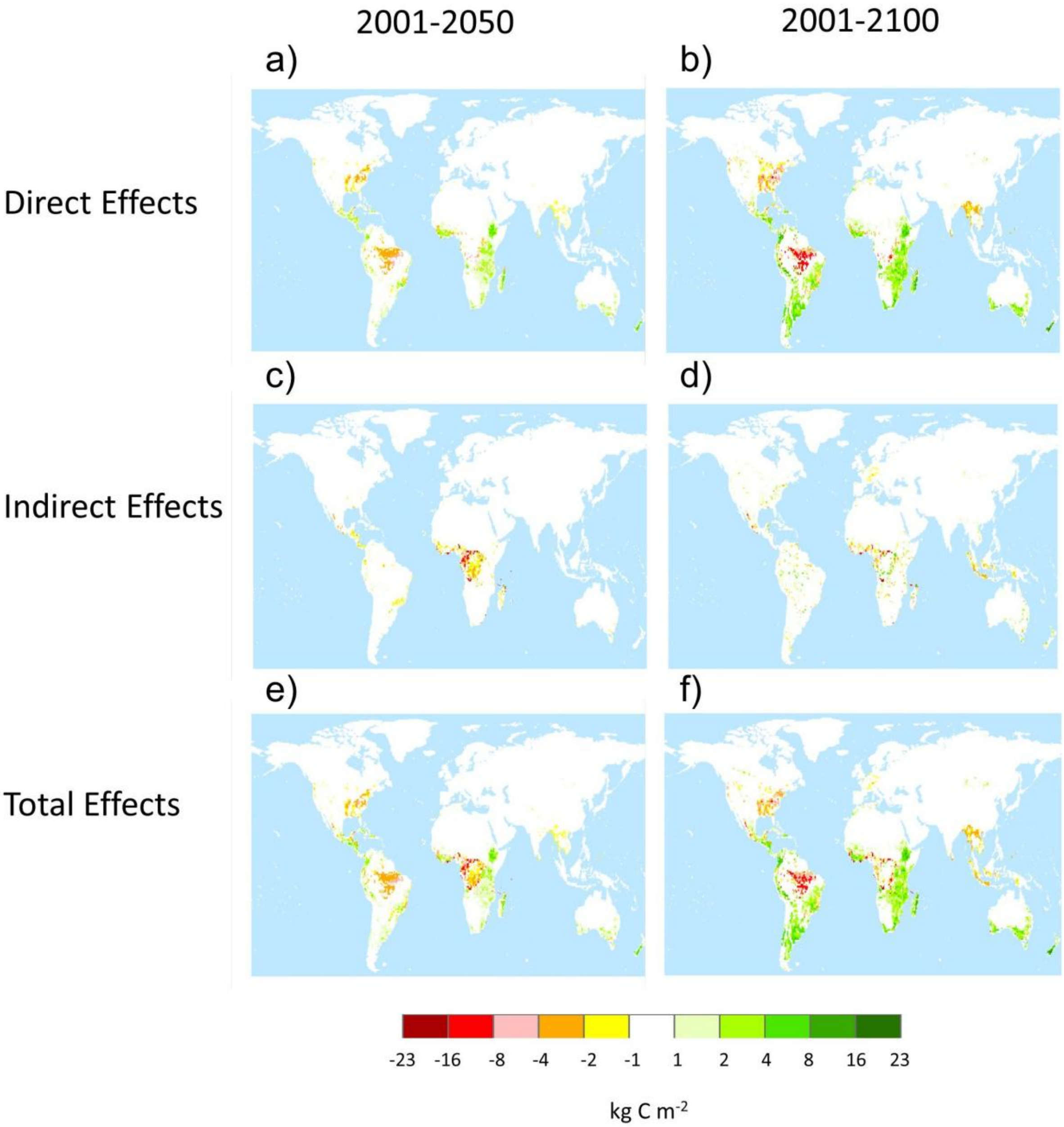

Figure 8. Distribution of the direct, indirect and total (direct+indirect) effects of cellulosic biofuels on the projected cumulative land carbon flux from 2001 to years 2050 (a, c, e) and 2100 (b, d, f) for the Case 2 land-use scenario.

ecosystems. In addition, ozone pollution tends to be higher in northern temperate ecosystems and reduces the production of crops (Felzer *et al*., 2005) including cellulosic biofuels (Wang, 2008) in these regions. Thus, larger responses to the disturbances represented by cellulosic biofuels production and displaced managed lands occur in tropical regions due to both larger areas devoted to biofuels and the higher metabolism rates in these regions. However, these responses may not be in the same direction across sub-regions within the tropics.

Cellulosic biofuels production enhances carbon sequestration over the 21st century in some regions and enhances carbon emissions associated with land use in other regions (**Tables 5** and **6**). For both of the land-use scenarios, most of the enhanced carbon sequestration (+15.8 Pg C in Case 1, +29.5 Pg C in Case 2) occurs in Africa (62% in both cases) and Australia/New Zealand (35% in Case 1, 20% in Case 2) where fertilized biofuels and food crops replace large areas of unfertilized pastures and ecosystems with low carbon stocks such as grasslands, savannas and shrublands (see Figures A1 and A4 in Appendix). Carbon losses occur where forests (managed or natural) with high carbon stocks are converted to production of biofuels or food. The regions with the most carbon losses depend on the land-use policy implemented, although less carbon is generally lost in Case 2 (-8,949 Tg C) than in Case 1 (-40,843 Tg C). In the United States of America, however, more carbon is lost in Case 2 (Table 6) than in Case 1 (Table 5). Most of the enhanced carbon emissions associated with biofuels production occur in Latin America (35%), Canada (21%) and Indonesia (16%) in Case 1; and the United States of America (59%) and Indonesia (18%) in Case 2.

The large responses of tropical regions to cellulosic biofuels production over the 21st century (**Figure 9**) are mostly responsible for the corresponding global responses of land carbon fluxes to cellulosic biofuels production (Figure 3e,f). As most cellulosic biofuels production occurs in Africa for both land-use scenario cases, it is interesting to note that the temporal changes of direct and indirect effects of biofuels production on terrestrial carbon fluxes in this region mimics the global-scale effects for Case 2, but not for Case 1. This is because the gains in carbon storage from biofuels production in Africa during the first half of the 21st century in Case 1 are mostly compensated by losses of carbon from forests converted to biofuels production in Indonesia (Table 5) even though Africa and Indonesia contain 37% and 3%, respectively, of the global land devoted to cellulosic biofuels production in 2050. Thus, the disturbance of high carbon density forests for either biofuels production or displaced managed lands over relatively

Table 5. Direct, indirect and total effects of cellulosic biofuels production on cumulative net land carbon fluxes (Tg C) across the globe in Case 1 over the 21st century.

EPPA Region	Time Period	Direct	Indirect						Total
		Biofuels	Food Crops	Pastures	Managed Forests	Natural Forest	Natural Shrub	Natural Grass	
AFR	2001-2030	+1,852	-2,562	-48	-4,923	-86	-12	-39	-5,818
	2001-2050	+6,969	-6,430	-749	-5,594	-371	-14	-351	-6,540
	2001-2100	+18,523	-5,958	-1,619	-1,166	+462	-42	-420	+9,780
LAM	2001-2030	-1,193	+1,097	-18	-50	-1	-3	+6	-162
	2001-2050	-9,086	-1,743	+930	-7,718	-150	-19	-18	-17,804
	2001-2100	-698	-6,994	+1,092	-6,712	-805	+170	-193	-14,140
ROW	2001-2030	-659	+3	+2	+95	-3	+1	+3	-558
	2001-2050	-4,578	-730	+92	+539	-50	+43	+94	-4,590
	2001-2100	-6,123	-48	+104	+1,168	-163	+40	+92	-4,930
ANZ	2001-2030	+240	-10	-3	-55	-3	-3	+9	+175
	2001-2050	+1,979	+101	-5	-98	-30	-1	+20	+1,966
	2001-2100	+5,086	+936	-145	-90	-93	-151	+49	+5,592
MEX	2001-2030	0	0	0	-6	-1	-1	0	-8
	2001-2050	+592	-464	-139	-171	-37	-2	-3	-224
	2001-2100	+664	-354	-110	+161	-111	-6	+28	+272
CAN	2001-2030	-19	+2	-2	+21	0	0	0	+2
	2001-2050	-1,686	-1,970	-79	-1,880	-315	-27	+4	-5,953
	2001-2100	-4,227	+282	-14	-2,503	-1,841	-108	-48	-8,459
USA	2001-2030	0	-10	-1	-15	-1	0	0	-27
	2001-2050	-1,442	-47	+7	-192	-22	+2	+22	-1,672
	2001-2100	-4,388	+239	-85	+1,200	-268	-477	+74	-3,705
IDZ	2001-2030	-310	-53	-2	+2	-2	0	0	-365
	2001-2050	-6,149	-431	-1	-50	-79	0	0	-6,710
	2001-2100	-6,982	-245	-14	+454	+214	-4	+4	-6,573

Table 5 (continued). Direct, indirect and total effects of cellulosic biofuels production on cumulative net land carbon fluxes (Tg C) across the globe in Case 1 over the 21st century.

EPPA Region	Time Period	Direct	Indirect						Total
		Biofuels	Food Crops	Pastures	Managed Forests	Natural Forest	Natural Shrub	Natural Grass	
IND	2001-2030	-334	-66	+9	+24	-4	0	+1	-370
	2001-2050	-802	-164	+21	+224	-15	+4	-7	-739
	2001-2100	-888	+159	+21	+430	-31	+3	-34	-340
CHN	2001-2030	0	+7	0	+2	-2	0	0	+7
	2001-2050	0	+46	-12	+1	-4	+7	+1	+39
	2001-2100	0	+42	+6	-24	-10	+3	+1	+18
EUR	2001-2030	0	-66	-9	-43	-2	-1	0	-121
	2001-2050	0	-570	-134	-96	-30	-3	-1	-834
	2001-2100	0	-1,106	-258	-546	-119	+1	-1	-2,029
FSU	2001-2030	0	+138	+16	-183	-7	-2	-2	-316
	2001-2050	0	+1	+106	-581	-57	-14	-11	-556
	2001-2100	0	+265	+277	-828	-276	-17	-3	-582
EET	2001-2030	0	-4	0	-1	-3	0	0	-8
	2001-2050	0	-3	+2	+3	-1	0	0	+1
	2001-2100	0	+60	+8	+31	+2	0	-1	+100
MES	2001-2030	0	0	-1	-4	-1	-1	0	-7
	2001-2050	+12	-4	-9	+1	-4	-7	-13	-24
	2001-2100	+51	+100	-52	+52	-12	-47	-39	+53
ASI	2001-2030	0	-3	0	+2	-1	0	0	-2
	2001-2050	+14	-34	0	+42	+6	0	0	+28
	2001-2100	+30	-28	0	-54	+24	0	-5	-33
JPN	2001-2030	0	0	0	-17	+1	0	0	-16
	2001-2050	0	-20	-12	-200	-7	0	0	-239
	2001-2100	0	-18	-17	+2	-16	0	0	-49
Globe	2001-2030	-423	-1,803	-57	-5,151	-116	-22	-22	-7,594
	2001-2050	-14,177	-12,462	+18	-15,770	-1,166	-31	-263	-43,850
	2001-2100	+1,048	-12,668	-806	-8,425	-3,043	-635	-496	-25,025

Table 6. Direct, indirect and total effects of cellulosic biofuels production on cumulative net land carbon fluxes (Tg C) across the globe in Case 2 over the 21st century.

EPPA Region	Time Period	Direct	Indirect						Total
		Biofuels	Food Crops	Pastures	Managed Forests	Natural Forest	Natural Shrub	Natural Grass	
AFR	2001-2030	+1,830	-1,991	-46	-3,966	-84	-6	-14	-4,277
	2001-2050	+12,905	-5,541	-743	-6,426	-578	+12	-315	-686
	2001-2100	+23,483	-4,940	-897	+1,542	-462	+14	-316	+18,424
LAM	2001-2030	-1,064	-4,519	+5,156	-167	-3	0	0	-597
	2001-2050	-490	-872	+1,231	-915	-126	-4	-58	-1,234
	2001-2100	+2,637	-2,221	+2,317	+891	+195	+122	+58	+3,999
ROW	2001-2030	0	+1	0	-2	0	-1	+1	-1
	2001-2050	-677	-69	+134	+161	-7	+22	+84	-352
	2001-2100	-1,824	+250	-51	+461	-65	+25	+269	-935
ANZ	2001-2030	+240	+8	+8	-33	-2	0	+4	+225
	2001-2050	+1,895	+198	-16	-42	-28	+5	-2	+2,010
	2001-2100	+4,523	+1,388	-133	+208	-124	-31	+93	+5,924
MEX	2001-2030	0	+2	0	-3	0	0	0	-1
	2001-2050	+797	-258	-74	0	-23	+4	+2	+448
	2001-2100	+767	-573	+8	+154	-77	+4	+27	+310
CAN	2001-2030	-2	-1	+1	-5	0	0	0	-7
	2001-2050	+81	-50	+53	+63	-6	0	+4	+145
	2001-2100	-86	-5	+384	+68	-35	0	-4	+322
USA	2001-2030	0	+2	+6	-1	0	0	0	+7
	2001-2050	-2,507	-8	+11	-265	-41	+1	+22	-2,787
	2001-2100	-6,023	+43	+121	+726	-248	-23	+130	-5,274
IDZ	2001-2030	0	-2	0	-2	0	0	0	-4
	2001-2050	0	-71	+5	-120	-5	0	0	-191
	2001-2100	0	-272	-2	-1,326	-17	0	-1	-1,618

Table 6 (continued). Direct, indirect and total effects of cellulosic biofuels production on cumulative net land carbon fluxes (Tg C) across the globe in Case 2 over the 21st century.

EPPA Region	Time Period	Direct	Indirect						Total
		Biofuels	Food Crops	Pastures	Managed Forests	Natural Forest	Natural Shrub	Natural Grass	
IND	2001-2030	0	-11	+3	+1	0	0	0	-7
	2001-2050	-451	-99	-9	-23	-17	-2	-11	-612
	2001-2100	-455	-16	-4	+43	-10	-4	-22	-468
CHN	2001-2030	0	+8	0	-2	0	0	0	+6
	2001-2050	0	+27	+18	+18	0	0	+2	+65
	2001-2100	0	+8	+23	+13	-1	0	+1	+44
EUR	2001-2030	0	-4	+1	+10	0	0	0	+7
	2001-2050	0	-106	-2	+23	-5	+3	+1	-86
	2001-2100	0	-383	+55	-172	-23	+11	+3	-509
FSU	2001-2030	0	+35	+7	-6	-1	-1	+3	+37
	2001-2050	0	+185	+42	-27	+1	-1	+21	+221
	2001-2100	0	+195	+95	-95	+5	-9	+51	+242
EET	2001-2030	0	-1	0	+1	0	0	0	0
	2001-2050	0	-1	+3	-1	0	0	0	+1
	2001-2100	0	+48	+8	+35	+2	0	0	+93
MES	2001-2030	0	0	-1	0	0	0	-1	-2
	2001-2050	+25	+1	0	+2	0	0	-2	+26
	2001-2100	+57	+104	-18	+1	0	-7	-11	+126
ASI	2001-2030	0	-1	0	-4	+1	0	+1	-3
	2001-2050	-2	-6	-1	-43	-3	0	-6	-61
	2001-2100	-5	-3	0	-124	-4	0	-6	-142
JPN	2001-2030	0	+1	0	+4	+1	0	0	+6
	2001-2050	0	0	-4	+9	-1	0	0	+4
	2001-2100	0	-1	-9	+12	0	0	0	+2
Globe	2001-2030	+1,004	-6,473	+5,135	-4,175	-88	-8	-6	-4,611
	2001-2050	+11,576	-6,670	+648	-7,586	-839	+40	-258	-3,089
	2001-2100	+23,074	-6,378	+1,897	+2,437	-864	+102	+272	+20,540

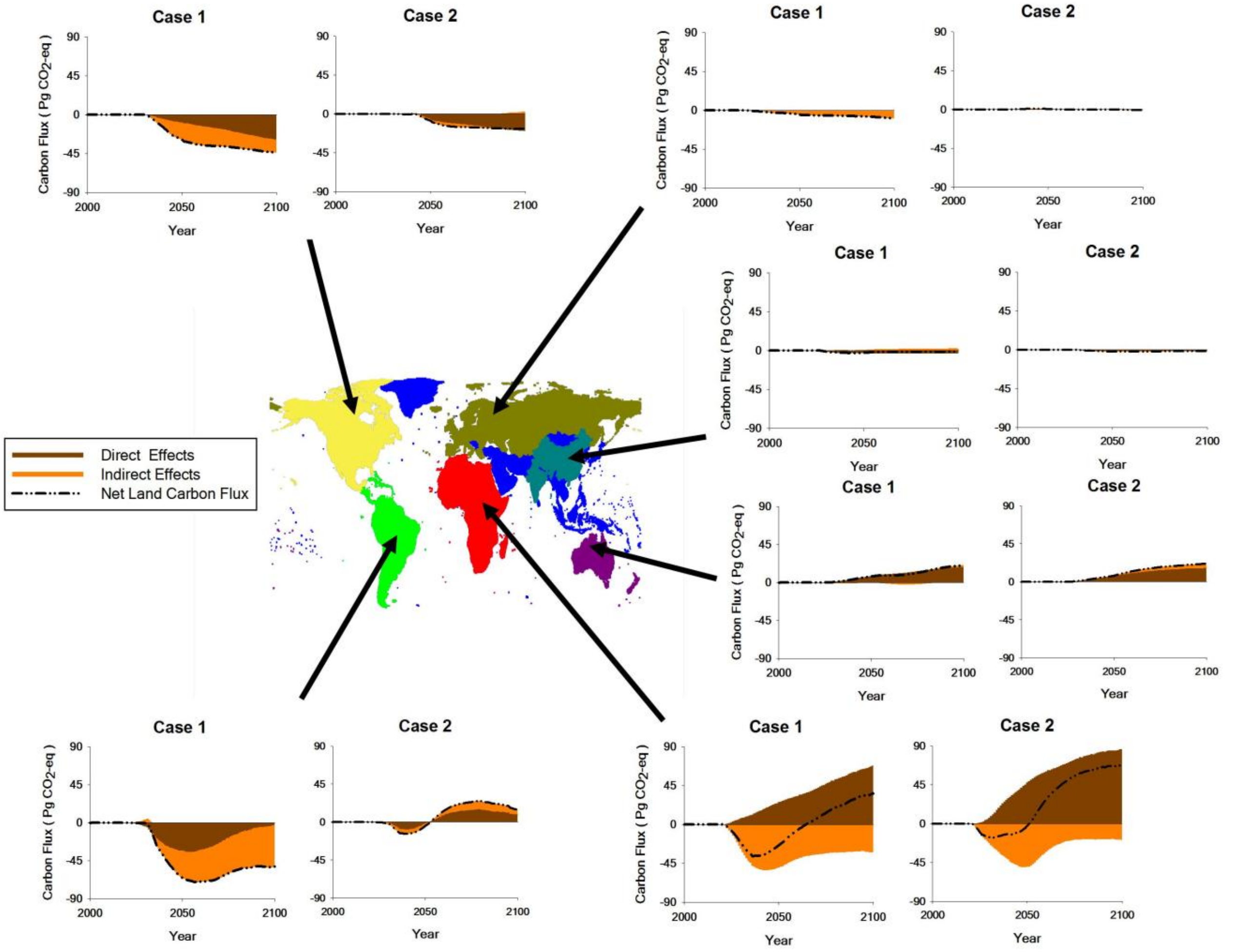

Figure 9. Partitioning of direct and indirect effects on projected cumulative land carbon flux from cellulosic biofuel production over the 21st century for land-use Case 1 and Case 2 in select EPPA regions: Africa (reddish brown), Latin America (green), North America (yellow), Europe-Russia (gold), China-India (teal), and Australia-New Zealand (purple). North America contains the EPPA regions of Canada, Mexico and the United States of America. Europe-Russia contains the EPPA regions of the European Union, Eastern Europe and the Former Soviet Union.

small areas can have a disproportionate effect on global carbon fluxes. As a result of the compensating effects on carbon dynamics in these two regions, the temporal changes of direct and indirect effects of global biofuels production in Case 1 mimics the effects found in Latin America rather than Africa.

The relationship between direct and indirect effects of biofuels on land carbon fluxes varies across the globe over time and differs between land-use scenario cases (Figure 9**,** see also Figures A1 to A16 in Appendix). These different relationships are highlighted in a comparison of the six EPPA regions, described earlier, which had either the largest gains or losses of carbon as a result of biofuels production. In Australia/New Zealand, most if not all of the area devoted to biofuels production could have come from existing agricultural lands with very little natural vegetation disturbed either directly by biofuels production or indirectly by displacement of other managed lands. The replacement of unfertilized pastures, savannas, grasslands and shrublands with fertilized biofuel and food crops causes indirect carbon gains to enhance direct carbon gains. In Africa, the replacement of unfertilized pastures, savannas, grasslands and shrublands by fertilized biofuel crops also cause these ecosystems to gain carbon directly from biofuels production, but the displacement of other managed lands leads to deforestation, which causes indirect carbon losses that compensate for some of the carbon gained. In contrast, biofuels production causes initial deforestation in the United States in Case 2 and Indonesia in Case 1 leading to carbon losses as a direct result of biofuels production, but later abandonment of these biofuel croplands allows carbon to be sequestered indirectly by regrowing natural vegetation or managed forests. Finally, both biofuels production and displaced managed lands lead to deforestation in Latin America and Canada in Case 1 so that indirect carbon losses enhance direct carbon losses. Thus, biofuels production and/or the displacement of managed lands may either enhance carbon sequestration or enhance carbon emissions from land-use change depending upon the carbon stocks of the former vegetation and whether or not nitrogen fertilizers are applied.

3.2.2 Effects on Natural Carbon Sequestration Capacity

Terrestrial ecosystems have been providing a valuable ecosystem service of sequestering atmospheric carbon which has helped to moderate increases in atmospheric carbon dioxide concentrations. The conversion of large tracts of natural forests, grasslands and shrublands to cellulosic biofuels or displaced food or timber production has altered the capacity of these ecosystems to sequester carbon in the future. Most assessments of biofuels production have not considered the impacts of this altered carbon sequestration capacity on greenhouse gas budgets (see Searchinger *et al*., 2008). With our comparisons of carbon fluxes between biofuel and no biofuel scenario pairs, these impacts are considered in our analysis, but are somewhat confounded in our estimates of direct and indirect effects. However, we are able to discern changes in the carbon sequestration capacity of natural ecosystems and the associated greenhouse gas forcing benefits that are usually ignored (Tables 5 and 6). Overall, cellulosic biofuels production leads to a decrease of carbon sequestration in natural terrestrial ecosystems of 1.5 Pg C (5.4 Pg CO_2-eq) by 2050 and 4.2 Pg C (15.3 Pg CO_2-eq) by 2100 in Case 1; and 1.1 Pg C (3.9 Pg CO_2-eq) by 2050 and 0.5 Pg C (1.8 Pg CO_2-eq) by 2100 in Case 2. Most of these losses occur in natural forests. A loss of 6.5 million km^2 of forests by 2050 and 7.4 million km^2 by 2100 in Case 1 cause an associated loss of 1.2 Pg C (4.4 Pg CO_2-eq) and 3.0 Pg C (11.0 Pg CO_2-eq), respectively, in carbon sequestration. In Case 2, the loss of less natural forests (3.0 million km^2 lost in 2050, 3.4 million km^2 lost in 2100) leads to smaller losses in carbon sequestration: 0.8 Pg C (3.1 Pg CO_2-eq) up to 2050 and 0.9 Pg C (3.2 Pg CO_2-eq) up to 2100.

Besides forests, cellulosic biofuels production and displaced food production also lead to the loss of natural grasslands and shrublands in the future. The relative importance of these losses varies between the two land-use scenario cases. In Case 1, the combined loss of grasslands and shrublands is only 37% of the losses of forested areas by 2050 and 44% by 2100 with larger losses of shrublands than grasslands (Table 3). In contrast, the combined loss of grasslands and shrublands in Case 2 is 90% of the losses of forest land by 2050 and are greater than forest land losses by 2100 with larger losses of grasslands than shrublands (Table 4). Despite these losses, however, biofuels production actually increased carbon sequestration in natural grasslands and shrublands in Case 2 (Table 6) to compensate for the loss of carbon sequestration capacity of natural forests during the latter half of the 21st century. This increase in biofuels-related carbon sequestration in natural grasslands and shrublands is a result of converting natural lands that experience less favorable environmental conditions for plant growth relative to decomposition rates and/or not converting natural lands that experience more favorable environmental conditions for plant growth relative to decomposition rates.

The effects of biofuels on natural carbon sequestration vary across the globe and with land management. In Case 1 (Table 5), almost half of the global loss in natural carbon sequestration capacity (4.2 Pg C or 15.3 Pg CO_2-eq) over the 21st century occurs in Canada (2.0 Pg C or 7.3 Pg CO_2-eq) with significant losses also occurring in Latin America (0.8 Pg C or 3.0 Pg CO_2-eq) and the United States of America (0.7 Pg C or 2.5 Pg CO_2-eq). In Case 2 (Table 6), the loss of 0.8 Pg C (2.8 Pg CO_2-eq) in Africa, which is more than 1.5 times the global loss of natural carbon sequestration capacity (0.5 Pg C or 1.8 Pg CO_2-eq), is compensated by an increase in carbon sequestration in other parts of the world as a result of biofuels production such as Latin America (0.4 Pg C or 1.4 Pg CO_2-eq) and the "Rest of the World" (0.2 Pg C or 0.8 Pg CO_2-eq). Again, this increase in sequestration capacity occurs because the biofuels-related redistribution of land-use changes causes the conversion of some natural lands that experience less favorable environmental conditions for plant growth relative to decomposition rates or contain ecosystems that are close to equilibrium (i.e. net primary production equal to decomposition rates), and/or not converting natural lands that experience more favorable environmental conditions for plant growth relative to decomposition rates.

3.3 Biofuels Production Effects on Land Nitrous Oxide Emissions

At the global scale, we estimate the production of cellulosic biofuels increases the rate of N_2O emissions from the terrestrial biosphere in both land-use scenarios (**Figure 10a,b**). These N_2O emissions account for an additional greenhouse gas forcing of 40 Pg CO_2-eq in Case 1 and 38 Pg CO_2-eq in Case 2 by 2050 and increases to 219 Pg CO_2-eq in Case 1 and 205 Pg CO_2-eq in Case 2 by the end of the 21st century. These estimates are less than those reported in Melillo *et al.* (2009) because that study only considered the effects of biofuels production on N_2O emissions resulting from the application of nitrogen fertilizers and did not account for the potential abatement of N_2O emissions from natural ecosystems.

We estimate that land conversions associated with biofuels production and displaced agriculture reduced non-fertilizer N_2O emissions by 69 Pg CO_2-eq in Case 1 (**Table 7**) and 34 Pg CO_2-eq in Case 2 (**Table 8**) by the end of the 21st century to compensate for about 24% and 14%, respectively, of the N_2O emissions from fertilizer applications to biofuel and displaced food crops. Most of the reductions (76% in Case 1, 68% in Case 2) occur in the N_2O emissions from natural forests, particularly those in Africa and Latin America (**Tables 9** and **10**) with additional reductions in N_2O emissions occurring in managed forests, pastures and natural grasslands.

In addition to the abatement of non-fertilizer N_2O emissions, biofuels production also reduced the N_2O emissions from fertilizer applications associated with food production by 23 Pg CO_2-eq in Case 1 and 35 Pg CO_2-eq in Case 2 by 2100. The indirect abatement of fertilizer and non-fertilizer N_2O emissions became relatively less important over time (**Figure 10a,b**) as they compensated for 30-35% of the N_2O emissions directly related to biofuels production in 2050 and only 25-30% of direct N_2O emissions by 2100.

Land-use policy also has a large influence on both the direct and indirect effects of biofuels production on N_2O emissions. The larger direct enhancements of N_2O emissions in Case 1 are a consequence of applying nitrogen fertilizer to almost an additional million square kilometers

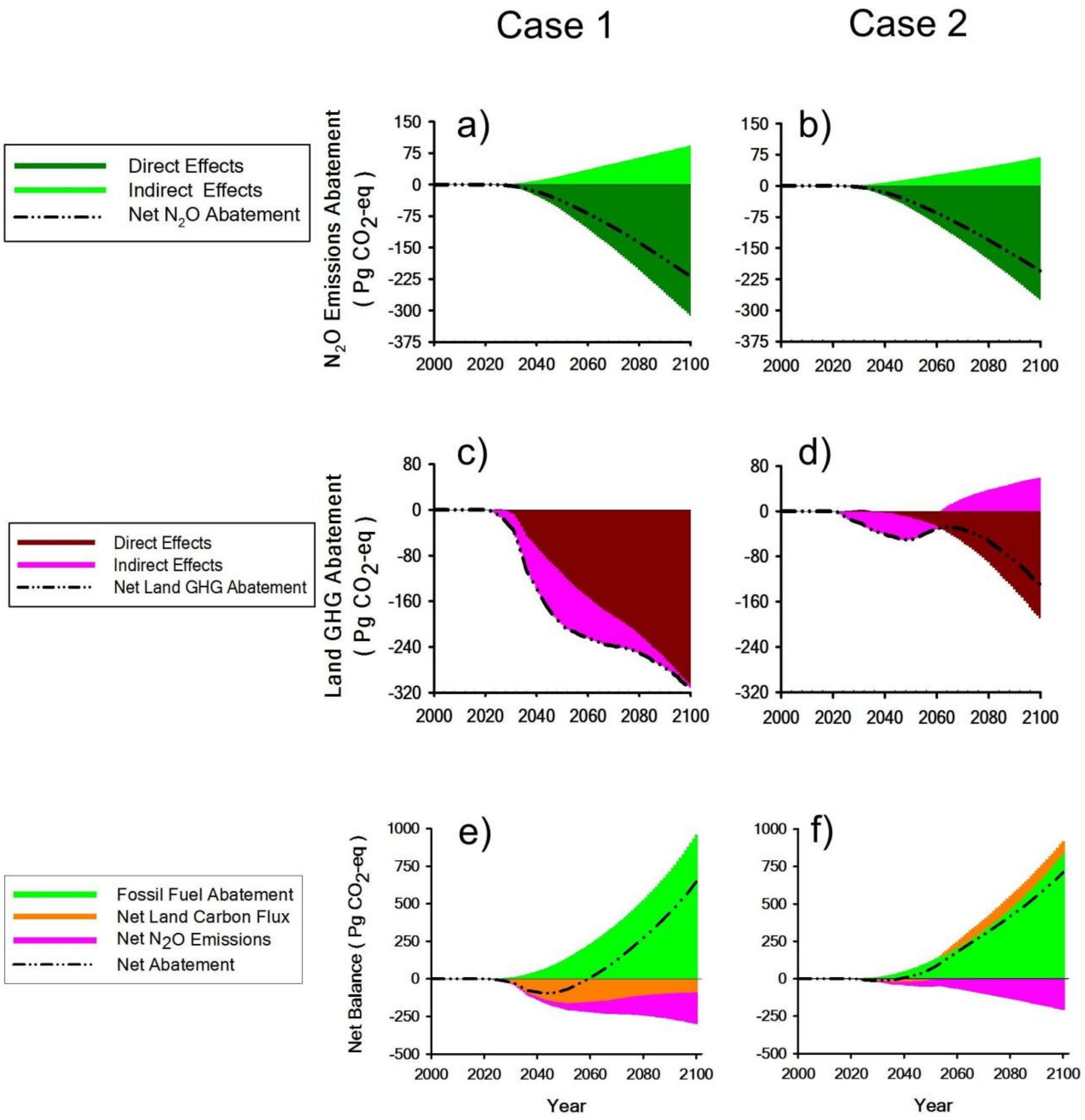

Figure 10. Partitioning of direct and indirect effects of cellulosic biofuels production for Case 1 and Case 2 land-use scenarios on global land nitrous oxide emissions (a and b), global land greenhouse gas fluxes (c and d) along with the partitioning of net greenhouse balance (e and f) among fossil fuel abatement, net land carbon fluxes and net N_2O emissions.

Table 7. Influence of cellulosic biofuels production on partitioning of the net land greenhouse gas (GHG) fluxes (Tg CO_2-eq) across the globe in Case 1 over the 21st century. Positive values indicate abatement of GHG emissions and negative values indicate enhanced GHG emission to the atmosphere.

EPPA Region	Time Period	Δ Net Land Carbon Flux	Δ Fertilizer N_2O Emissions	Δ Non-Fertilizer N_2O Emissions	Δ Net Land GHG Flux
AFR	2001-2030	-21,337	-3,569	+784	-24,122
	2001-2050	-23,978	-26,761	+6,143	-44,596
	2001-2100	+35,859	-115,184	+22,178	-57,147
LAM	2001-2030	-594	+8	0	-586
	2001-2050	-65,278	-12,108	+3,642	-73,744
	2001-2100	-51,848	-107,759	+27,945	-131,662
ROW	2001-2030	-2,049	-86	+37	-2,098
	2001-2050	-16,836	-3,690	+1,334	-19,192
	2001-2100	-18,079	-14,005	+5,270	-26,814
ANZ	2001-2030	+636	-166	+12	+482
	2001-2050	+7,203	-2,314	+162	+5,051
	2001-2100	+20,503	-13,544	+885	+7,844
MEX	2001-2030	-27	-5	+1	-31
	2001-2050	-820	-1,412	+261	-1,971
	2001-2100	+998	-8,269	+1,136	-6,135
CAN	2001-2030	+9	-2	+1	+8
	2001-2050	-21,826	-1,903	+624	-23,105
	2001-2100	-31,015	-7,856	+3,144	-35,727
USA	2001-2030	-98	-1	0	-99
	2001-2050	-6,135	-580	+188	-6,527
	2001-2100	-13,585	-3,840	+1,878	-15,547
IDZ	2001-2030	-1,342	-47	+17	-1,372
	2001-2050	-24,606	-3,543	+1,229	-26,920
	2001-2100	-24,105	-14,519	+5,025	-33,599

Table 7 (continued). Influence of cellulosic biofuels production on partitioning of the net land greenhouse gas (GHG) fluxes (Tg CO_2-eq) across the globe in Case 1 over the 21st century. Positive values indicate abatement of GHG emissions and negative values indicate enhanced GHG emission to the atmosphere.

EPPA Region	**Time Period**	**Δ Net Land Carbon Flux**	**Δ Fertilizer N_2O Emissions**	**Δ Non-Fertilizer N_2O Emissions**	**Δ Net Land GHG Flux**
IND	2001-2030	-1,358	-63	+34	-1,387
	2001-2050	-2,710	-1,088	+529	-3,269
	2001-2100	-1,247	-1,460	+782	-1,925
CHN	2001-2030	+26	-7	-1	+18
	2001-2050	+137	-56	+6	+87
	2001-2100	+67	-125	0	-58
EUR	2001-2030	-443	-7	+6	-444
	2001-2050	-3,051	-141	+84	-3,108
	2001-2100	-7,436	-753	+622	-7,567
FSU	2001-2030	-1,156	-33	+7	-1,182
	2001-2050	-2,033	-395	+78	-2,350
	2001-2100	-2,133	-1,270	+279	-3,124
EET	2001-2030	-17	0	0	-17
	2001-2050	+5	-3	+1	+3
	2001-2100	+368	+10	-19	+359
MES	2001-2030	-23	+1	-1	-23
	2001-2050	-85	-28	+5	-108
	2001-2100	+193	-290	+55	-42
ASI	2001-2030	-7	-4	+1	-10
	2001-2050	+101	+121	-35	+187
	2001-2100	-118	+577	-144	+315
JPN	2001-2030	-61	0	0	-61
	2001-2050	-873	0	+5	-868
	2001-2100	-181	-4	+28	-157
Globe	2001-2030	-27,841	-3,981	+898	-30,924
	2001-2050	-160,785	-53,901	+14,256	-200,430
	2001-2100	-91,759	-288,291	+69,064	-310,986

Table 8. Influence of cellulosic biofuels production on partitioning of the net land greenhouse gas (GHG) fluxes (Tg CO_2-eq) across the globe in Case 2 over the 21st century. Positive values indicate reduction of GHG emissions and negative values indicate enhanced GHG emissions to the atmosphere.

EPPA Region	**Time Period**	**Δ Net Land Carbon Flux**	**Δ Fertilizer N_2O Emissions**	**Δ Non-Fertilizer N_2O Emissions**	**Δ Net Land GHG Flux**
AFR	2001-2030	-15,683	-3,689	+802	-18,570
	2001-2050	-2,510	-27,346	+4,983	-24,873
	2001-2100	+67,554	-115,474	+15,776	-32,144
LAM	2001-2030	-2,188	-97	+40	-2,245
	2001-2050	-4,529	-11,752	+2,115	-14,166
	2001-2100	+14,661	-85,350	+11,029	-59,660
ROW	2001-2030	-2	-2	0	-4
	2001-2050	-1,290	-1,505	+384	-2,411
	2001-2100	-3,428	-6,852	+1,875	-8,405
ANZ	2001-2030	+827	-176	+12	+663
	2001-2050	+7,369	-2,478	+174	+5,065
	2001-2100	+21,723	-17,086	+1,093	+5,730
MEX	2001-2030	-3	-5	+2	-6
	2001-2050	+1,644	-1,451	+195	+388
	2001-2100	+1,136	-8,100	+876	-6,088
CAN	2001-2030	-27	-3	0	-30
	2001-2050	+532	-145	+29	+416
	2001-2100	+1,179	-848	+220	+551
USA	2001-2030	+27	+1	0	+28
	2001-2050	-10,219	-599	+231	-10,587
	2001-2100	-19,337	-4,385	+2,410	-21,312
IDZ	2001-2030	-16	+1	0	-15
	2001-2050	-707	+95	-30	-642
	2001-2100	-5,934	+236	+36	-5,662

Table 8 (continued). Influence of cellulosic biofuels production on partitioning of the net land greenhouse gas (GHG) fluxes (Tg CO_2-eq) across the globe in Case 2 over the 21st century. Positive values indicate reduction of GHG emissions and negative values indicate enhanced GHG emissions to the atmosphere.

EPPA Region	Time Period	Δ Net Land Carbon Flux	Δ Fertilizer N_2O Emissions	Δ Non-Fertilizer N_2O Emissions	Δ Net Land GHG Flux
IND	2001-2030	-25	-2	+1	-26
	2001-2050	-2,245	-337	+173	-2,409
	2001-2100	-1,716	-314	+279	-1,751
CHN	2001-2030	+21	-2	+1	+20
	2001-2050	+239	-58	+4	+185
	2001-2100	+164	-78	-12	+74
EUR	2001-2030	+27	-7	+2	+22
	2001-2050	-315	-133	+46	-402
	2001-2100	-1,867	-614	+293	-2,188
FSU	2001-2030	+134	-12	0	+122
	2001-2050	+812	-139	+2	+675
	2001-2100	+887	-301	-40	+546
EET	2001-2030	-2	-1	0	-3
	2001-2050	+1	-2	-1	-2
	2001-2100	+341	+10	-19	+332
MES	2001-2030	-6	0	-1	-7
	2001-2050	+93	-16	+3	+80
	2001-2100	+462	-263	+17	+216
ASI	2001-2030	-12	0	0	-12
	2001-2050	-220	+30	-5	-195
	2001-2100	-517	+215	-36	-338
JPN	2001-2030	+21	0	0	+21
	2001-2050	+20	-1	+1	+20
	2001-2100	+5	-3	+1	+3
Globe	2001-2030	-16,907	-3,994	+859	-20,042
	2001-2050	-11,325	-45,837	+8,304	-48,858
	2001-2100	+75,313	-239,207	+33,798	-130,096

Table 9. Direct, indirect and total effects of cellulosic biofuels production on cumulative net land nitrous oxide N_2O emissions (Tg CO_2-eq) across the globe in Case 1 over the 21st century. Positive values indicate abatement of N_2O emissions and negative values indicate enhanced N_2O losses to the atmosphere.

EPPA Region	Time Period	Direct	Indirect						Total
		Biofuels	Food Crops	Pastures	Managed Forests	Natural Forest	Natural Shrub	Natural Grass	
AFR	2001-2030	-3,701	+132	+33	+81	+637	0	+33	-2,785
	2001-2050	-28,508	+1,747	+123	+883	+4,995	0	+142	-20,618
	2001-2100	-120,131	+4,947	+895	+5,594	+15,061	0	+628	-93,006
LAM	2001-2030	-245	+253	0	-8	+8	0	0	+8
	2001-2050	-14,374	+2,266	+37	+443	+3,104	+2	+56	-8,466
	2001-2100	-113,301	+5,542	+662	+5,085	+21,712	+10	+476	-79,814
ROW	2001-2030	-110	+24	0	+8	+28	0	+1	-49
	2001-2050	-5,359	+1,669	+29	+406	+863	0	+36	-2,356
	2001-2100	-21,918	+7,913	+141	+1,149	+3,831	0	+149	-8,735
ANZ	2001-2030	-169	+3	+4	0	+6	0	+2	-154
	2001-2050	-2,223	-91	+62	-8	+85	0	+23	-2,152
	2001-2100	-14,167	+623	+356	-75	+502	0	+102	-12,659
MEX	2001-2030	0	-5	0	0	+1	0	0	-4
	2001-2050	-1,715	+303	+7	+32	+219	0	+3	-1,151
	2001-2100	-10,821	+2,552	+120	+120	+860	0	+36	-7,133
CAN	2001-2030	-16	+14	0	0	+1	0	0	-1
	2001-2050	-2,012	+109	+1	+37	+582	+2	+2	-1,279
	2001-2100	-7,686	-170	+14	+55	+3,047	+13	+15	-4,712
USA	2001-2030	0	-1	0	-1	+1	0	0	-1
	2001-2050	-692	+112	+8	+121	+51	0	+8	-392
	2001-2100	-4,154	+314	+71	+474	+1,276	+1	+56	-1,962
IDZ	2001-2030	-49	+2	0	+1	+16	0	0	-30
	2001-2050	-3,657	+114	+1	+101	+1,127	0	0	-2,314
	2001-2100	-16,131	+1,612	+7	+222	+4,796	0	0	-9,494

Table 9 (continued). Direct, indirect and total effects of cellulosic biofuels production on cumulative net land nitrous oxide N_2O emissions (Tg CO_2-eq) across the globe in Case 1 over the 21st century. Positive values indicate abatement of N_2O emissions and negative values indicate enhanced N_2O losses to the atmosphere.

EPPA Region	Time Period	Direct Biofuels	Indirect						Total
			Food Crops	Pastures	Managed Forests	Natural Forest	Natural Shrub	Natural Grass	
IND	2001-2030	-92	+29	0	+12	+22	0	0	-29
	2001-2050	-2,017	+929	+2	+284	+240	0	+3	-559
	2001-2100	-2,890	+1,430	+3	+303	+471	0	+5	-678
CHN	2001-2030	0	-7	0	0	0	0	-1	-8
	2001-2050	0	-56	+3	+3	0	0	0	-50
	2001-2100	0	-125	+8	-9	+1	0	0	-125
EUR	2001-2030	0	-7	0	-1	+6	0	+1	-1
	2001-2050	0	-141	-1	+12	+72	+1	0	-57
	2001-2100	0	-753	-8	+238	+389	+3	0	-131
FSU	2001-2030	0	-33	0	-6	+12	+1	0	-26
	2001-2050	0	-395	+5	-40	+110	+1	+2	-317
	2001-2100	0	-1,270	+31	-181	+417	+9	+3	-991
EET	2001-2030	0	0	0	0	0	0	0	0
	2001-2050	0	-3	0	0	+1	0	0	-2
	2001-2100	0	+10	0	-7	-12	0	0	-9
MES	2001-2030	0	+1	-1	-1	+1	0	0	0
	2001-2050	-32	+4	-3	-6	+9	0	+5	-23
	2001-2100	-79	-211	-3	-53	+94	0	+17	-235
ASI	2001-2030	0	-4	0	+1	0	0	0	-3
	2001-2050	-34	+155	0	-37	+2	0	0	+86
	2001-2100	-117	+694	0	-101	-42	0	-1	+433
JPN	2001-2030	0	0	0	0	0	0	0	0
	2001-2050	0	0	0	-17	+22	0	0	+5
	2001-2100	0	-4	0	-21	+49	0	0	+24
Globe	2001-2030	-4,382	+401	+36	+86	+739	+1	+36	-3,083
	2001-2050	-60,623	+6,722	+274	+2,214	+11,482	+6	+280	-39,645
	2001-2100	-311,395	+23,104	+2,297	+12,793	+52,452	+36	+1,486	-219,227

Table 10. Direct, indirect and total effects of cellulosic biofuels production on cumulative net land nitrous oxide (N_2O) emissions (Tg CO_2-eq) across the globe in Case 2 over the 21st century. Positive values indicate abatement of N_2O emissions and negative values indicate enhanced N_2O losses to the atmosphere.

EPPA Region	Time Period	Direct	Indirect						Total
		Biofuels	Food Crops	Pastures	Managed Forests	Natural Forest	Natural Shrub	Natural Grass	
AFR	2001-2030	-3,817	+128	+33	+83	+650	0	+36	-2,887
	2001-2050	-29,105	+1,759	+253	+648	+3,855	0	+227	-22,363
	2001-2100	-122,841	+7,367	+1,595	+3,176	+9,885	0	+1,120	-99,698
LAM	2001-2030	-405	+308	0	+5	+34	0	+1	-57
	2001-2050	-15,188	+3,436	+147	+40	+1,807	0	+121	-9,637
	2001-2100	-99,845	+14,495	+1,390	+221	+8,155	+5	+1,258	-74,321
ROW	2001-2030	0	-2	0	0	0	0	0	-2
	2001-2050	-2,868	+1,363	+22	+172	+168	0	+22	-1,121
	2001-2100	-13,756	+6,904	+105	+562	+1,106	0	+102	-4,977
ANZ	2001-2030	-173	-3	+6	-1	+4	0	+3	-164
	2001-2050	-2,423	-55	+75	-16	+87	0	+28	-2,304
	2001-2100	-18,668	+1,582	+530	-231	+637	0	+157	-15,993
MEX	2001-2030	0	-5	0	0	+1	0	+1	-3
	2001-2050	-1,738	+287	+16	+16	+156	0	+7	-1,256
	2001-2100	-10,587	+2,487	+151	-2	+682	0	+45	-7,224
CAN	2001-2030	-21	+18	0	0	0	0	0	-3
	2001-2050	-435	+290	+2	+17	+9	0	+1	-116
	2001-2100	-1,476	+628	+14	+140	+61	0	+5	-628
USA	2001-2030	0	+1	0	-1	+1	0	0	+1
	2001-2050	-855	+256	+15	+103	+98	0	+15	-368
	2001-2100	-5,513	+1,128	+138	+463	+1,709	0	+100	-1,975
IDZ	2001-2030	0	+1	0	0	0	0	0	+1
	2001-2050	0	+95	+1	-48	+18	0	-1	+65
	2001-2100	0	+236	+1	-350	+385	0	0	+272

Table 10 (continued). Direct, indirect and total effects of cellulosic biofuels production on cumulative net land nitrous oxide (N_2O) emissions (Tg CO_2-eq) across the globe in Case 2 over the 21st century. Positive values indicate abatement of N_2O emissions and negative values indicate enhanced N_2O losses to the atmosphere.

EPPA Region	Time Period	Direct	Indirect						Total
		Biofuels	Food Crops	Pastures	Managed Forests	Natural Forest	Natural Shrub	Natural Grass	
IND	2001-2030	-6	+4	0	0	+1	0	0	-1
	2001-2050	-829	+492	+1	+33	+138	0	+1	-164
	2001-2100	-913	+599	+2	-128	+403	0	+2	-35
CHN	2001-2030	0	-2	+1	0	0	0	0	-1
	2001-2050	0	-58	+2	0	0	0	+2	-54
	2001-2100	0	-78	+5	-17	-3	0	+3	-90
EUR	2001-2030	0	-7	0	+1	+1	0	0	-5
	2001-2050	0	-133	+1	+35	+10	0	0	-87
	2001-2100	0	-614	+7	+194	+91	+1	0	-321
FSU	2001-2030	0	-12	+1	-1	0	0	0	-12
	2001-2050	0	-139	+8	-7	-2	0	+3	-137
	2001-2100	0	-301	+27	-56	-20	-1	+10	-341
EET	2001-2030	0	-1	0	0	0	0	0	-1
	2001-2050	0	-2	0	-1	0	0	0	-3
	2001-2100	0	+10	+1	-8	-12	0	0	-9
MES	2001-2030	0	0	-1	0	0	0	0	-1
	2001-2050	-22	+6	-1	-1	0	0	+5	-13
	2001-2100	-48	-215	+4	-7	0	0	+20	-246
ASI	2001-2030	0	0	0	0	0	0	0	0
	2001-2050	-34	+64	0	-9	+5	0	-1	+25
	2001-2100	-150	+365	0	-100	+66	0	-2	+179
JPN	2001-2030	0	0	0	0	0	0	0	0
	2001-2050	0	-1	0	+1	0	0	0	0
	2001-2100	0	-3	-2	+5	-2	0	0	-2
Globe	2001-2030	-4,422	+428	+40	+86	+692	0	+41	-3,135
	2001-2050	-53,497	+7,660	+542	+983	+6,349	0	+430	-37,533
	2001-2100	-273,797	+34,590	+3,968	+3,862	+23,143	+5	+2,820	-205,409

devoted to biofuels production in Case 1 than in Case 2. The larger indirect abatement of N_2O emissions in Case 1 is primarily a result of more deforestation occurring in Case 1 than Case 2 with the associated larger reductions in N_2O emissions from both natural and managed forests (Tables 9 and 10).

Similar to carbon emissions described earlier, the impact of biofuels production on N_2O emissions varies over space and time (**Figure 11**). Most of the biofuels-induced N_2O emissions over the 21st century will occur in Africa (93 Pg CO_2-eq in Case 1, 100 Pg CO_2-eq in Case 2) and Latin America (80 Pg CO_2-eq in Case 1, 74 Pg CO_2-eq in Case 2) where most of the production of cellulosic biofuels occurs (Tables 9 and 10). The high productivity rates in tropical regions require the addition of more nitrogen fertilizer than other regions to sustain crop productivity as nutrients are continually removed from the soil with harvest. In some regions (e.g., Africa, Latin America, Australia/New Zealand), the rate of N_2O emissions continues to increase over the 21st century (Figure 11). These increases are a result of both more land being devoted to biofuels production over time and more favorable environmental conditions for growing crops (warmer and wetter climate, enhanced atmospheric CO_2 concentrations) in the future leading to more applications of nitrogen fertilizer and N_2O emissions. In other regions (e.g., Canada, United States of America, Indonesia, India), however, the rate of N_2O emissions declines after an initial enhancement (see also **Figures A17** to **A32** in **Appendix**). These trends are based mostly on the responses of nitrogen fertilizer applications to the temporal changes in land area devoted to biofuels production in these regions described earlier (see Section 3.1.3).

While the direct effects of biofuels production enhances N_2O emissions in all regions from the application of nitrogen fertilizer, the indirect effects of biofuels production vary among regions. As indicated earlier, many natural ecosystems are sources of atmospheric N_2O primarily from the microbial processes of nitrification and denitrification in soils. In most regions, N_2O emissions are indirectly reduced as natural land is converted to biofuels production or displaced agriculture. In addition, N_2O emissions are indirectly reduced in some regions as less area is devoted to food production leading to less application of nitrogen fertilizers. However, in other regions (China, European Union, Former Soviet Union, Eastern Europe, Middle East), the displacement of food production causes more area to be devoted to food production leading to additional applications of nitrogen fertilizer and indirect enhancement of N_2O emissions.

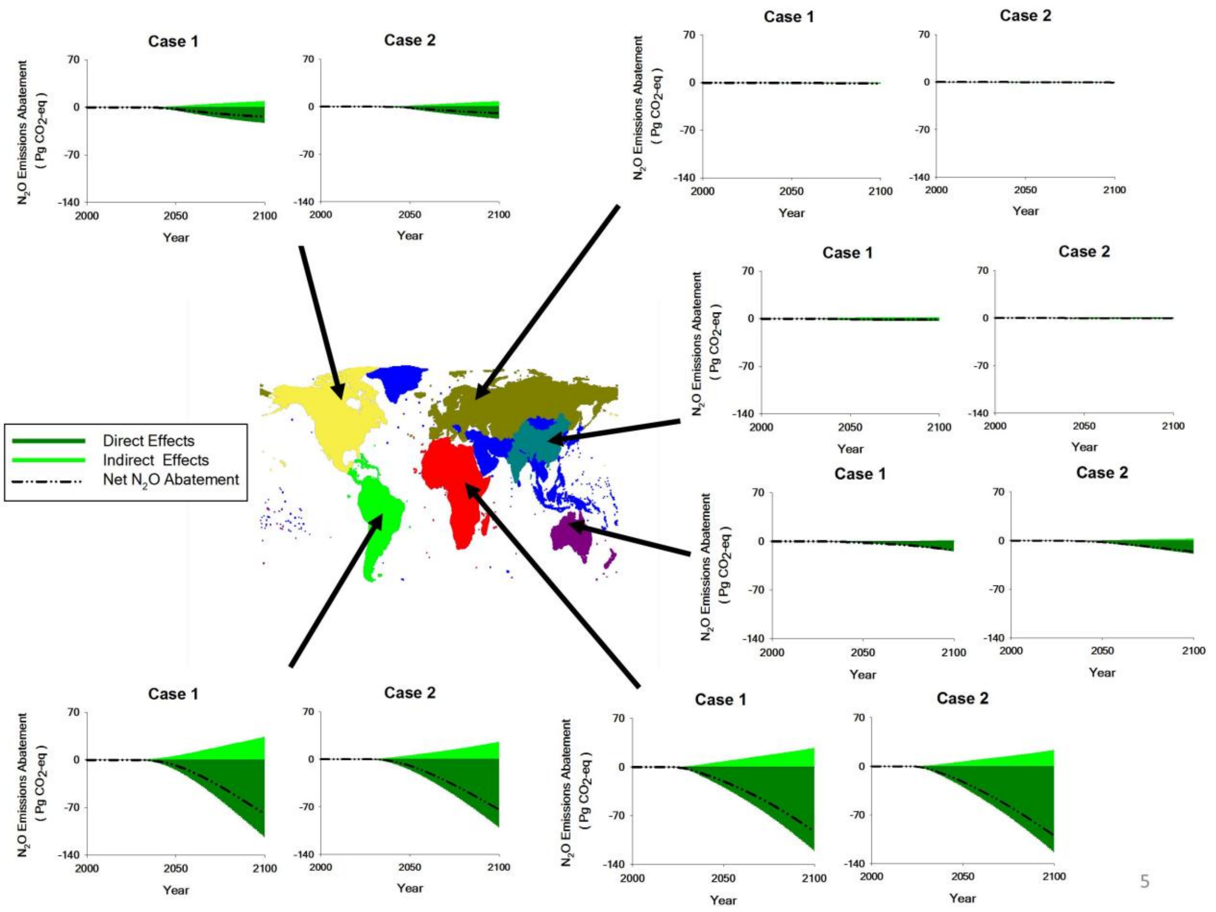

Figure 11. Partitioning of direct and indirect effects on projected cumulative land nitrous oxide emissions from cellulosic biofuel production over the 21st century for land-use Case 1 and Case 2 in select EPPA regions: Africa (reddish brown), Latin America (green), North America (yellow), Europe-Russia (gold), China-India (teal), and Australia-New Zealand (purple). North America contains the EPPA regions of Canada, Mexico and the United States of America. Europe-Russia contains the EPPA regions of the European Union, Eastern Europe and the Former Soviet Union.

Land-use policy also influences regional N_2O emissions from biofuels production based on how land devoted to biofuels production or displaced food production is distributed and whether these lands are derived from natural or already existing managed lands. In Africa, Latin America, Mexico, and the United States of America, there are relatively little differences in the net N_2O emissions induced by biofuels production between the two land-use scenarios although large differences in the indirect abatement of N_2O emissions in food production and natural and managed forests may still occur. Biofuels-induced N_2O emissions from Canada and the Rest of the World in Case 1 (Table 9), however, are 650% and 75% higher, respectively, than comparable emissions in Case 2 (Table 10). In contrast, biofuels-induced N_2O emissions from

Australia/New Zealand in Case 2 are 26% higher than Case 1. In Indonesia, biofuels production induces relatively large N_2O emissions in Case 1 (9.5 Pg CO_2-eq), but reduces N_2O emissions in Case 2 by 0.3 Pg CO_2-eq.

3.4 Biofuels Production Effects on Net Land Greenhouse Gas Fluxes

When the influence of biofuels on both land carbon fluxes and N_2O emissions are considered together, we find that biofuels enhances the emissions of greenhouse gases over the 21st century by 311 Pg CO_2-eq in Case 1 and 130 Pg CO_2-eq in Case 2. The N_2O emissions from nitrogen fertilizer applications to biofuel and displaced food crops enhance greenhouse gas forcing and negate any benefits of carbon sequestration or reductions of natural N_2O emissions resulting from cellulosic biofuels production at the global scale (Tables 7 and 8), but the relative importance of these fertilizer N_2O emissions varies over time and with land-use policy. In Case 1, these fertilizer N_2O emissions are only about one-third of the GHG forcing of carbon emissions during the first half of the 21st century, but then increase to become more than three times the GHG forcing of carbon emissions by the end of the 21st century (Table 7). In contrast, the GHG forcing of fertilizer N_2O emissions in Case 2 are more than four times the forcing by carbon emissions by 2050 and then overwhelms the carbon sequestered (75 Pg CO_2-eq) by the end of the 21st century (Table 8).

The variations in the relative importance of carbon and N_2O emissions also influence the relative importance of direct and indirect effects of biofuels on net land GHG fluxes. Unlike carbon emissions in Case 1 where indirect effects dominated the response to biofuels throughout the 21st century (Figure 3a), the N_2O emissions from fertilizer applications to biofuel crops enhance the concurrent greenhouse forcing of carbon emissions from deforestation in Case 1 (Figure 10a) such that the direct effects dominate the response of greenhouse gas emissions to biofuels throughout the 21st century accounting for 56% of the GHG emissions by 2050 and 99% of the GHG emissions by 2100 (Figure 10c). In Case 2, the carbon emissions from displaced agriculture along with reduced carbon sequestration in natural ecosystems (Figure 3b) dominate the response of GHG emissions to biofuels during the first half of the 21st century (Figure 10d). However, N_2O emissions from fertilizer applications (Figure 10b) dominate the response of GHG emissions to biofuels in Case 2 during the last half of the 21st century (Figure 10d) by overwhelming the benefits of carbon sequestration (Figure 3b) during this period.

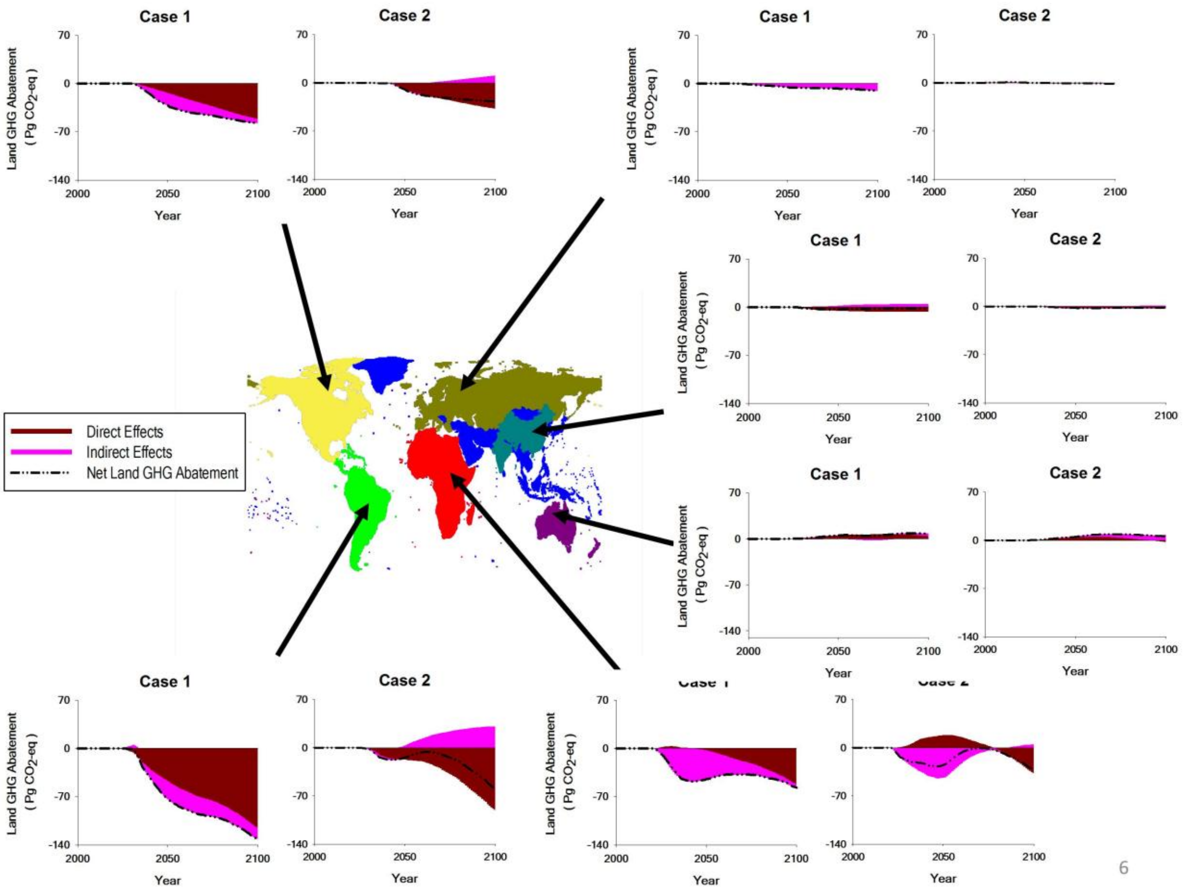

Figure 12. Partitioning of direct and indirect effects on projected cumulative land greenhouse gas flux from cellulosic biofuel production over the 21st century for land-use Case 1 and Case 2 in select EPPA regions: Africa (reddish brown), Latin America (green), North America (yellow), Europe-Russia (gold), China-India (teal), and Australia-New Zealand (purple). North America contains the EPPA regions of Canada, Mexico and the United States of America. Europe-Russia contains the EPPA regions of the European Union, Eastern Europe and the Former Soviet Union.

The net land GHG fluxes varies across the surface of the earth and over time (**Figure 12**) and reflect spatial and temporal differences in the relative importance of land carbon fluxes and N_2O emissions to GHG forcing. By the end of the 21st century, most of the biofuels-induced land GHG emissions occur from Latin America (42% in Case 1, 44% in Case 2) and Africa (18% in Case 1, 25% in Case 2) in both land-use scenarios (Tables 7 and 8). The United States of America (11% in Case 1, 16% in Case 2) and the Rest of the World (9% in Case 1, 6% in Case 2) are also relatively large contributors of GHG emissions along with Canada in Case 1 (11%). In contrast, biofuels-induced carbon sequestration and N_2O abatement reduces net land GHG emissions in Australia/New Zealand, and Eastern Europe in both land-use scenarios; Higher Income East Asia in Case 1; and Canada, the Former Soviet Union, the Middle East, China and Japan in Case 2. For both land-use scenarios, the GHG fluxes within a region are mostly a consequence of fertilizer N_2O emissions in Latin America, Africa, and Mexico, but in Australia/New Zealand, the United States of America, Indonesia, the European Union and Eastern Europe, GHG fluxes are mostly a consequence of carbon emissions. In some regions, the relative importance of carbon fluxes and N_2O emissions depends on land-use policy. For example, fertilizer N_2O emissions accounted for most of the GHG emissions from India in Case 1, but carbon emissions are more important in Case 2. In contrast, carbon emissions are more important in the Rest of the World in Case 1, but fertilizer N_2O emissions are more important in Case 2.

The variations in the relative importance of regional carbon fluxes and N_2O emissions also influence the relative importance of direct and indirect effects of biofuels on regional net land GHG fluxes and their changes over time (Figure 12). Similar to the global-scale results in Case 1, N_2O emissions from fertilizers applied to biofuel crops enhances the GHG forcing of carbon emissions from deforestation in some regions (e.g., Latin America in Case 1 and first half of the 21st century in Case 2; Rest of the World, United States of America, and India in both Case 1 and 2; Canada and Indonesia in Case 1) so that most of the GHG emissions are from the direct effects of biofuels (see also **Figures A17 to A32 in Appendix**). In other regions (e.g., Africa, Australia/New Zealand, Mexico in both Case 1 and 2; Latin America in the second half of the 21st century), biofuels-induced fertilizer N_2O emissions reduce the benefits of concurrent biofuels-induced carbon sequestration such that the indirect effects of biofuels account for more of the net GHG emissions during some period of the 21st century.

This compensatory effect of land carbon fluxes and N_2O emissions also occurs in natural ecosystems. Biofuels production reduces both the carbon sequestration capacity (Tables 5 and 6) and N_2O emissions (Tables 9 and 10) of natural ecosystems with the largest reductions occurring in forests. Due to the relatively large global warming potential of nitrous oxide, the reductions in GHG forcing from the reduced natural N_2O emissions are larger than the concurrent increases in GHG forcing that result from reducing the carbon sequestration capacity. As a result, land conversion of natural ecosystems for biofuels production and displaced agriculture reduces the atmospheric GHG forcing from these natural ecosystems in our study.

3.5 Biofuels Production Effects on Net Greenhouse Gas Balances

While biofuels are projected to increase land emissions of greenhouse gases, our estimates of land carbon flux include carbon emissions associated with the use of biofuels in addition to their production. Because biofuels reduce the use of fossil fuels, credits for avoiding fossil fuels should be included when assessing the impacts of biofuels on net greenhouse gas balance. As described in Melillo *et al*. (2009), we find that the production of cellulosic biofuels will initially incur direct and indirect GHG costs that are greater than the GHG benefits of using biofuels. With time, however, the cumulative GHG benefits of avoiding fossil-fuel use more than compensates for the cumulative GHG costs of producing cellulosic biofuels for both of the land-use scenario cases. These net benefits are realized earlier in Case 2 (year 2039) than in Case 1 (year 2060). Because of the reduction of nitrous oxide emissions from natural ecosystems, we estimate larger net benefits of biofuels on the global net greenhouse gas balance than reported in Melillo *et al.* (2009). We estimate a net benefit of 646 Pg CO_2-eq for Case 1 (Figure 10e) and 711 Pg CO_2-eq for Case 2 by the end of the 21st century (Figure 10f) compared to 579 Pg CO_2-eq and 679 Pg CO_2-eq, respectively, that were reported previously. Larger net benefits are realized in Case 2 than Case 1 mostly because Case 2 avoided more deforestation through more intensive use of managed lands.

3.5.1 Effects of Biofuels Trade on Regional Greenhouse Gas Budgets

Up to this point in our analyses, we have assumed that biofuel-induced changes in carbon storage within regions result in net carbon fluxes to the atmosphere from those same regions; i.e. biofuels are consumed in the same regions where they are produced. With the EPPA model, we note large variations among regions in the ability to produce energy from cellulosic biofuels and the corresponding energy needs of the region (**Table 11**). In both land-use cases, Africa and Latin America produce much more energy from cellulosic biofuels than they need for their regional energy needs and thus will become large exporters of biofuels. In contrast, the United States of America, the European Union, and High Income East Asia are projected to need much more energy from biofuels than they will produce so that they become large importers of biofuels. Thus, international trade in cellulosic biofuels may cause considerable horizontal transport of biofuels products to occur before the carbon stored in these products is returned to the atmosphere.

Table 11. Cumulative production, demand, and net export of energy derived from biofuels in Case 1 over several time periods during the 21st century. Units are EJ. Negative values for exports represent imports of biofuels into a region.

EPPA Region	**Time period**	**Production**		**Demand**		**Net Exports.**	
		Case 1	**Case 2**	**Case 1**	**Case 2**	**Case 1**	**Case 2**
AFR	2001-2030	100	97	0	0	+100	+97
	2001-2050	715	727	146	138	+569	+589
	2001-2100	4,236	4,219	960	888	+3,276	+3,331
LAM	2001-2030	11	17	0	0	+11	+17
	2001-2050	633	669	242	227	+391	+442
	2001-2100	7,302	6,156	1,938	1,643	+5,364	+4,513
ROW	2001-2030	3	0	0	0	+3	0
	2001-2050	112	65	73	64	+39	+1
	2001-2100	624	434	536	432	+88	+2
ANZ	2001-2030	4	4	4	4	0	0
	2001-2050	38	43	38	39	0	+4
	2001-2100	385	591	190	175	+195	+416
MEX	2001-2030	0	0	0	0	0	0
	2001-2050	53	54	42	38	+11	+16
	2001-2100	426	404	346	296	+80	+108
CAN	2001-2030	0	1	0	0	0	+1
	2001-2050	44	9	24	21	+20	-12
	2001-2100	251	36	337	309	-86	-273
USA	2001-2030	0	0	106	103	-106	-103
	2001-2050	59	76	385	346	-326	-270
	2001-2100	379	568	3,021	2,741	-2,642	-2,173
IDZ	2001-2030	1	0	1	1	0	-1
	2001-2050	74	0	65	57	9	-57
	2001-2100	405	0	502	397	-97	-397
IND	2001-2030	6	0	1	1	+5	-1
	2001-2050	113	45	68	54	+45	-9
	2001-2100	172	51	676	569	-504	-518

Table 11 (continued). Cumulative production, demand, and net export of energy derived from biofuels over several time periods during the 21st century. Units are EJ. Negative values for exports represent imports of biofuels into a region.

EPPA Region	**Time period**	**Production**		**Demand**		**Net Exports.**	
		Case 1	**Case 2**	**Case 1**	**Case 2**	**Case 1**	**Case 2**
CHN	2001-2030	0	0	0	0	0	0
	2001-2050	0	0	0	0	0	0
	2001-2100	0	0	33	9	-33	-9
EUR	2001-2030	0	0	3	2	-3	-2
	2001-2050	0	0	230	213	-230	-213
	2001-2100	0	0	2,164	1,987	-2,164	-1,987
FSU	2001-2030	0	0	0	0	0	0
	2001-2050	0	0	0	0	0	0
	2001-2100	0	0	55	24	-55	-24
EET	2001-2030	0	0	0	0	0	0
	2001-2050	0	0	3	3	-3	-3
	2001-2100	0	0	54	38	-54	-38
MES	2001-2030	0	0	8	6	-8	-6
	2001-2050	3	2	172	163	-169	-161
	2001-2100	5	3	746	675	-741	-672
ASI	2001-2030	0	0	0	0	0	0
	2001-2050	2	1	242	221	-240	-220
	2001-2100	4	4	1,885	1,642	-1,881	-1,638
JPN	2001-2030	0	0	2	2	-2	-2
	2001-2050	0	0	116	107	-116	-107
	2001-2100	0	0	746	641	-746	-641
Total	2001-2030	125	119	125	119	0	0
	2001-2050	1,846	1,691	1,846	1,691	0	0
	2001-2100	14,189	12,466	14,189	12,466	0	0

We estimate that trade in biofuels will result in the net redistribution of about 166 Pg C (607 Pg CO_2-eq) in Case 1 and 154 Pg C (565 Pg CO_2-eq) in Case 2 across the surface of the earth over the 21st century. Towards the beginning of the century, most of horizontal transfer of biofuel carbon occurs between Africa and the United States (**Figure 13a**). Later in the century, however, the contribution of Latin America to biofuel exports grows and this region eventually becomes the largest contributor to the horizontal transfer of carbon by the end of the century (Figure 13). Besides the United States, the European Union, High Income East Asia, Japan and the Middle East are also projected to become large importers of biofuel carbon over the 21st century.

3.5.2 Effects of Biofuel-induced Changes in Food Trade on Regional Greenhouse Gas Budgets

The production and trade of cellulosic biofuels has also affected the trade in food products, which also influences the horizontal transfer of carbon among regions. In general, big food exporters in a world without biofuels considerably reduce their food exports in a bioenergy economy to allow space for biofuels production (**Table 12**). For Latin America and Africa, food exports are 60-70% lower in the presence of biofuels production than in the scenario without biofuels as these regions have become major exporters of biofuels. The United States of America and Canada, on the other hand, export three to seven times more food in the scenario with biofuels than the scenario without biofuels, but have become net importers of biofuels to support their energy needs. Other regions that do not produce biofuels, such as the European Union and the Former Soviet Union, tend to increase their food production (Tables 3 and 4) and decrease their food imports under the global biofuels economy (Table 12). The global trade patterns in biofuels and food suggests that tropical countries will use their comparative advantage in biomass production to supply biofuels while the United States of America and Canada become relatively more important in supplying food in a biofuels economy.

The trade in food products has resulted in an additional net redistribution of 15 Pg C (55 Pg CO_2-eq) in both Case 1 and Case 2 (**Figure 14**). This redistribution, however, is less than that which would be projected if cellulosic biofuels are not part of the future (21 Pg C or 76 Pg CO_2-eq in Case 1, 22 Pg C or 80 Pg CO_2-eq in Case 2) as the biofuels-induced reduction in the trade of food products also reduces the associated horizontal transfer of carbon in the future. Within this overall reduced global trade of food products, however, the United States of America and

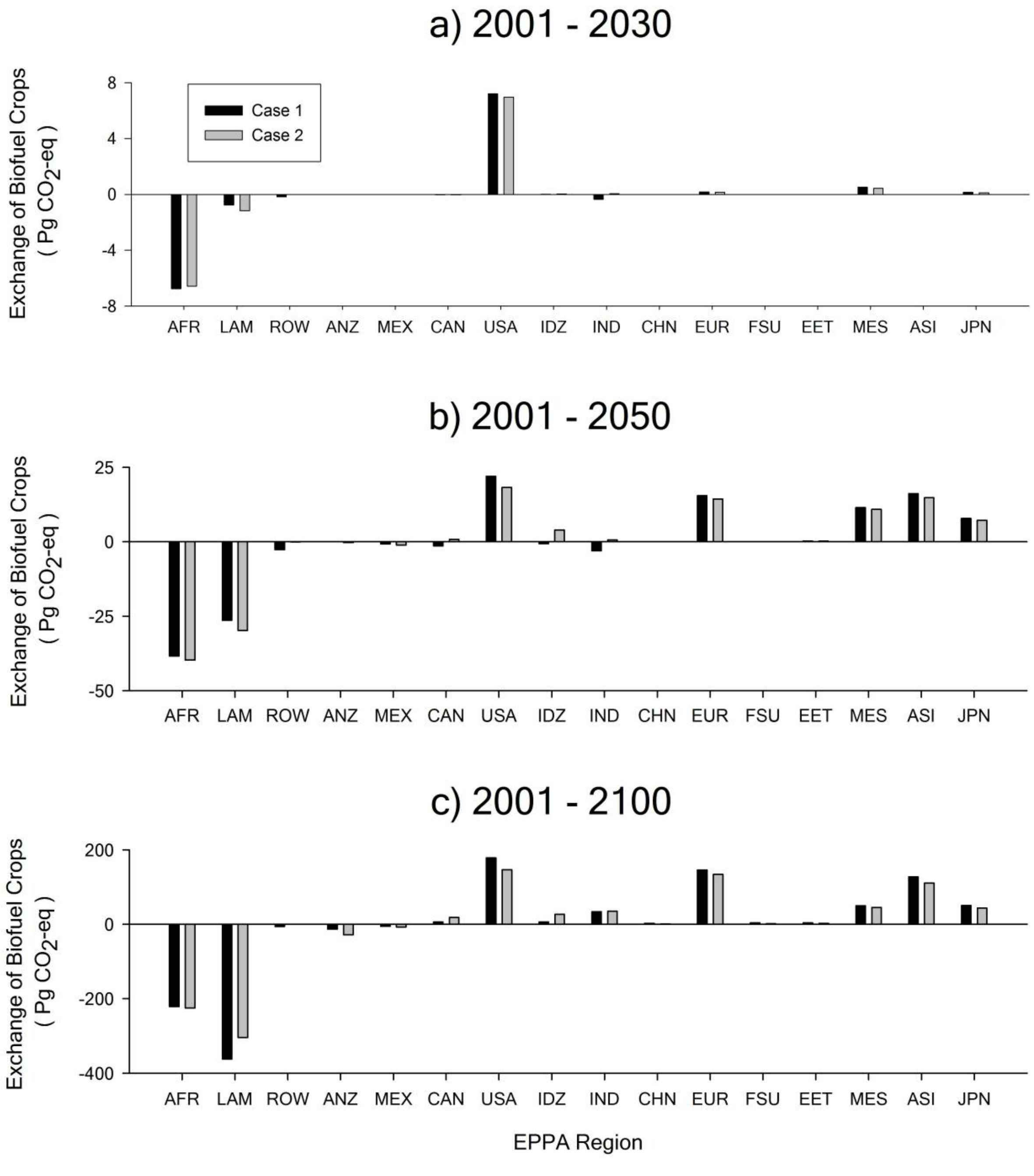

Figure 13. Changes in the distribution of cumulative imports (positive values) and exports (negative values) of cellulosic biofuels among EPPA regions for Case 1 and Case 2 over different time periods during the 21st century.

Table 12. Cumulative demand and net export of food products for several time periods over the 21^{st} century. Units are 1997 10 billion US$. Negative values for exports represent food imports into a region.

EPPA Region	**Time Period**	**With Biofuels**				**Without Biofuels**			
		Demand		**Net Exports**		**Demand**		**Net Exports**	
		Case 1	**Case 2**	**Case 1**	**Case 2**	**Case 1**	**Case 2**	**Case 1**	**Case 2**
AFR	2001-2030	783	743	+25	+29	780	743	+34	+38
	2001-2050	1,669	1,577	+47	+50	1,665	1,587	+104	+114
	2001-2100	6,060	5,766	+200	+172	6,059	5,794	+500	+536
LAM	2001-2030	1,011	992	+81	+84	1,013	993	+85	+89
	2001-2050	2,399	2,318	+132	+130	2,376	2,306	+185	+194
	2001-2100	10,126	9,763	+170	+201	9,595	9,216	+607	+676
ROW	2001-2030	772	741	+44	+42	771	741	+44	+42
	2001-2050	1,636	1,568	+75	+75	1,617	1,559	+97	+90
	2001-2100	5,432	5,232	+242	+200	5,220	5,077	+433	+407
ANZ	2001-2030	147	146	+53	+55	147	145	+53	+55
	2001-2050	318	315	+134	+136	314	311	+124	+128
	2001-2100	1,094	1,086	+541	+533	1,063	1,061	+529	+573
MEX	2001-2030	260	253	+27	+29	260	254	+27	+29
	2001-2050	560	535	+106	+110	560	541	+105	+108
	2001-2100	1,938	1,785	+514	+530	1,951	1,848	+573	+598
CAN	2001-2030	188	184	+17	+17	188	184	+17	+17
	2001-2050	401	392	+31	+33	396	390	+27	+28
	2001-2100	1,330	1,307	+157	+187	1,242	1,227	+29	+35
USA	2001-2030	1,154	1,146	+51	+58	1,153	1,146	+46	+53
	2001-2050	2,400	2,382	+96	+100	2,395	2,381	+55	+69
	2001-2100	7,618	7,547	+580	+620	7,441	7,408	+82	+179
IDZ	2001-2030	262	233	+15	+10	262	233	+14	+10
	2001-2050	601	521	+29	+33	587	509	+42	+41
	2001-2100	2,247	1,816	+109	+162	2,110	1,707	+235	+253

Table 12 (continued). Cumulative demand and net export of food products for several time periods over the 21st century. Units are 1997 10 billion US$. Negative values for exports represent food imports into a region.

EPPA Region	Time Period	With Biofuels				Without Biofuels			
		Demand		Net Exports		Demand		Net Exports	
		Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
IND	2001-2030	1,028	999	0	-3	1,027	999	+1	-3
	2001-2050	2,217	2,148	+2	-2	2,200	2,134	+27	+10
	2001-2100	8,285	8,033	+8	-51	8,023	7,769	+151	+25
CHN	2001-2030	1,956	1,942	-49	-52	1,955	1,941	-49	-52
	2001-2050	4,402	4,381	-80	-97	4,381	4,363	-87	-105
	2001-2100	16,759	16,470	-502	-672	16,446	16,186	-419	-618
EUR	2001-2030	1,967	1,961	-126	-118	1,967	1,961	-130	-122
	2001-2050	4,118	4,103	-221	-199	4,077	4,065	-282	-264
	2001-2100	13,722	13,633	-539	-365	12,639	12,594	-1,067	-957
FSU	2001-2030	261	256	1	-5	261	257	0	-6
	2001-2050	605	593	-7	-28	604	594	-18	-37
	2001-2100	2,262	2,204	-130	-269	2,231	2,182	-186	-303
EET	2001-2030	246	244	-5	-4	246	244	-5	-5
	2001-2050	544	539	-15	-14	542	537	-18	-17
	2001-2100	1,923	1,906	-158	-150	1,895	1,881	-151	-148
MES	2001-2030	234	233	-30	-29	234	233	-31	-30
	2001-2050	476	474	-68	-67	455	453	-88	-86
	2001-2100	1,823	1,822	-218	-208	1,642	1,636	-383	-369
ASI	2001-2030	677	611	-22	-34	676	610	-23	-35
	2001-2050	1,515	1,368	-88	-93	1,499	1,358	-82	-89
	2001-2100	6,399	5,784	-363	-316	5,944	5,423	-282	-263
JPN	2001-2030	545	544	-82	-79	545	544	-83	-80
	2001-2050	1,165	1,163	-173	-167	1,149	1,147	-191	-184
	2001-2100	3,869	3,864	-611	-574	3,772	3,769	-651	-624
Globe	2001-2030	11,491	11,228	0	0	11,485	11,228	0	0
	2001-2050	25,026	24,377	0	0	24,817	24,235	0	0
	2001-2100	90,887	88,018	0	0	87,273	84,778	0	0

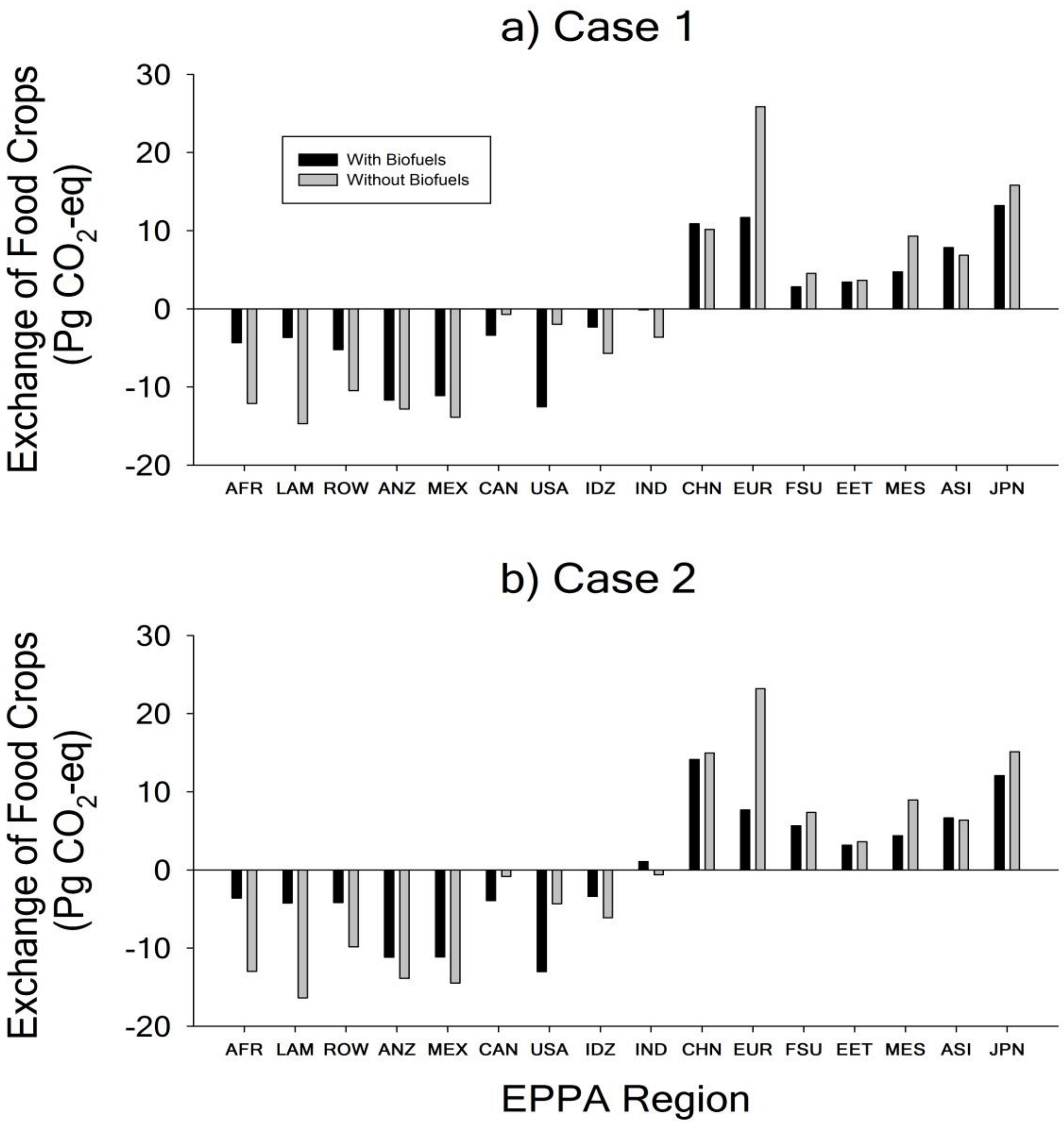

Figure 14. Comparison of cumulative imports (positive values) and exports (negative values) of food crops (Pg CO_2-eq) among EPPA regions with and without cellulosic biofuels production for (a) Case 1 and (b) Case 2 land-use scenarios over the 21st century.

Canada have still increased the horizontal transport of carbon out of their respective regions due to the increase in food exports.

3.5.3 Attribution of Fossil Fuel Abatement Credits to Producer versus Consumer Regions

A basic question in the assessment of biofuel impacts is whether to attribute GHG emissions and fossil fuel abatement credits to regions that produce biofuels or to regions that consume biofuels. To examine the consequences of these two approaches, we determine regional net GHG balances by first attributing all GHG emissions and fossil fuel abatements to regions that produce biofuels with fossil fuel abatements based on the energy supplied by the biofuels produced. We then determine regional net GHG balances again, but use the exports and imports of biofuels and food products described above to adjust land GHG emissions and determine fossil fuel abatements based on the energy demands of the consumer regions (see Section 2.5.4). For both approaches, the regional net greenhouse gas balance varies across the surface of the earth (**Tables 13** and **14**). While biofuels lead to a net abatement of GHG fluxes in most regions, there are some regions where GHG emissions associated with producing biofuels (Indonesia and Canada in Case 1, Higher Income East Asia in Case 2) or from displaced agriculture (European Union, Former Soviet Union, China in Case 1, Indonesia in Case 2) overwhelm the benefits of avoiding the use of fossil fuels. Most of the net abatement benefits occur in Latin America and Africa. While a larger area of Africa is devoted to production of cellulosic biofuels, Latin America realizes larger net GHG benefits by 2100 than Africa because more biomass is created on the areas devoted to biofuels, and the biofuels (along with displaced food crops) required less nitrogen fertilizer in Latin America than Africa (Tables 7 and 8). The attribution of fossil fuel abatements to consumer regions rather than producer regions reduces the abatement credits attributed to the producer regions, but adjustments of the net land GHG fluxes for exports enhance the apparent biofuel-induced sink in the producer regions as the carbon sequestered in biofuel products is transported out of the region before being returned to the atmosphere. As a result, the net GHG abatement in these regions only declined by 3-4% when emissions from biofuel use and fossil fuel abatement credits are attributed to consumer regions rather than producer regions.

In other regions, the attribution approaches can lead to much more dramatic differences in regional net GHG balances. For example, biofuels cause the European Union to be a larger source of atmospheric greenhouse gases when biofuel GHG emissions and fossil fuel abatements are attributed to producer regions because no biofuels are produced in this region and GHG emissions are enhanced by land conversions and additional fertilizer applications associated with displaced food production. When GHG emissions related to biofuels and food production along with fossil fuel abatements are attributed to consumer regions, biofuels lead to an increase in the net abatement of atmospheric greenhouse gases in the European Union. While the use of imported biofuels increases carbon emissions to the atmosphere from this region, these increases are more than compensated by the credit of fossil fuel abatements in the regional net GHG

Table 13. Comparison of the partitioning of the net greenhouse balance (Tg CO_2-eq) across the globe in Case 1 over the 21st century based on assigning fossil fuel abatement to biofuel producers versus biofuel consumers.

EPPA Region	Time Period	Producer			Consumer		
		Net Land GHG Flux	Fossil Fuel Abatement	Net Abatement	Net Land GHG Flux	Fossil Fuel Abatement	Net Abatement
AFR	2001-2030	-24,122	6,747	-17,375	-17,834	0	-17,834
	2001-2050	-44,596	48,214	+3,618	-8,716	9,862	+1,146
	2001-2100	-57,147	285,797	+228,650	156,078	64,778	+220,856
LAM	2001-2030	-586	751	+165	-11	0	-11
	2001-2050	-73,744	42,712	-31,032	-49,849	16,357	-33,492
	2001-2100	-131,662	492,668	+361,006	219,187	130,774	+349,961
ROW	2001-2030	-2,098	166	-1,932	-1,932	0	-1,932
	2001-2050	-19,192	7,554	-11,638	-17,592	4,901	-12,691
	2001-2100	-26,814	42,125	+15,311	-26,127	36,184	+10,057
ANZ	2001-2030	482	233	+715	472	233	+705
	2001-2050	5,051	2,592	+7,643	5,194	2,592	+7,786
	2001-2100	7,844	25,966	+33,810	19,886	12,797	+32,683
MEX	2001-2030	-31	0	-31	-6	0	-6
	2001-2050	-1,971	3,566	+1,595	-1,381	2,815	+1,434
	2001-2100	-6,135	28,758	+22,623	-3,501	23,353	+19,852
CAN	2001-2030	+8	25	+33	30	0	+30
	2001-2050	-23,105	2,975	-20,130	-21,604	1,589	-20,015
	2001-2100	-35,727	16,897	-18,830	-38,852	22,706	-16,146
USA	2001-2030	-99	0	-99	-7,052	7,207	+155
	2001-2050	-6,527	3,977	-2,550	-27,032	25,979	-1,053
	2001-2100	-15,547	25,566	+10,019	-183,271	203,840	+20,569
IDZ	2001-2030	-1,372	78	-1,294	-1,388	94	-1,294
	2001-2050	-26,920	5,025	-21,895	-26,874	4,379	-22,495
	2001-2100	-33,599	27,318	-6,281	-43,521	33,903	-9,618

Table 13 (continued). Comparison of the partitioning of the net greenhouse balance (Tg CO_2-eq) across the globe in Case 1 over the 21st century based on assigning fossil fuel abatement to biofuel producers versus biofuel consumers.

EPPA Region	Time Period	Producer			Consumer		
		Net Land GHG Flux	Fossil Fuel Abatement	Net Abatement	Net Land GHG Flux	Fossil Fuel Abatement	Net Abatement
IND	2001-2030	-1,387	434	-953	-1,094	75	-1,019
	2001-2050	-3,269	7,611	+4,342	-1,323	4,612	+3,289
	2001-2100	-1,925	11,624	+9,699	-39,377	45,590	+6,213
CHN	2001-2030	+18	0	+18	49	0	+49
	2001-2050	87	0	+87	556	0	+556
	2001-2100	-58	0	-58	-2,977	2,213	-764
EUR	2001-2030	-444	0	-444	-395	172	-223
	2001-2050	-3,108	0	-3,108	-15,580	15,484	-96
	2001-2100	-7,567	0	-7,567	-139,372	145,997	+6,625
FSU	2001-2030	-1,182	0	-1,182	-1,135	0	-1,135
	2001-2050	-2,350	0	-2,350	-1,882	0	-1,882
	2001-2100	-3,124	0	-3,124	-5,124	3,705	-1,419
EET	2001-2030	-17	0	-17	-5	0	-5
	2001-2050	3	0	+3	-50	211	+161
	2001-2100	359	0	+359	-3,034	3,625	+591
MES	2001-2030	-23	0	-23	-475	510	+35
	2001-2050	-108	194	+86	-10,539	11,603	+1,064
	2001-2100	-42	327	+285	-45,487	50,353	+4,866
ASI	2001-2030	-10	0	-10	13	0	+13
	2001-2050	187	103	+290	-16,109	16,293	+184
	2001-2100	315	233	+548	-127,613	127,150	-463
JPN	2001-2030	-61	0	-61	-161	143	-18
	2001-2050	-868	0	-868	-7,649	7,846	+197
	2001-2100	-157	0	-157	-47,881	50,311	+2,430
Globe	2001-2030	-30,924	8,434	-22,490	-30,924	8,434	-22,490
	2001-2050	-200,430	124,523	-75,907	-200,430	124,523	-75,907
	2001-2100	-310,986	957,279	+646,293	-310,986	957,279	+646,293

Table 14. Comparison of the partitioning of the net greenhouse balance (Tg CO_2-eq) across the globe in Case 2 over the 21st century based on assigning fossil fuel abatement to biofuel producers versus biofuel consumers.

EPPA Region	Time Period	Producer			Consumer		
		Net Land GHG Flux	Fossil Fuel Abatement	Net Abatement	Net Land GHG Flux	Fossil Fuel Abatement	Net Abatement
AFR	2001-2030	-18,570	6,571	-11,999	-12,502	0	-12,502
	2001-2050	-24,873	49,052	+24,179	12,036	9,301	+21,337
	2001-2100	-32,144	284,675	+252,531	183,269	59,885	+243,154
LAM	2001-2030	-2,245	1,176	-1,069	-1,315	0	-1,315
	2001-2050	-14,166	45,107	+30,941	12,619	15,315	+27,934
	2001-2100	-59,660	415,295	+355,635	232,636	110,837	+343,473
ROW	2001-2030	-4	0	-4	22	0	+22
	2001-2050	-2,411	4,381	+1,970	-3,120	4,316	+1,196
	2001-2100	-8,405	29,248	+20,843	-13,956	29,137	+15,181
ANZ	2001-2030	663	235	+898	659	235	+894
	2001-2050	5,065	2,871	+7,936	5,396	2,619	+8,015
	2001-2100	5,730	39,868	+45,598	31,128	11,785	+42,913
MEX	2001-2030	-6	0	-6	26	0	+26
	2001-2050	388	3,664	+4,052	1,346	2,541	+3,887
	2001-2100	-6,088	27,280	+21,192	-2,113	19,967	+17,854
CAN	2001-2030	-30	32	+2	-3	0	-3
	2001-2050	416	574	+990	-251	1,395	+1,144
	2001-2100	551	2,462	+3,013	-14,752	20,852	+6,100
USA	2001-2030	28	0	+28	-6,694	6,975	+281
	2001-2050	-10,587	5,124	-5,463	-27,730	23,370	-4,360
	2001-2100	-21,312	38,322	+17,010	-159,213	184,912	+25,699
IDZ	2001-2030	-15	0	-15	-43	40	-3
	2001-2050	-642	0	-642	-4,960	3,880	-1,080
	2001-2100	-5,662	0	-5,662	-35,193	26,801	-8,392

Table 14 (continued). Comparison of the partitioning of the net greenhouse balance (Tg CO_2-eq) across the globe in Case 2 over the 21st century based on assigning fossil fuel abatement to biofuel producers versus biofuel consumers.

EPPA Region	Time Period	Producer			Consumer		
		Net Land GHG Flux	**Fossil Fuel Abatement**	**Net Abatement**	**Net Land GHG Flux**	**Fossil Fuel Abatement**	**Net Abatement**
IND	2001-2030	-26	29	+3	-75	74	-1
	2001-2050	-2,409	3,066	+657	-3,494	3,662	+168
	2001-2100	-1,751	3,427	+1,676	-38,394	38,393	-1
CHN	2001-2030	20	0	+20	55	0	+55
	2001-2050	185	0	+185	722	0	+722
	2001-2100	74	0	+74	285	641	+926
EUR	2001-2030	22	0	+22	93	159	+252
	2001-2050	-402	0	-402	-11,585	14,362	+2,777
	2001-2100	-2,188	0	-2,188	-120,698	134,022	+13,324
FSU	2001-2030	122	0	+122	162	0	+162
	2001-2050	675	0	+675	1,098	0	+1,098
	2001-2100	546	0	+546	603	1,634	+2,237
EET	2001-2030	-3	0	-3	10	0	+10
	2001-2050	-2	0	-2	-10	176	+166
	2001-2100	332	0	+332	-1,795	2,563	+768
MES	2001-2030	-7	0	-7	-395	443	+48
	2001-2050	80	117	+197	-9,831	10,975	+1,144
	2001-2100	216	187	+403	-40,580	45,564	+4,984
ASI	2001-2030	-12	0	-12	14	0	+14
	2001-2050	-195	99	-96	-14,970	14,928	-42
	2001-2100	-338	281	-57	-111,092	110,777	-315
JPN	2001-2030	21	0	+21	-56	117	+61
	2001-2050	20	0	+20	-6,124	7,215	+1,091
	2001-2100	3	0	+3	-40,231	43,275	+3,044
Globe	2001-2030	-20,042	8,043	-11,999	-20,042	8,043	-11,999
	2001-2050	-48,858	114,055	+65,197	-48,858	114,055	+65,197
	2001-2100	-130,096	841,045	+710,949	-130,096	841,045	+710,949

budget. In addition, the concurrent biofuel-induced reduction in food imports (Figure 14) decreases carbon emissions from the consumption of these imported food products to also compensate for some of the additional carbon emissions resulting from the use of imported biofuels in this region.

International trade can have a dominating effect on the assumed exchange of carbon between land and the atmosphere within a region (**Figures 15** and **16**; see also Figures A17 to A32 in Appendix). For example, biofuels production enhances carbon emissions in Latin America throughout the 21st century in Case 1 if the effects of biofuel exports are not considered (Figure 15), but enhances carbon sequestration during the second half of the 21st century if biofuel exports are considered (Figure 16). The enhanced carbon sequestration is a result of carbon being taken up from the atmosphere, stored in the biofuels produced, and then transported out of the region before it is returned to the atmosphere with the consumption of biofuels. In regions that import biofuels, however, the imported carbon leads to both larger carbon emissions and more fossil fuel abatement when these biofuel emissions are attributed to consumer regions (Figure 16) than when the emissions are attributed to producer regions (Figure 15). The additional carbon emissions from the use of these imported biofuels dominate the land carbon fluxes in many of these consumer regions such that the regional net GHG balance throughout the 21st century is mostly determined by the compensatory effects of carbon emissions and associated fossil fuel abatement from the imported biofuels (e.g., United States of America, European Union, Eastern Europe, India).

While the attribution of biofuel emissions has a large effect on the magnitude of regional fossil fuel abatement and land carbon fluxes, it has little effect on the timing of these net GHG abatement benefits within the regions. The realization of these net GHG abatement benefits, however, does vary by region and management policy. The Australia/New Zealand region experiences early net benefits (the 2020s) of biofuels production whereas these net benefits are not realized until much later in the United States of America (the 2070s). For some regions, the timing of the net GHG abatement benefits of biofuels depends on land-use policy. For example, the net benefits of biofuels for the Rest of the World are realized in the 2040s in Case 2, but not until the 2080s in Case 1.

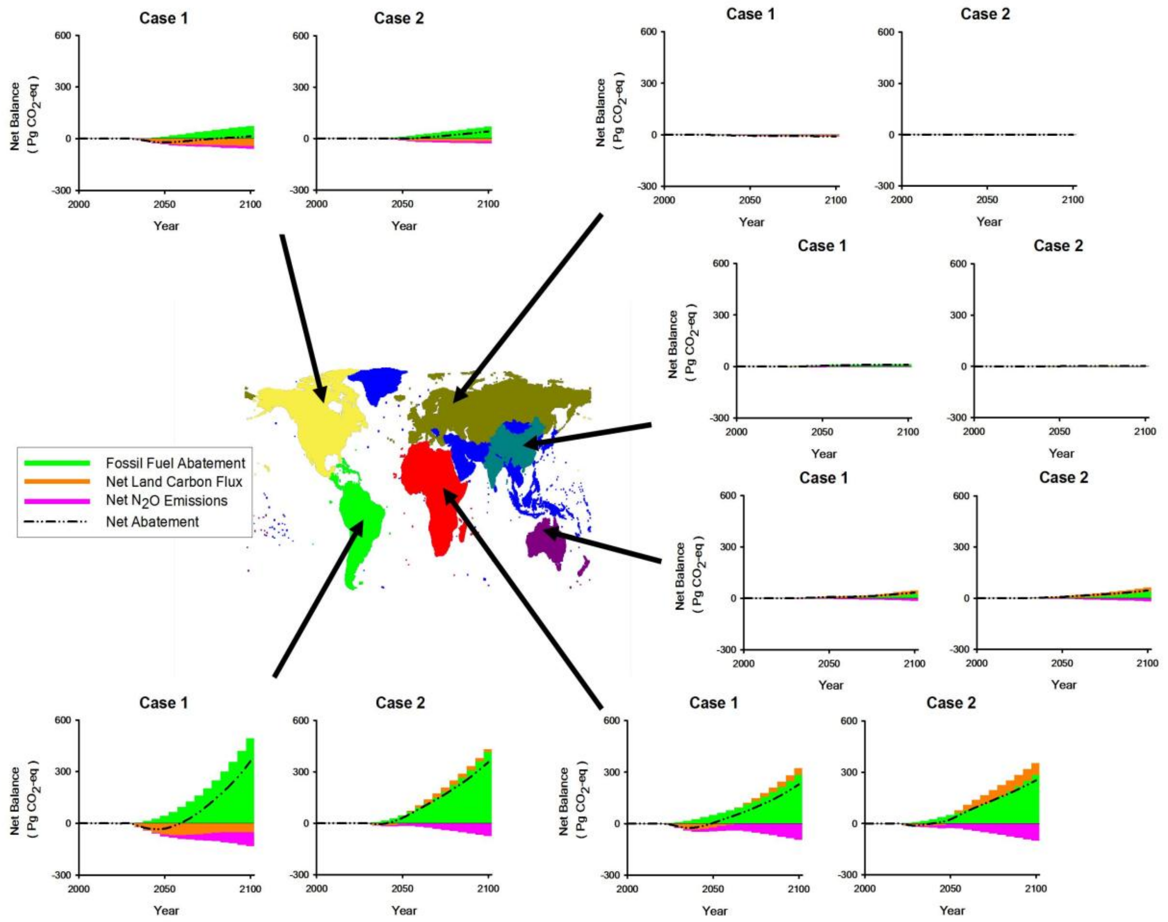

Figure 15. Partitioning of greenhouse gas balance with biofuel emissions and fossil fuel abatements attributed to biofuel producer regions over the 21st century for land-use Case 1 and Case 2 in regions: Africa (reddish brown), Latin America (green), North America (yellow), Europe-Russia (gold), China-India (teal), and Australia-New Zealand (purple). North America contains the EPPA regions of Canada, Mexico and the United States of America. Europe-Russia contains the EPPA regions of the European Union, Eastern Europe and the Former Soviet Union.

4. DISCUSSION

Our analyses suggest that, with nitrogen fertilizer subsidies and future improvements in biofuel crop technology, the terrestrial biosphere will be able to support a global cellulosic biofuels program to help satisfy anthropogenic energy needs over the 21st century. The production of these biofuels, however, will require a large commitment of land resources. We estimate that by 2100, 15-16% of current ice-free land will need to be devoted to the production of cellulosic biofuels with most of these areas located in tropical regions including about one-third of both Africa and Latin America.

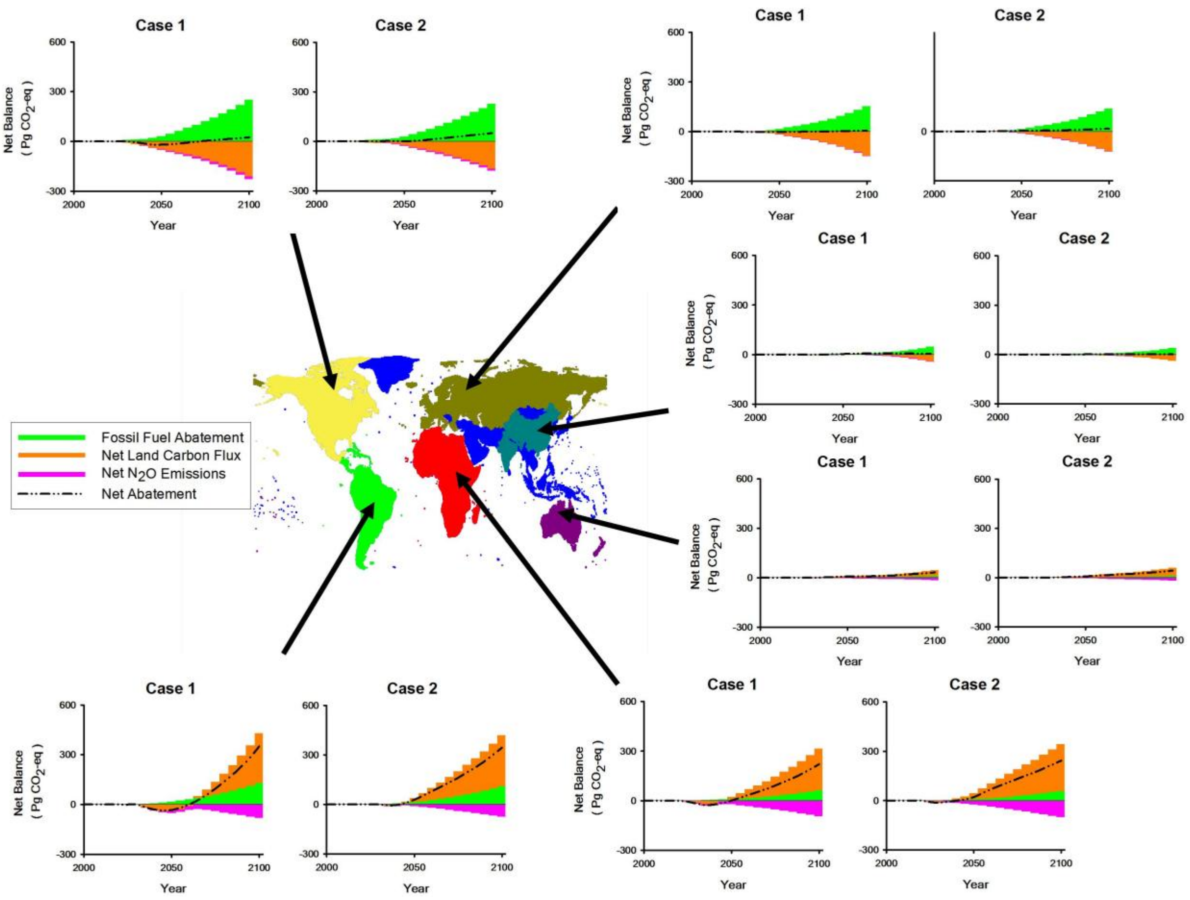

Figure 16. Partitioning of greenhouse gas balance with biofuel emissions and fossil fuel abatements attributed to biofuel consumer regions over the 21st century for land-use Case 1 and Case 2 in regions: Africa (reddish brown), Latin America (green), North America (yellow), Europe-Russia (gold), China-India (teal), and Australia-New Zealand (purple). North America contains the EPPA regions of Canada, Mexico and the United States of America. Europe-Russia contains the EPPA regions of the European Union, Eastern Europe and the Former Soviet Union.

These area estimates are about one-third of those of a recent study (Wise *et al.*, 2009) in which land-use emissions are also not included in an emissions cap, but are two to five times more than that required when land-use emissions are included in an emissions cap (Leemans *et al.*, 1996; Strengers *et al.*, 2004; Wise *et al.*, 2009). The previous studies are based on analyses that have a lower concentration target (450 ppmv CO_2) than the 550 ppmv CO_2 target used in our study and do not account for price-induced intensification of land use (Gurgel *et al.*, 2007) although, similar to our estimates, they do account for future technological improvements in agricultural productivity. Furthermore, the Wise *et al.* (2009) analyses do not explicitly consider concurrent changes in other environmental factors. The Leemans *et al*. (1996) and Strengers *et al*. (2004) studies do consider the effects of other environmental factors on biofuel productivity, but do not consider the potential detrimental effects of ozone pollution on this future productivity.

In an earlier study using EPPA and TEM, Wang (2008) has found that the productivity of biofuel crops decreased by 7% over the 21st century when the effects of other environmental factors are considered under a climate-policy case similar to that used in our study. This decrease occurs even with an assumed 1% increase in biofuel crop productivity due to technological innovation. The reduced productivity meant that 33% more area was required to be devoted to biofuels under changing environmental conditions than under constant environmental conditions.

In our analyses, the productivity of biofuel crops increased by 7-14% from 2022 to 2100 as an assumed 1% technological increase in biofuel crop productivity combined with CO_2 fertilization along with warmer and wetter conditions more than compensated for exposure of these crops to a 18-22% increase in the AOT40 ozone index. However, the productivity of food crops during the same period decreased by 22-24% when exposed to a 79-81% increase in the AOT40 ozone index indicating that ozone pollution is limiting plant productivity in some regions. As Wang (2008) projects a larger percentage of biofuel crops will be located in regions with high ozone concentrations (United States of America, European Union, Former Soviet Union and the Middle East, see Felzer *et al.*, 2005) than our analysis, the differences in biofuels productivity between our studies indicate that ozone pollution may have a large effect on the magnitude and location of future biofuels production.

The projected distribution of biofuel crops in our study has some general similarities, but also some interesting differences, with the distributions projected from earlier studies. In Leemans *et al.* (1996), the largest areas devoted to biofuels production by 2100 also occur in Africa and Latin America when arable lands are not assumed to expand with future climate change in an analysis using the IMAGE 2.1 model. While Latin America accounts for a similar proportion of area devoted to biofuel production (34%) as our study, Africa accounts for a smaller proportion (38%) and China plus C. P. Asia accounts for a larger proportion (12%). In addition, unlike our study where Africa contains most of the land devoted to biofuels production throughout the 21st century, more land is devoted to biofuels production in Latin America (42%) than in Africa

(22%) during the first half of the 21st century in the Leemans *et al.* (1996) study. When arable lands are able to expand with climate change, Leemans *et al.* (1996) project that Africa (16%) and China and C. P. Asia (<1%) becomes less important in producing biofuels and Latin America (34%), the Commonwealth of Independent States (25%), and Canada (14%) become more important by 2100. In a later study using IMAGE 2.2 with the Intergovernmental Panel on Climate Change (IPCC) series of Standardized Reference Emissions Scenarios (SRES), Strengers *et al*. (2004) also find most of the land devoted to biofuels production to be in Africa (19-25%), Latin America (18-25%) and the Former USSR (16-20%) for the A1T, A1B and B1 scenarios. In our analysis, we assumed tundra will always be unsuitable for biofuels production so that the expansion of biofuels production into arctic regions is greatly hindered in our simulations.

The net loss of pastures due to biofuels production observed in our study for the two land-use scenarios is consistent with the results of the Leemans *et al*. (1996) study based on a comparison of areas between biofuels and no biofuel scenarios. The Leemans *et al*. (1996) study, however, also indicates a net increase of area devoted to producing food (both with and without climatic expansion of arable lands) as a result of including biofuels production by 2100 whereas our study indicates the area of food crops depends on the land-use policy being implemented: a net increase in Case 1 and a net decrease in Case 2. Thus, the Leemans *et al*. (1996) study suggests that all of the area required for biofuels must have come from the conversion of natural lands whereas our study indicates that net decreases in area under food crops and pastures can account for 22-58% of the area required for biofuel crops.

While many studies report information on the changes in area devoted to future biofuels production, most have not separated the effects of this biofuels production on carbon emissions from those of other land-use changes. One exception is the study by Leemans *et al*. (1996) that conducted simulations both with biofuels and no biofuels in future land-use change scenarios. The carbon losses associated with the combined direct and indirect biofuel emissions estimated for our Case 1 are similar to the biofuels-induced changes in carbon emissions associated with land-use change (25 Pg C or 92 Pg CO_2-eq) estimated by Leemans *et al*. (1996) over the 21st century. However, in addition to these carbon emissions from land-use change, the Leemans *et al.* (1996) study indicate that the uptake of atmospheric carbon by the terrestrial biosphere will also be reduced by 50 Pg C (183 Pg CO_2-eq) over the same period. Because our estimate of carbon losses already includes the effects of biofuels-induced reduction of carbon sequestration capacity, our estimate of global carbon emissions induced by the production and use of biofuels in Case 1 are only about one-third of that suggested by the Leemans *et al.* (1996) study.

The larger carbon losses in the Leemans *et al*. (1996) study result from a combination of factors. First, Leemans *et al.* (1996) do not consider the potential effects of changes in nitrogen availability on limiting the response of plant productivity to future changes in climate and atmospheric CO_2 (Kicklighter *et al*., 1999; Hungate *et al*., 2003; Thornton *et al*., 2007, 2009; Sokolov *et al*., 2008, Ostle *et al*., 2009; Gerber *et al*., 2010; Zaehle *et al*., 2010) so that they simulate larger carbon accumulation in vegetation with climate change (Sokolov *et al*., 2008). The additional vegetation biomass results in higher carbon emissions when land is converted to biofuels or food production. Besides nitrogen limitations, the Leemans *et al*. (1996) analyses also do not consider any negative effects on plant productivity of elevated tropospheric ozone (Felzer *et al*., 2005, 2007; Wang, 2008), which would also reduce the accumulation of carbon in vegetation and carbon emissions during land conversions. Finally, TEM estimates that carbon can accumulate in soils of some areas used for biofuels and food production with subsidies of optimal fertilizer applications. This carbon sequestration reduces estimates of net carbon emissions resulting from biofuels production and is not considered in the Leemans *et al.* (1996) analysis.

Leemans *et al*. (1996) also indicated that in one of their biofuel scenarios, most of the carbon emissions from land-use change occur in regions that are major exporters of biofuels (Canada, Commonwealth of Independent States, and Latin America) while in the other biofuels scenario, the land-use emissions are more evenly spread across the globe. In our analyses when biofuel emissions are attributed to producer regions, we also see the largest carbon emissions induced by biofuels production coming from the biofuel exporting region of Latin America in Case 1. In the other major biofuel exporting region of Africa in both land-use scenario cases and Latin America in Case 2, however, cultivation of biofuels enhances carbon sequestration in these regions to reduce land-use emissions. As a result, the biofuels importing region of the United States of America has the largest biofuels-induced carbon emissions in Case 2.

While many studies have examined the potential effects of biofuels on carbon emissions, we are unaware of any study that has examined the potential effects of biofuels on nitrous oxide emissions before Melillo *et al.* (2009). As we have shown in this study, the application of nitrogen fertilizers to support the production of cellulosic biofuels can have very large effects on nitrous oxide emissions and these effects may be larger than concurrent effects of biofuels on carbon emissions in many regions. In addition, we find that biofuels-induced land conversion may also have large effects on the contribution of nitrous oxide emissions from natural ecosystems to influence regional greenhouse gas budgets. In our study, the biofuels-induced reduction of natural nitrous oxide emissions had a larger effect on the greenhouse gas balance than the concurrent biofuels-induced reduction of natural carbon sequestration capacity. In other regional studies (Galford *et al*., 2010), however, land conversions have had a larger effect on carbon sequestration capacity than on natural nitrous oxide emissions. In addition, both logging and land conversion have also been found to increase nitrous oxide emissions in some tropical ecosystems (e.g., Luizão *et al*., 1989; Keller *et al*., 2005) rather than decrease emissions, but these enhanced emissions may be ephemeral and may eventually lead to reduced emissions after conversion (Melillo *et al*., 2001). More research is needed to better understand how the responses of nitrous oxide emissions to disturbance, including those associated with biofuels production, may vary over space and time.

In our simulations, we assume an appropriate amount of nitrogen fertilizer will be applied at the appropriate times to support an optimum level of biofuel and food crop productivity. While large advances have been made in precision farming, it may still be difficult to apply the right amount of nitrogen fertilizer at exactly the right time in the future due to both physical and economic factors. Thus, our estimates of the productivity and yield of biofuel and food crops may be too optimistic and result in overestimates of the practical ability of terrestrial ecosystems to provide biofuels. In addition, because of difficulties on applying nitrogen fertilizers at exactly the right time, farmers may apply more nitrogen fertilizers than is necessary to obtain optimal crop production. As a result, N_2O emissions from fertilizer applications may be larger than that estimated from our study.

On the other hand, we also assume that all biofuels and food crops are rain-fed in our analyses and do not consider the potential effects of irrigation on both the productivity of biofuel and food crops or the area required to grow these crops. Currently, only 25% of the areas devoted to food crops across the globe are irrigated, but these areas are responsible for 33% of the global crop and 44% of total cereal production (Portmann *et al.*, 2010). In drier regions of the world, irrigation would increase the productivity of both biofuel and food crops. As a result, less area might need to be devoted to the production of biofuels and lessen the carbon emissions caused by land conversions. However, the application of irrigation requires access to water, either surface or groundwater, and may require considerable time and effort to develop the infrastructure to provide such access. While irrigation may reduce carbon emissions from land conversions, additional nitrogen fertilizers may need to be applied to support the higher optimum productivities associated with irrigated crops and lead to higher N_2O emissions. We did not have the information available to address these issues in this study, but these issues should be examined in future studies to improve our understanding of the impacts of biofuels on carbon and N_2O emissions across the globe.

In our simulations, we assume that 40% of biofuel crops are harvested and that 60% of the crop biomass remains behind as crop residue, some of which becomes incorporated into the soil organic matter. With the enhanced plant productivities associated with optimum fertilizer applications, carbon accumulates in these cropland soils to enhance carbon storage in many regions. One way to reduce the area required to produce biofuels would be to harvest and use a larger proportion of the biofuel crop. However, this would reduce the carbon inputs into the soil and reduce or even eliminate any carbon sequestration estimated by our study and lead to higher net carbon emissions from areas devoted to biofuels production. In addition, the removal of nitrogen inputs associated with crop residue may also require the application of additional amounts of nitrogen fertilizer leading to higher N_2O emissions. The enhanced carbon and N_2O emissions associated with harvesting a larger proportion of a biofuel crop may or may not be less than the GHG emissions associated with land conversion. This issue should also be examined more closely in future studies to determine how to minimize the impacts of biofuels production.

In this study, our primary interest has been to determine whether or not the terrestrial biosphere would have the physical capacity to supply projected global anthropogenic energy needs using cellulosic biofuels in the future in addition to supplying food to future human populations. Our analyses indicate that terrestrial biogeochemistry can indeed support such a global biofuels and food production program although both food and energy security will become much more susceptible to how climate may change in the future. Our analyses, however, did not attempt to account for the disruption that this program might impose on various social systems across the globe (e.g. land tenure) and how resistance to the implementation of such an ambitious program may influence the actual benefits realized. Serious consideration should be give to these issues in the future.

5. CONCLUSION

Our study indicates that the terrestrial biosphere has the capacity to support the production of biofuels to help meet future global energy needs, but this production will require the use of extensive areas of both managed and natural land and lead to increased emissions of greenhouse gases. We find that biofuel expansion leads to additional emissions of carbon from land use in the short run, but over the century, we find that additional biofuel production actually increases carbon storage compared to scenarios without biofuels, in strong contrast to previous literature which has mainly emphasized biofuel-driven land-use change as a net source of emissions. We get this result because we find that the most significant change in land use to make way for biofuels is intensification of production on land that is already used for crops and pasture. More intense management of former pasture, especially the addition of fertilizer, leads to increased carbon storage over time that more than compensates for losses from deforestation. The extent of carbon savings depends on how we model land-use decisions with regard to willingness to convert natural lands, and this differs from previous work. We estimate responses both on the extensive margin (i.e., more natural lands converted, 10.7 million km^2 in Case 1 and 6.9 million km^2 in Case 2) and on the intensive margin (i.e., more intense use of existing crop and pasture land, 13.3 million km^2 for Case1 and 14.8 million km^2 for Case 2). Because there can be a significant cost to converting forests to croplands, there we find much more change on the intensive margin. Previous work also has not considered the possible implications for nitrous oxide emissions associated with expanded production of biofuels. Here, we find a substantial GHG penalty because nitrogen fertilizers would need to be added indefinitely to maintain cropland productivity. However, because natural systems and tropical forests in particular, are also a source of nitrous oxide, we find that reducing the extent of these forests somewhat offsets the increased nitrous oxide emissions from more croplands by 54.0 Pg CO_2-eq in Case 1 and 26.0 Pg CO_2-eq in Case 2 over the 21st century. We find that the addition of biofuels to world energy supplies has significant effects on international trade. In general, we find that tropical regions, particularly Africa and Latin America, would become major net exporters of biofuels to the rest of the world over the 21st century. We also generally find somewhat less trade in food, except for North America, which imports much of the biofuel is uses and increases its exports of conventional agricultural goods by 13.2 Pg CO_2-eq in Case 1 and 11.8 Pg CO_2-eq in Case 2. A significant conclusion is that whether and to what extent biofuels are carbon-saving or carbon-emitting depends on the time scale of interest and whether room for biofuel production is made through intensification of production on existing land, especially pasture and grazing land, or at the extensive margin by converting largely natural lands with a significant stock of terrestrial carbon. Policy incentives to further discourage conversion of high carbon stock land (e.g., tropical forests) would improve the GHG balance of biofuels.

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6. REFERENCES

Babiker, M., J. M. Reilly, M. Mayer, R. S. Eckaus, I. Sue Wing and R. Hyman, 2001: The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Revisions, Sensitivities, and Comparison of Results. MIT JPSPGC *Report 71*, February, 94 p. (http://mit.edu/globalchange/www/MITJPSPGC_Rpt71.pdf).

Bowden, R. D., G. Rullo, G. R. Stevens and P. A. Steudler, 2000: Soil fluxes of carbon dioxide, nitrous oxide, and methane at a productive temperate deciduous forest. *Journal of Environmental Quality,* **29(1)**: 268-276.

California Environmental Protection Agency (EPA), 2009: *Proposed Regulation to Implement the Low Carbon Fuel Standard, Volume I (Release Date: March 5, 2009)*; (http://www.arb.ca.gov/fuels/lcfs/030409lcfs_isor_vol1.pdf).

Chapin, F.S., III, G.M. Woodwell, J.T. Randerson, E.B. Rastetter, G.M. Lovett, D.D. Baldocchi, D.A. Clark, M.E. Harmon, D.S. Schimel, R. Valentini, C. Wirth, J.D. Aber, J.J. Cole, A. Giblin, M.L. Goulden, J.W. Harden, M. Heimann, R.W. Howarth, P.A. Matson, A.D. McGuire, J.M. Melillo, H.A. Mooney, J.C. Neff, R.A. Houghton, M.L. Pace, M.G. Ryan, S.W. Running, O.E. Sala, W.H. Schlesinger and E.-D. Schulze, 2006: Reconciling carbon-cycle concepts, terminology, and methods. *Ecosystems,* **9:** 1041-1050 (doi: 10.1007/s10021-005-0105-7).

Crutzen, P. J., A. R. Mosier, K. A. Smith and W. Winiwarter, 2008: N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys.,* **8**: 389-395.

Davidson, E. A., 2009: The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience,* **2**: 659-662 (doi: 10.1038/NGEO608).

Davidson, E. A., M. Keller, H. E. Erickson, L. V. Verchot and E. Veldkamp, 2000: Testing a conceptual model of soil emissions of nitrous and nitric oxide. *BioScience,* **50(8)**: 667-680.

Denman, K. L., G. Brasseur, A. Chidthaisong, P. Ciais, P. M. Cox, R. E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S. Ramachandran, P. L. da Silva Dias, S. C. Wofsy and X. Zhang, 2007: Couplings between changes in the climate system and biogeochemistry. pp. 499-587. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom.

Fargione, J., J. Hill, D. Tilman, S. Polasky and P. Hawthorne, 2008: Land clearing and the biofuel carbon debt. *Science*, **319**: 1235-1238 (doi: 10.1126/science.1152747).

Farrell, A. E., R. J. Plevin, B. T. Turner, A. D. Jones, M. O'Hare and D. M. Kammen, 2006: Ethanol can contribute to energy and environmental goals. *Science*, **311**: 506-508.

Felzer, B., D. Kicklighter, J. Melillo, C. Wang, Q. Zhuang and R. Prinn, 2004: Effects of ozone on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model. *Tellus*, **56B**: 230-248.

Felzer, B., J. Reilly, J. Melillo, D. Kicklighter, M. Sarofim, C. Wang, R. Prinn and Q. Zhuang, 2005: Future effects of ozone on carbon sequestration and climate change policy using a global biogeochemical model. *Climatic Change*, **73**: 345-373 (doi: 10.1007/s10584-005-6776-4).

Felzer, B. S., T. Cronin, J. M. Reilly, J. M. Melillo and X. Wang. 2007: Impacts of ozone on trees and crops. *Comptes Rendus Geoscience,* **339:** 784-798.

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D. W. Fahey, J. Haywood, J. Lean, D. C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in atmospheric constituents and in radiative forcing. pp. 129-234. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom.

Friedlingstein, P., P. Cox, R. Betts, L. Bopp, W. von Bloh, V. Brovkin, P. Cadule, S. Doney, M. Eby, I. Fung, G. Bala, J. John, C. Jones, F. Joos, T. Kato, M. Kawamiya, W. Knorr, K. Lindsay, H. D. Matthews, T. Raddatz, P. Rayner, C. Reick, E. Roeckner, K.-G. Schnitzler, R. Schnur, K. Strassmann, A. J. Weaver, C. Yoshikawa, and N. Zeng, 2006: Climate-carbon cycle feedback analysis: results from the C^4MIP model intercomparison. *Journal of Climate,* **19:** 3337-3353.

Galford, G. L., J. M. Melillo, D. W. Kicklighter, T. W. Cronin, C. E. P. Cerri, J. F. Mustard, and C. C. Cerri, 2010: Greenhouse gas emissions from alternative futures of deforestation and agricultural management in the southern Amazon. *Proceedings of the National Academy of Sciences*, **107:** 19,649-19,654, doi: 10.1073/pnas.1000780107.

Garcia-Montiel, D. C., J. M. Melillo, P. A. Steudler, C. C. Cerri, and M. C. Piccolo, 2003: Carbon limitations to nitrous oxide emissions in a humid tropical forest of the Brazilian Amazon. *Biology and Fertility of Soils*, **38:** 267-272, doi: 10.1007/s00374-003-0637-y.

Garcia-Montiel, D. C., J. M. Melillo, P. A. Steudler, H. Tian, C. Neill, D. W. Kicklighter, B. Feigl, M. Piccolo, and C. C. Cerri, 2004: Emissions of N_2O and CO_2 from terra firme forests in Rondônia, Brazil. *Ecological Applications*, **14(4) Supplement**: S214-S220.

Garcia-Montiel, D. C., P. A. Steudler, M. C. Piccolo, J. M. Melillo, C. Neill and C. C. Cerri, 2001: Controls on soil nitrogen oxide emissions from forest and pastures in the Brazilian Amazon. *Global Biogeochemical Cycles*, **15(4)**: 1021-1030.

Gerber, S., L. O. Hedin, M. Oppenheimer, S. W. Pacala and E. Shevliakova, 2010: Nitrogen cycling and feedbacks in a global dynamic land model. *Global Biogeochemical Cycles*, **24**, GB1001 (doi: 10.1029/2008GB003336).

Goodroad, L. L., and D. R. Keeney, 1984: Nitrous oxide emission from forest, marsh, and prairie ecosystems. *Journal of Environmental Quality*, **13(3)**: 448-452.

Gurgel, A., J. Reilly and S. Paltsev, 2007: Potential land use implications of a global biofuels industry. *J. Agric. Food Industrial Org*., **5(2)**: 1-34.

Hayes, D. J., A. D. McGuire, D. W. Kicklighter, K. R. Gurney, T. J. Burnside, and J. M. Melillo, 2011: Is the northern high latitude land-based CO_2 sink weakening? *Global Biogeochemical Cycles*, 25: GB3018 (doi: 10.1029/2010GB003813).

Hungate, B. A., J. S. Dukes, M. R. Shaw, Y. Luo and C. B. Field, 2003: Nitrogen and climate change. *Science*, **302**: 1512-1513.

Keller, M., R. Varner, J. D. Dias, H. Silva, P. Crill, R. Cosme de Oliveira Jr. and G. P. Asner, 2005: Soil-atmosphere exchange of nitrous oxide, nitric oxide, methane, and carbon dioxide in logged and undisturbed forest in the Tapajos National Forest, Brazil. *Earth Interactions*, **9(Paper 23)**, 28 p.

Kicklighter, D. W., M. Bruno, S. Dönges, G. Esser, M. Heimann, J. Helfrich, F. Ift, F. Joos, J. Kaduk, G. H. Kohlmaier, A. D. McGuire, J. M. Melillo, R. Meyer, B. Moore III, A. Nadler, I. C. Prentice, W. Sauf, A. L. Schloss, S. Sitch, U. Wittenberg and G. Würth, 1999: A first-order analysis of the potential role of CO_2 fertilization to affect the global carbon budget: A comparison study of four terrestrial biosphere models. *Tellus*, **51B:** 343-366.

Kiese, R., and K. Butterbach-Bahl, 2002: N_2O and CO_2 emissions from three different tropical forest sites in the wet tropics of Queensland, Australia. *Soil Biology and Biochemistry*, **34**: 975-987.

Koehler, B., M. D. Corre, E. Veldkamp, H. Wullaert and S. J. Wright, 2009: Immediate and long-term nitrogen oxide emissions from tropical forest soils exposed to elevated nitrogen input. *Global Change Biology*, **15**: 2049-2066 (doi: 10.1111/j.1365-2486.2008.01826.x)

Leemans, R., A. van Amstel, C. Battjes, E. Kreileman, and S Toet (1996) The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source. *Global Environ. Change*, **6:** 335-357.

Luizão, F., P. Matson, G. Livingston, R. Luizão and P. Vitousek, 1989: Nitrous oxide flux following tropical land clearing. *Global Biogeochemical Cycles*, **3(3)**: 281-285.

Matson, P. A., C. Volkmann, K. Coppinger and W. A. Reiners, 1991: Annual nitrous oxide flux and soil nitrogen characteristics in sagebrush steppe ecosystems. *Biogeochemistry*, **14**: 1-12.

McGuire, A. D., D. J. Hayes, D. W. Kicklighter, M. Manizza, Q. Zhuang, M. Chen, M. J. Follows, K. R. Gurney, J. W. McClelland, J. M. Melillo, B. J. Peterson, and R. G. Prinn, 2010: An analysis of the carbon balance of the Arctic Basin from 1997 to 2006. *Tellus,* **62B**: 455-474 (doi: 10.1111/j.1600-0889.2010.00497.x).

McGuire, A. D., J. M. Melillo, D. W. Kicklighter, Y. Pan, X. Xiao, J. Helfrich, B. Moore III, C. J. Vorosmarty, and A. L. Schloss, 1997: Equilibrium responses of global net primary production and carbon storage to doubled atmospheric carbon dioxide: Sensitivity to changes in vegetation nitrogen concentration. *Global Biogeochemical Cycles*, **11:** 173-189.

McGuire, A. D., S. Sitch, J. S. Clein, R. Dargaville, G. Esser, J. Foley, M. Heimann, F. Joos, J. Kaplan, D. W. Kicklighter, R. A. Meier, J. M. Melillo, B. Moore III, I. C. Prentice, N. Ramankutty, T. Reichenau, A. Schloss, H. Tian, L. J. Williams and U. Wittenberg, 2001: Carbon balance of the terrestrial biosphere in the twentieth century: analyses of CO_2, climate and land-use effects with four process-based ecosystem models. *Global Biogeochemical Cycles*, **15:** 183-206.

Melillo, J. M., A. D. McGuire, D. W. Kicklighter, B. Moore, C. J. Vorosmarty and A. L. Schloss, 1993: Global climate change and terrestrial net primary production. *Nature*, **363**: 234-240.

Melillo, J. M., J. M. Reilly, D. W. Kicklighter, A. C. Gurgel, T. W. Cronin, S. Paltsev, B. S. Felzer, X. Wang, A. P. Sokolov and C. A. Schlosser, 2009: Indirect emissions from biofuels: how important? *Science*, **326**: 1397-1399 (doi: 10.1126/science.1180251).

Melillo, J. M., P. A. Steudler, B. J. Feigl, C. Neill, D. Garcia, M. C. Piccolo, C. C. Cerri and H. Tian, 2001: Nitrous oxide emissions from forests and pastures of various ages in the Brazilian Amazon. *Journal of Geophysical Research*, **106(D24)**: 34,179-34,188.

Neill, C., P. A. Steudler, D. C. Garcia-Montiel, J. M. Melillo, B. J. Feigl, M. C. Piccolo and C. C. Cerri, 2005: Rates and controls of nitrous oxide and nitric oxide emissions following conversion of forest to pasture in Rondônia. *Nutrient Cycling in Agroecosystems*, **71(1)**: 1-15 (doi: 10.1007/s10705-004-0378-9).

Ostle, N. J., P. Smith, R. Fisher, F. I. Woodward, J. B. Fisher, J. U. Smith, D. Galbraith, P. Levy, P. Meir, N. P. McNamara and R. D. Bardgett, 2009: Integrating plant-soil interactions into global carbon cycle models. *Journal of Ecology*, **97**: 851-863 (doi: 10.1111/j.1365-2745.2009.01547.x)

Pacala, S., and R. Socolow, 2004: Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*, **305**: 968-972.

Paltsev, S., J. Reilly, H. Jacoby, A. Gurgel, G. Metcalf, A. Sokolov and J. Holak, 2008: Assessment of US GHG cap and trade proposals. *Climate Policy*, **8**(4): 395-420; MIT Joint Program *Reprint 2008-16;* (http://globalchange.mit.edu/files/document/MITJPSPGC_Reprint08-16.pdf)..

Paltsev, S., J. Reilly, H. Jacoby, R. Eckaus, J. McFarland and M. Babiker, 2005: The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4 MIT JPSPGC *Report 125*, August, 72 p. (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt125.pdf).

Pihlatie, M., J. Pumpanen, J. Rinne, H. Ilvesniemi, A. Simojoki, P. Hari and T. Vesala, 2007: Gas concentration driven fluxes of nitrous oxide and carbon dioxide in boreal forest soil. *Tellus*, **59B**: 458-469 (doi: 10.1111/j.1600-0889.2007.00278.x).

Plattner, G.-K., R. Knutti, F. Joos, T. F. Stocker, W. von Bloh, V. Brovkin, D. Cameron, E. Driesschaert, S. Dutkiewicz, M. Eby, N. R. Edwards, T. Fichefet, J. C. Hargreaves, C. D.

Jones, M. F. Loutre, H. D. Matthews, A. Mouchet, S. A. Müller, S. Nawrath, A. Price, A. Sokolov, K. M. Strassmann, and A. J. Weaver, 2008: Long-term climate commitments projected with climate-carbon cycle models. *Journal of Climate*, **21:** 2721-2751 (doi: 10.1175/2007JCLI1905.1).

Portmann, F. T., S. Siebert, and P. Döll, 2010: MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, **24**, GB1011 (doi: 10.1029/2008GB003435).

Reilly, J., J. Melillo, Y. Cai, D. Kicklighter, A. Gurgel, S. Paltsev, T. Cronin, A. Sokolov, and A. Schlosser, 2011: Using land to mitigate climate change: hitting the target, recognizing the tradeoffs. *Environmental Science and Technology* (*in review*).

Sanchez, P. A., 2002: Soil fertility and hunger in Africa. *Science,* **295:** 2019-2020 (doi: 10.1126/science.1065256*).*

Schlosser C. A., D. Kicklighter and A. P. Sokolov, 2007: A Land Model System for Integrated Global Change Assessments. MIT JPSPGC *Report 147*, May, 58p. (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt147.pdf).

Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes and T.-H. Yu, 2008: Use of U. S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science,* **319**: 1238-1240 (doi: 10.1126/science.1151861).

Serca, D., R. Delmas, C. Jambert, and L. Labroue, 1994: Emissions of nitrogen oxides from equatorial rain forest in central Africa:origin and regulation of NO emission from soils. *Tellus*, **46B**: 243-254.

Sokolov, A. P., D. W. Kicklighter, J. M. Melillo, B. S. Felzer, C. A. Schlosser and T. W. Cronin, 2008: Consequences of considering carbon-nitrogen interactions on the feedbacks between climate and the terrestrial carbon cycle. *Journal of Climate*, **21**: 3776-3796 (doi: 10.1175/2008JCLI2038.1).

Sokolov, A. P., P. H. Stone, C. E. Forest, R. Prinn, M. C. Sarofim, M. Webster, S. Paltsev, C. A. Schlosser, D. Kicklighter, S. Dutkiewicz, J. Reilly, C. Wang, B. Felzer, J. M. Melillo and H. D. Jacoby, 2009: Probabilistic forecast for twenty-first-century climate based on uncertainties in emissions (without policy) and climate parameters. *Journal of Climate,* **22**: 5175-5204 (doi: 10.1175/2009JCLI2863.1).

Strengers, B., R. Leemans, B. Eickhout, B. de Vries, and L. Bouwman, 2004: The land-use projections and resulting emissions in the IPCC SRES scenarios as simulated by the IMAGE 2.2 model. *GeoJournal* **61:** 381-393.

Thornton, P. E., J.-F. Lamarque, N. A. Rosenbloom and N. M. Mahowald, 2007: Influence of carbon-nitrogen cycle coupling on land model response to CO_2 fertilization and climate variability. *Global Biogeochemical Cycles,* **21**, GB4018 (doi: 10.1029/2006GB002868).

Thornton, P. E., S. C. Doney, K. Lindsay, J. K. Moore, N. Mahowald, J. T. Randerson, I. Fung, J.-F. Lamarque, J. J.Feddema and Y.-H. Lee, 2009: Carbon-nitrogen interactions regulate climate-carbon cycle feedbacks: results from an atmosphere-ocean general circulation model. *Biogeosciences,* **6**: 2099-2120.

Tian, H., J. M. Melillo, D. W. Kicklighter, A. D. McGuire and J. Helfrich, 1999: The sensitivity of terrestrial carbon storage to historical climate variability and atmospheric CO_2 in the United States. *Tellus*, **51B:** 414-452.

Tian, H., J. M. Melillo, D. W. Kicklighter, S. Pan, J. Liu, A. D. McGuire and B. Moore III, 2003: Regional carbon dynamics in monsoon Asia and its implications for the global carbon cycle. *Global and Planetary Change*, **37:** 201-217 (doi: 10.1016/S0921-8181(02)00205-9).

van Minnen, J. G., B. J. Strengers, B. Eickhout, R. J. Swart, and R. Leemans, 2008: Quantifying the effectiveness of climate change mitigation through forest plantations and carbon sequestration with an integrated land-use model. *Carbon Balance and Management*, **3**:3, 20 p. (doi: 10.1186/1750-0680-3-3).

Wang, X., 2008: *Impacts of Greenhouse Gas Mitigation Policies on Agricultural Land*, Doctoral Thesis, Massachusetts Institute of Technology (http://globalchange.mit.edu/files/document/Wang_PhD_08.pdf).

Wise, M. K. Calvin, A. Thomson, L. Clarke, B. Bond-Lamberty, R. Sands, S. J. Smith, A. Janetos and J. Edmonds, 2009: Implications of limiting CO_2 concentrations for land use and energy. *Science*, **324**: 1183-1186 (doi: 10.1126/science.1168475).

Xu, X., H. Tian and D. Hui, 2008: Convergence in the relationship of CO_2 and N_2O exchanges between soil and atmosphere within terrestrial ecosystems. *Global Change Biology*, **14**: 1651-1660 (doi: 10.1111/j.1365-2486.2008.01595.x).

Zaehle, S., P. Friedlingstein and A. D. Friend, 2010: Terrestrial nitrogen feedbacks may accelerate future climate change. *Geophysical Research Letters*, **37**, L01401 (doi: 10.1029/2009GL041345).

APPENDIX

As noted in the main text, the projected biofuel-induced changes in land cover, land carbon fluxes, nitrous oxide (N_2O) emissions and net greenhouse gas (GHG) budgets are much larger in tropical regions than in extra-tropical regions. As a result, it is difficult to deduce these temporal changes in the extra-tropical regions in the figures of the main text, which are scaled to the magnitude of changes in tropical regions. To better appreciate the spatial and temporal variations in the influence of biofuels on land cover, land carbon fluxes, N_2O emissions and regional GHG budgets, we have included figures in the Appendix that are comparable to those used in the main text for each of the sixteen EPPA regions and scaled to the magnitude of changes observed in those regions. In **Figures A1 to A16**, we compare projected land-use change characteristics between the Case 1 and Case 2 land-use scenarios for each of the EPPA regions. These characteristics include (a) changes in land cover in the no-biofuels scenario; (b) changes in land cover in the biofuels scenario; (c) changes in managed land co-opted or displaced by biofuels production; (d) changes in the areas of natural lands from land conversions for biofuels or displaced managed lands; and (e) changes in land carbon fluxes resulting from direct and indirect effects of cellulosic biofuels production. As in the main text, the total area of natural lands converted by biofuels production in (d) corresponds to the area of “Residual Biofuel” in (c).

In **Figures A17 to A32**, we compare additional projected land-use change characteristics between the Case 1 and Case 2 land-use scenarios for each of the EPPA regions. These characteristics include (a) changes in N_2O emissions resulting from direct and indirect effects of cellulosic biofuels production; (b) changes in net GHG fluxes resulting from direct and indirect effects of cellulosic biofuels production; (c) changes in net GHG balance when biofuel emissions and associated fossil fuel abatement are attributed to producer regions; and (d) changes in net GHG balance when biofuel emissions and associated fossil fuel abatement are attributed to consumer regions.

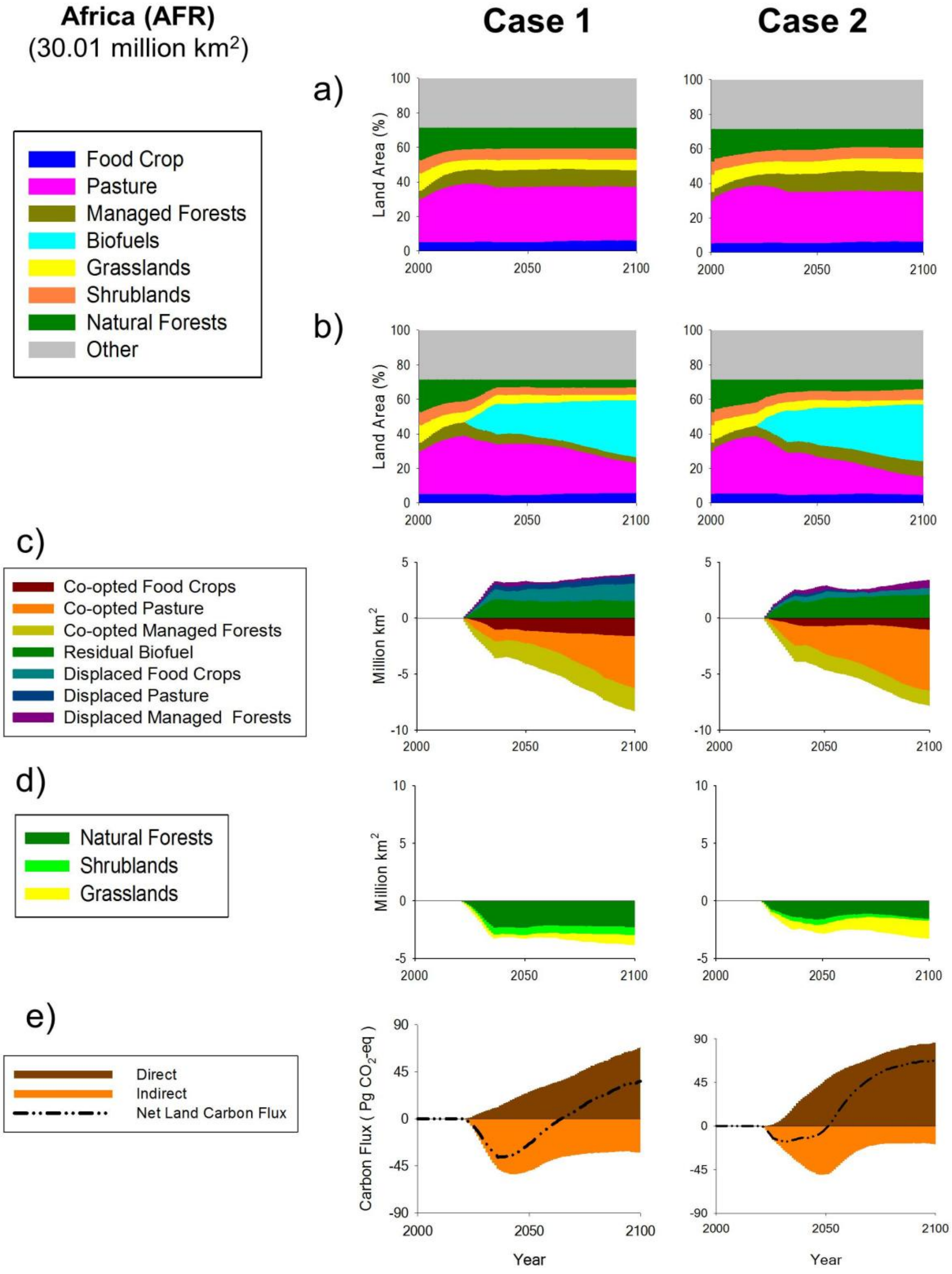


Figure A1. Comparison of temporal variations in land-use characteristics in Africa (AFR) between the Case 1 and Case 2 land-use scenarios.

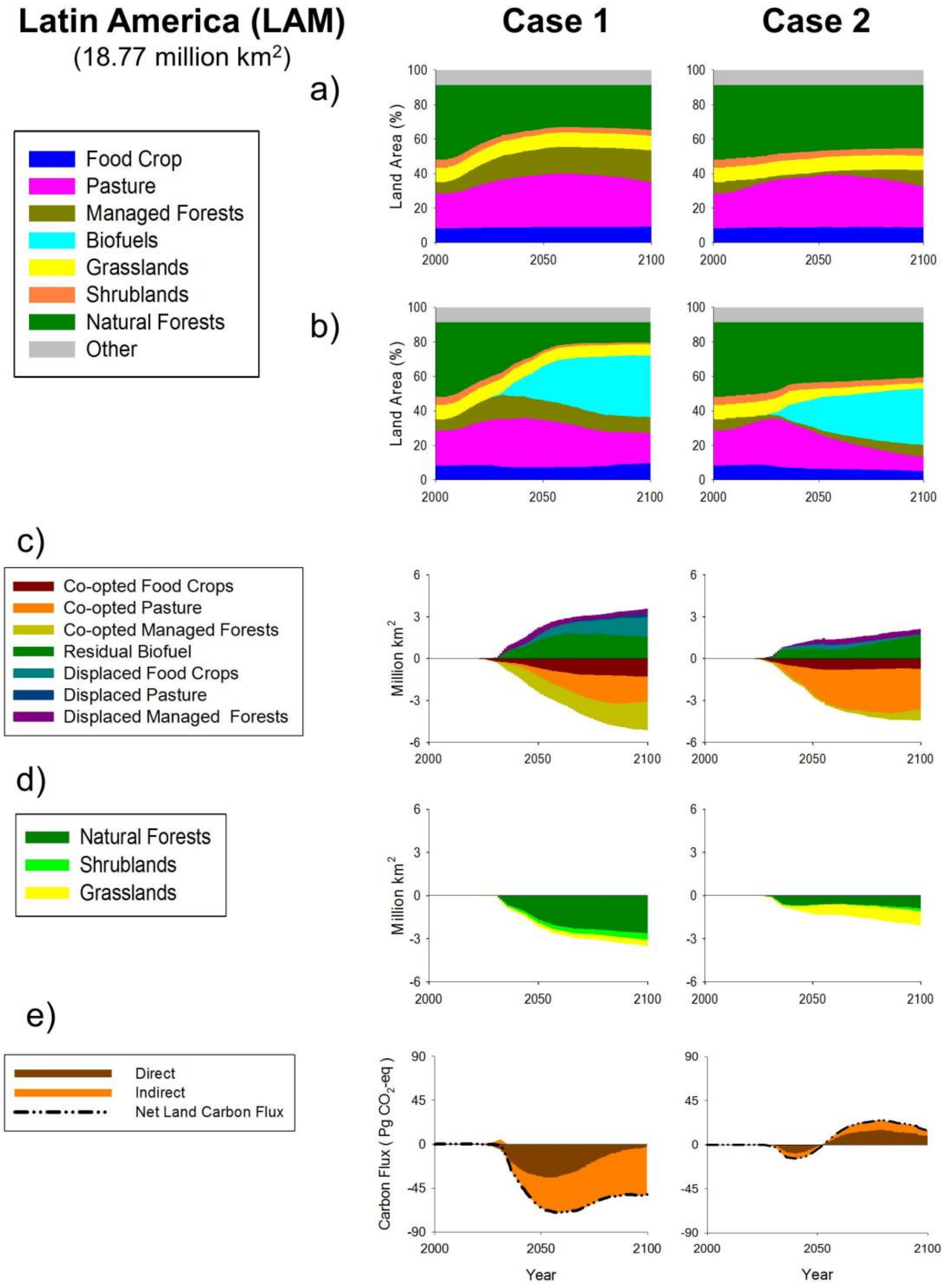


Figure A2. Comparison of temporal variations in land-use characteristics in Latin America (LAM) between the Case 1 and Case 2 land-use scenarios.

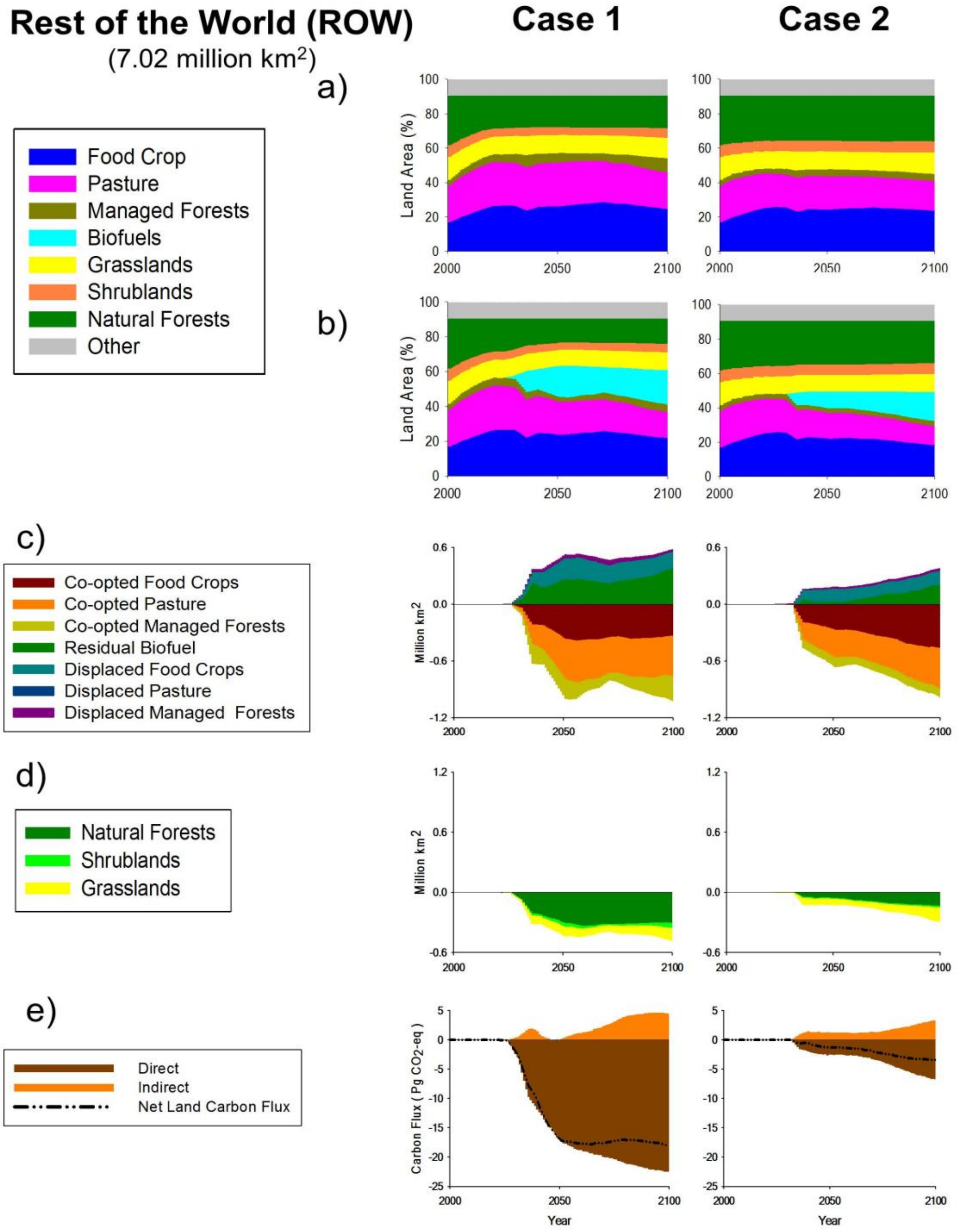


Figure A3. Comparison of temporal variations in land-use characteristics in the Rest of the World (ROW) between the Case 1 and Case 2 land-use scenarios.

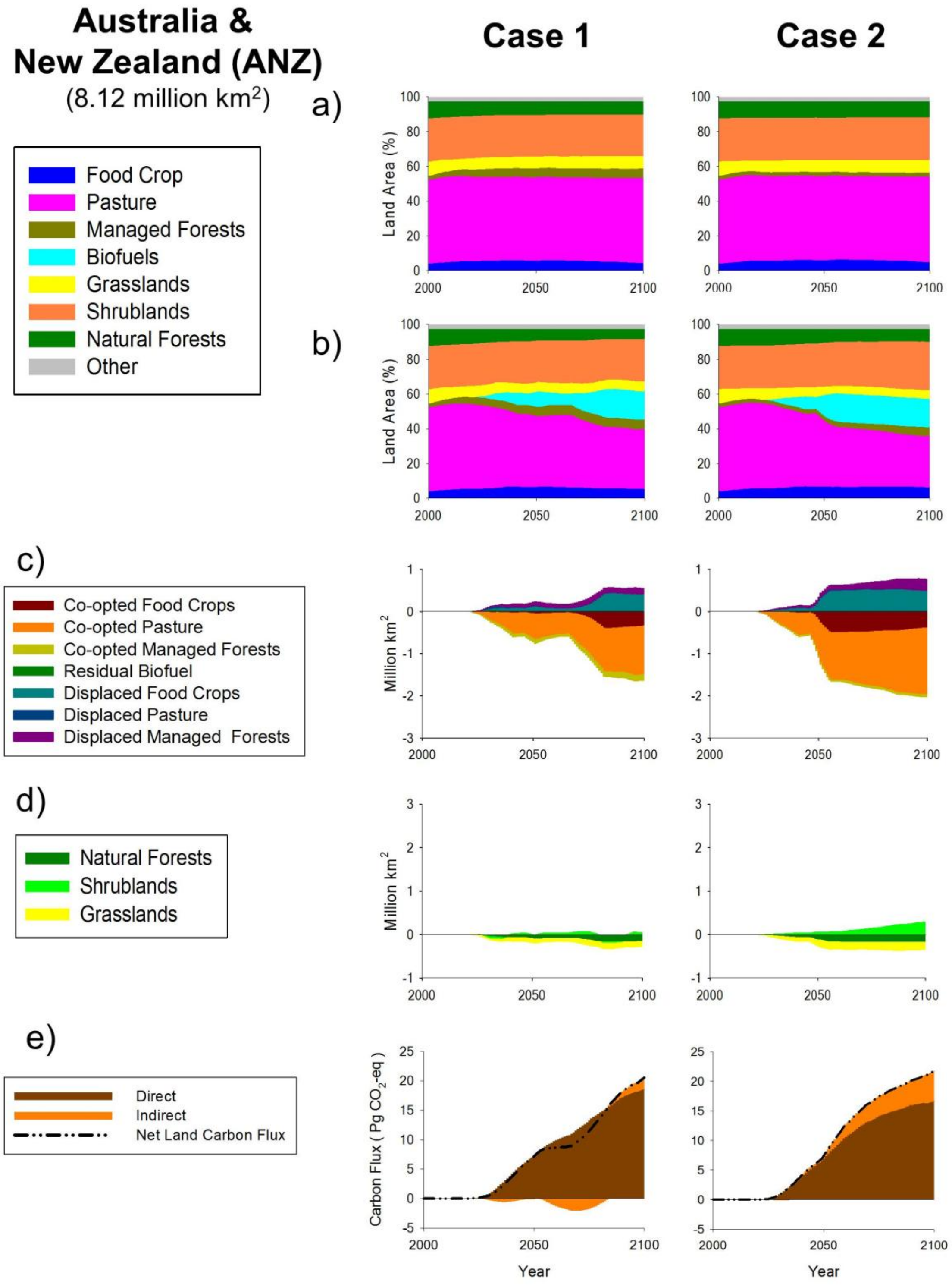


Figure A4. Comparison of temporal variations in land-use characteristics in Australia/New Zealand (ANZ) between the Case 1 and Case 2 land-use scenarios.

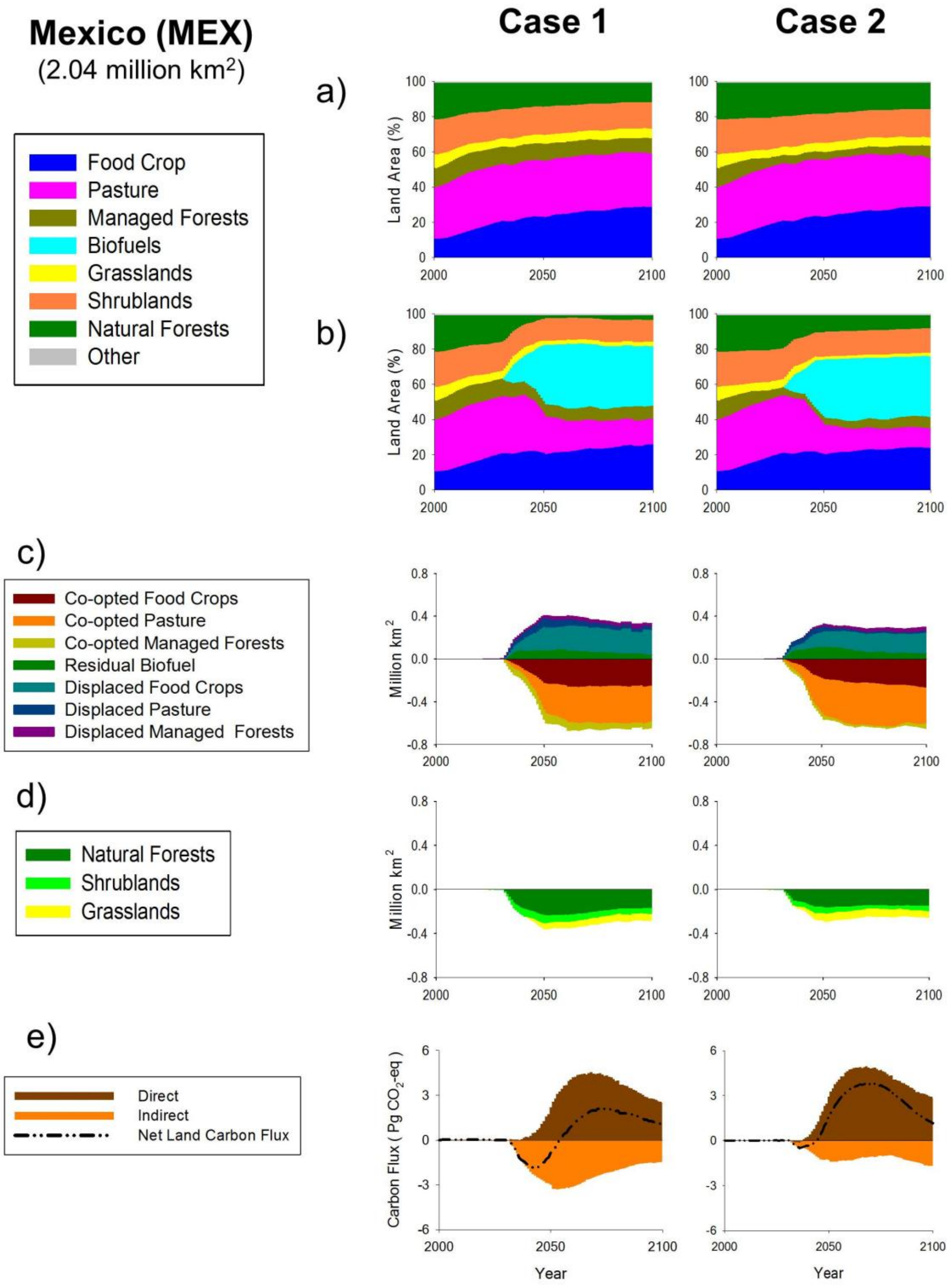


Figure A5. Comparison of temporal variations in land-use characteristics in Mexico (MEX) between the Case 1 and Case 2 land-use scenarios.

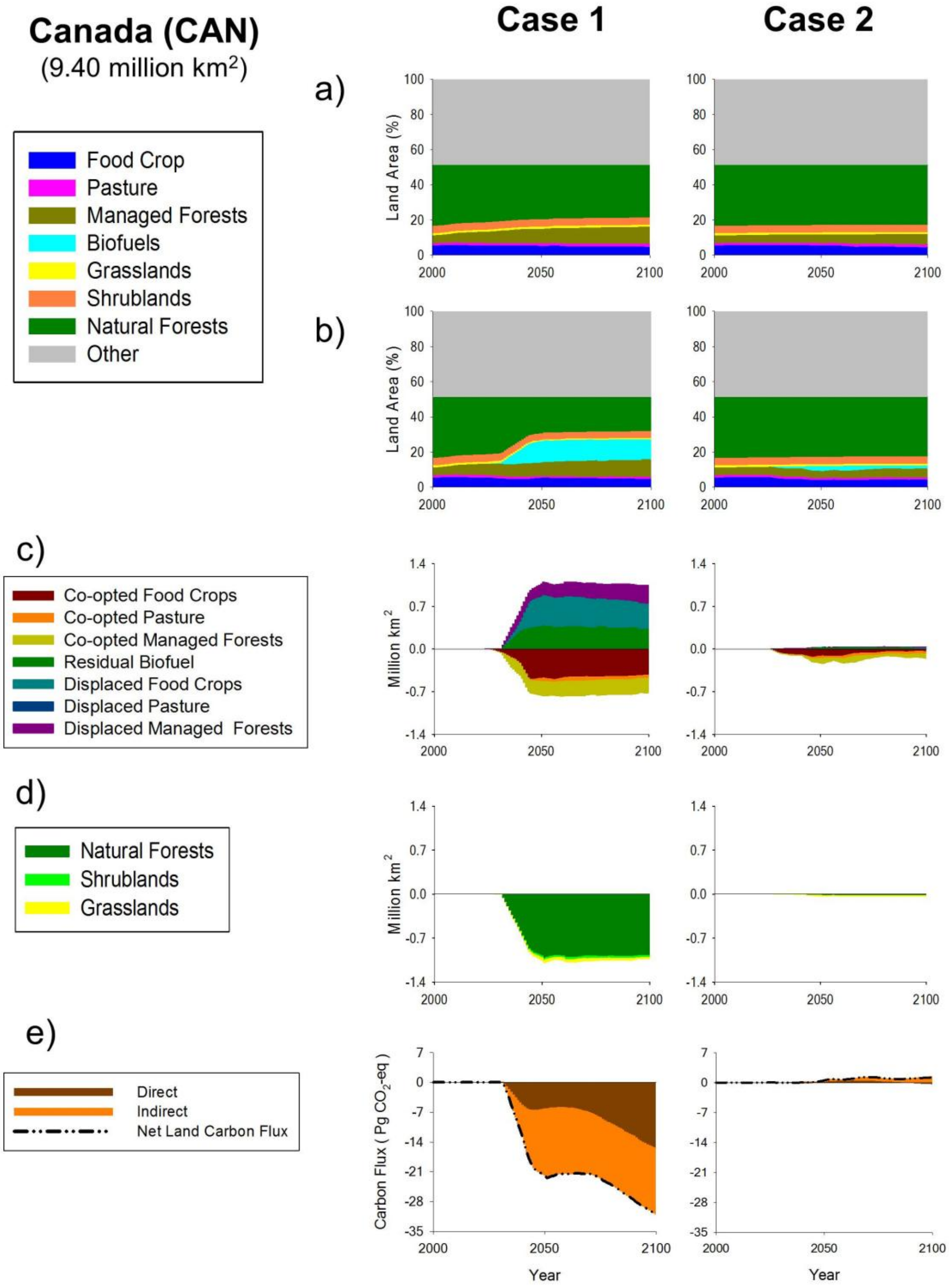


Figure A6. Comparison of temporal variations in land-use characteristics in Canada (CAN) between the Case 1 and Case 2 land-use scenarios.

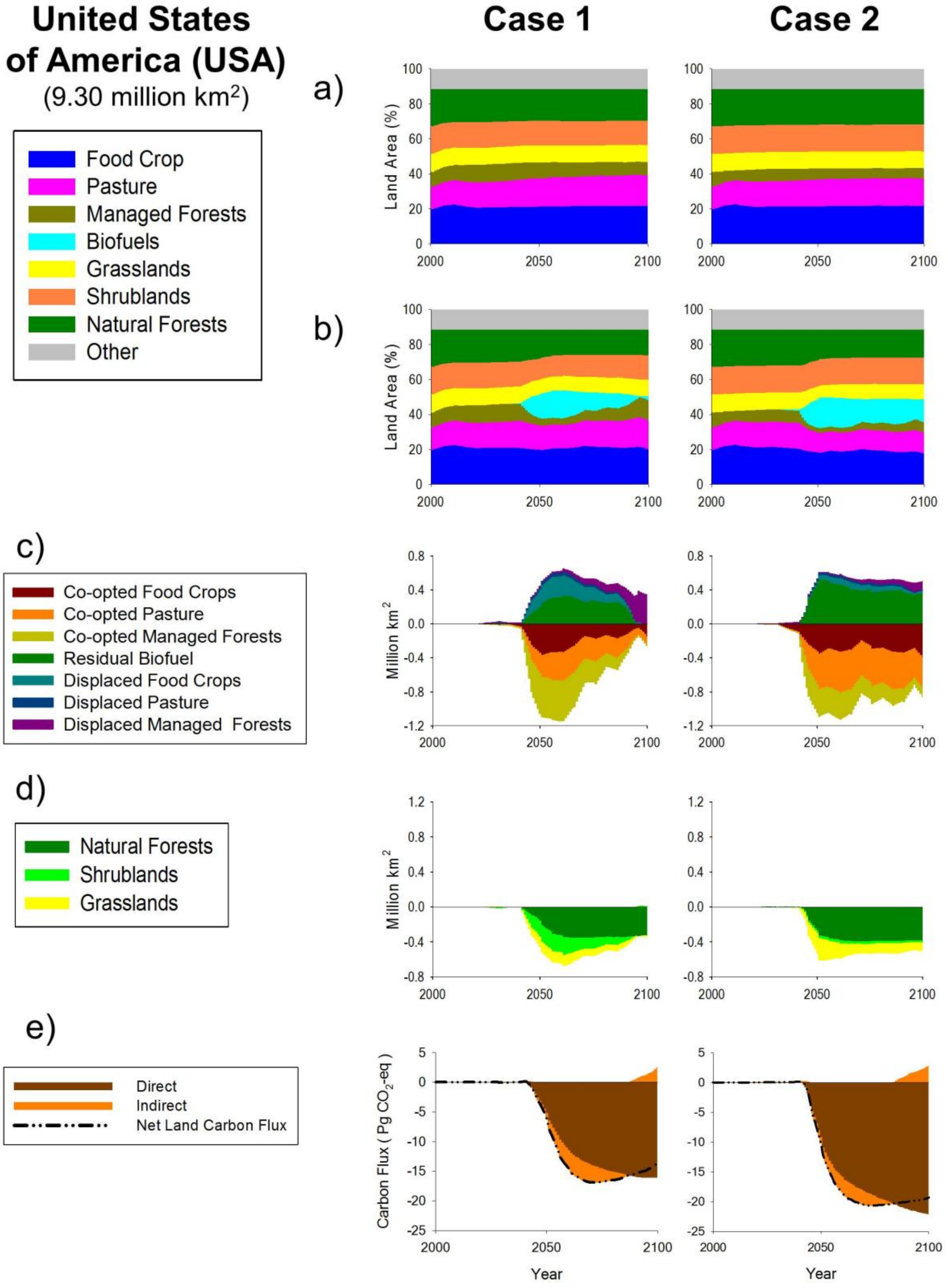


Figure A7. Comparison of temporal variations in land-use characteristics in the United States of America (USA) between the Case 1 and Case 2 land-use scenarios.

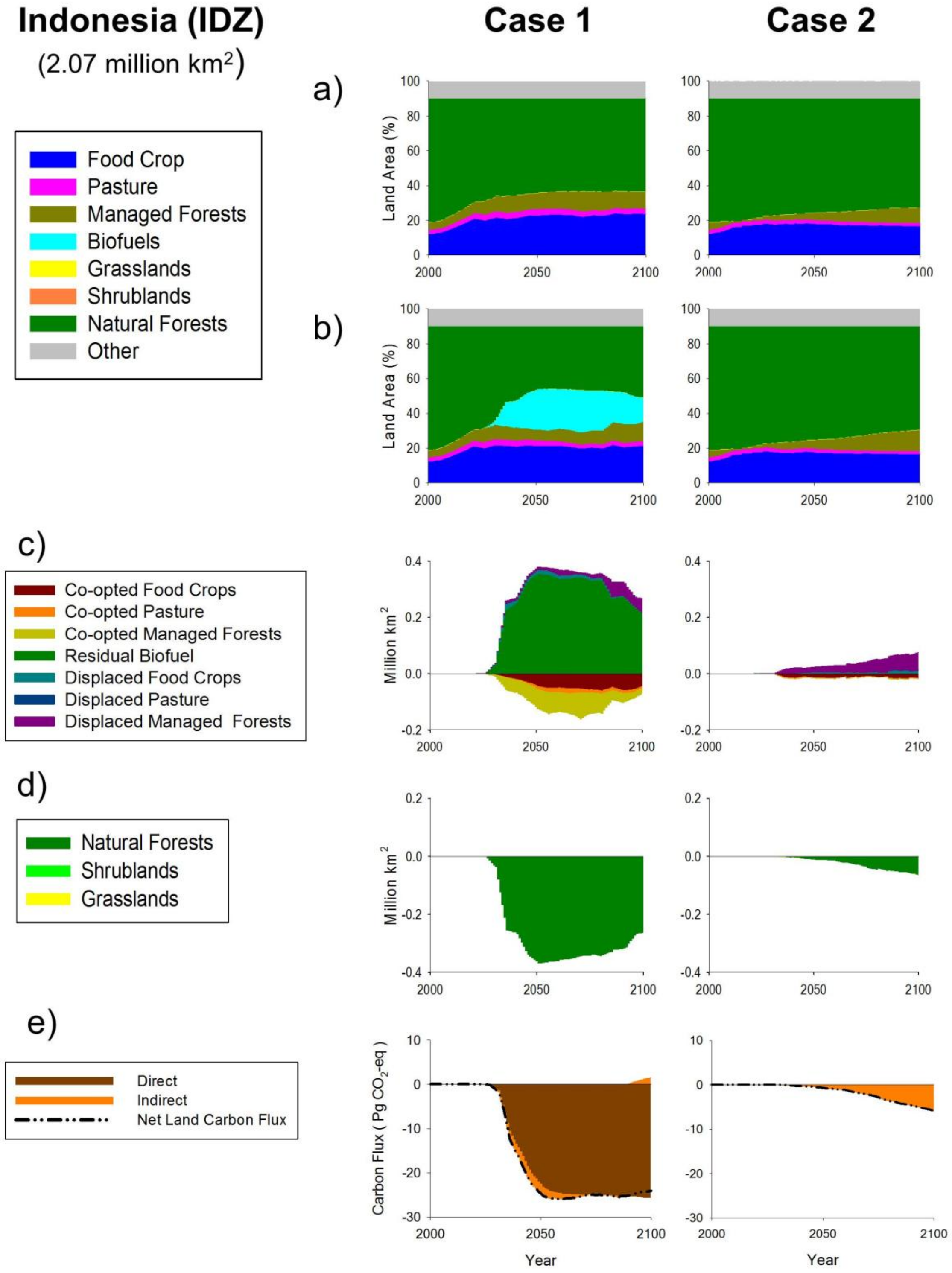


Figure A8. Comparison of temporal variations in land-use characteristics in Indonesia (IDZ) between the Case 1 and Case 2 land-use scenarios.

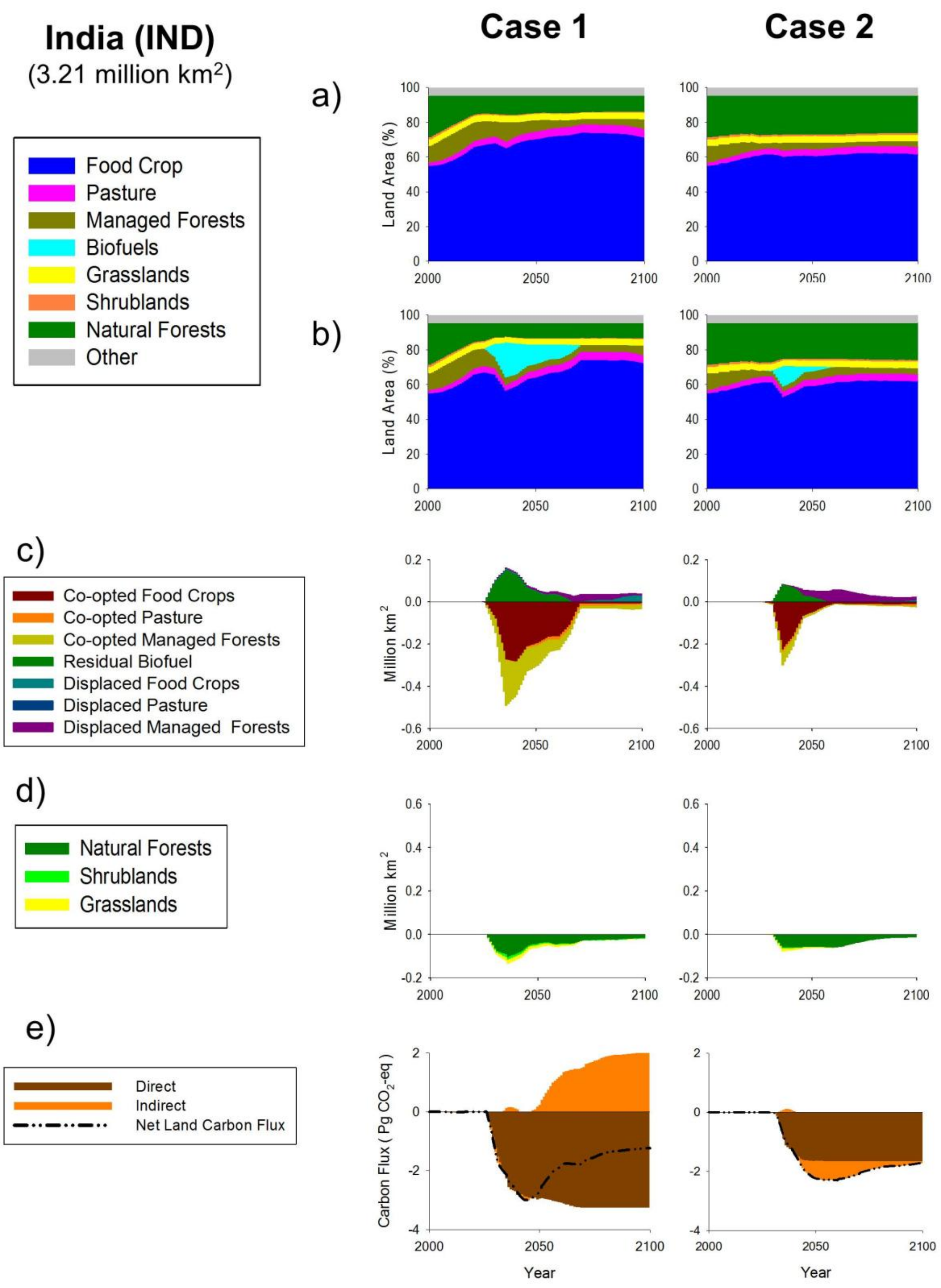


Figure A9. Comparison of temporal variations in land-use characteristics in India (IND) between the Case 1 and Case 2 land-use scenarios.

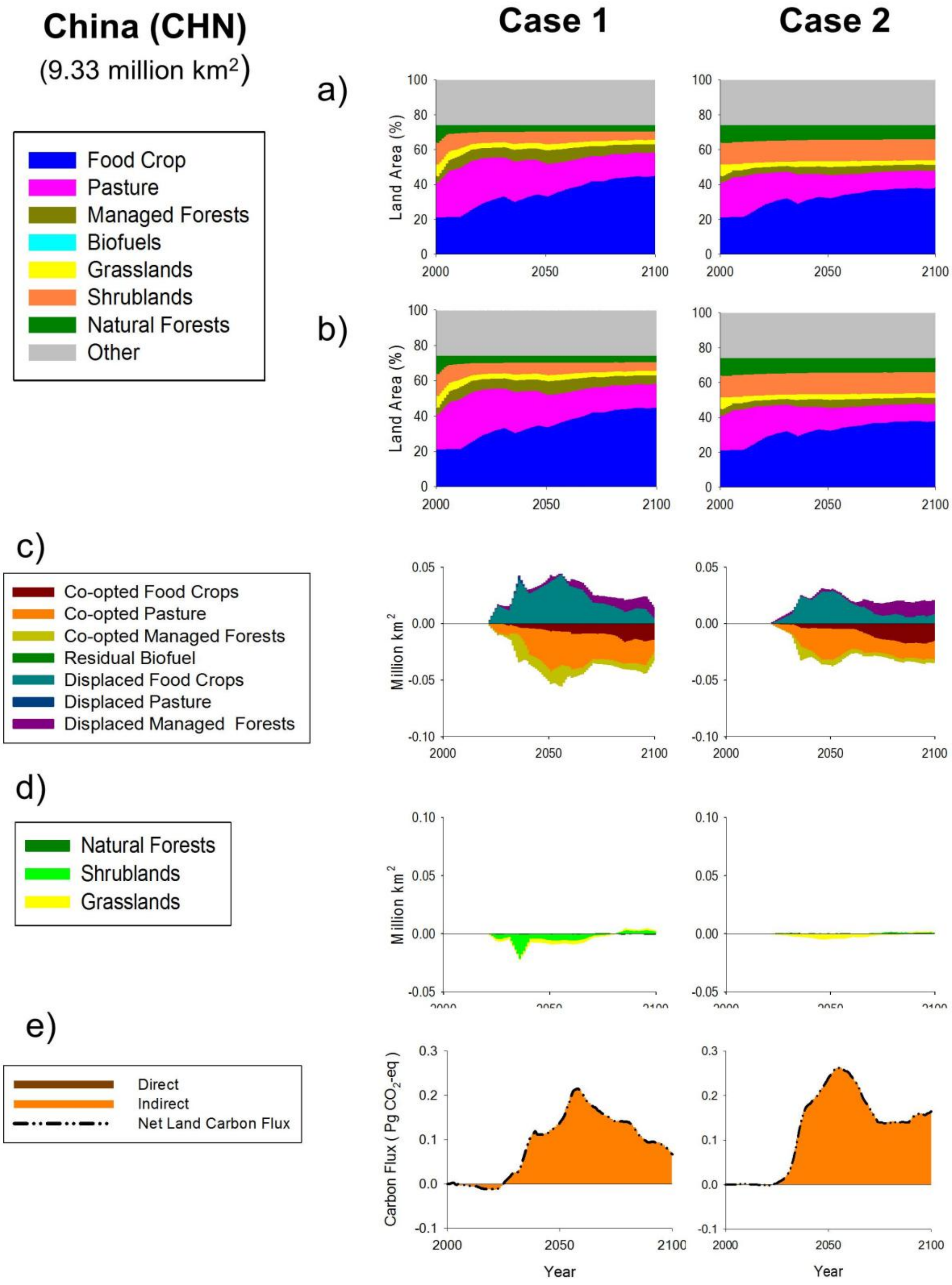


Figure A10. Comparison of temporal variations in land-use characteristics in China (CHN) between the Case 1 and Case 2 land-use scenarios.

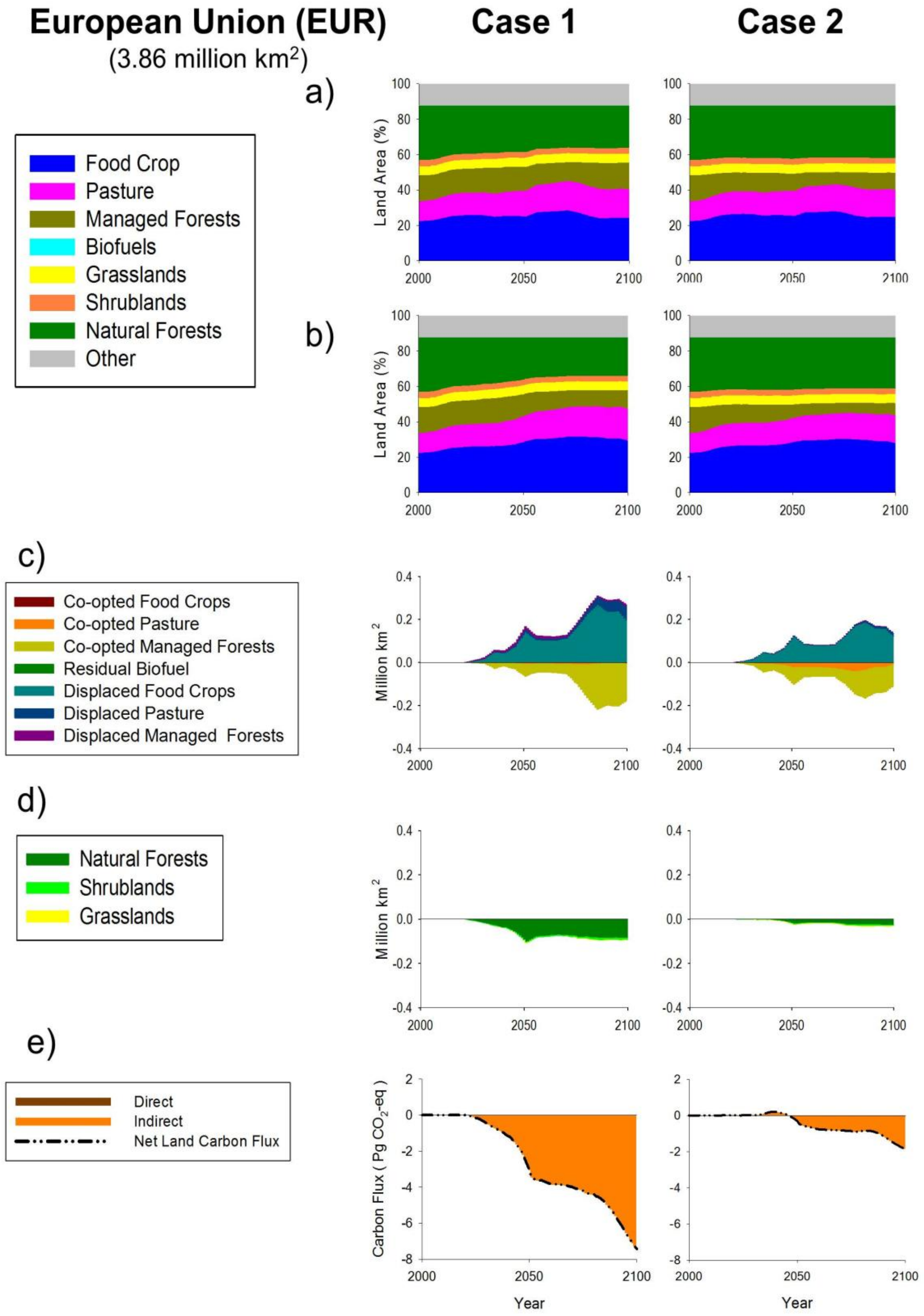


Figure A11. Comparison of temporal variations in land-use characteristics in the European Union (EUR) between the Case 1 and Case 2 land-use scenarios.

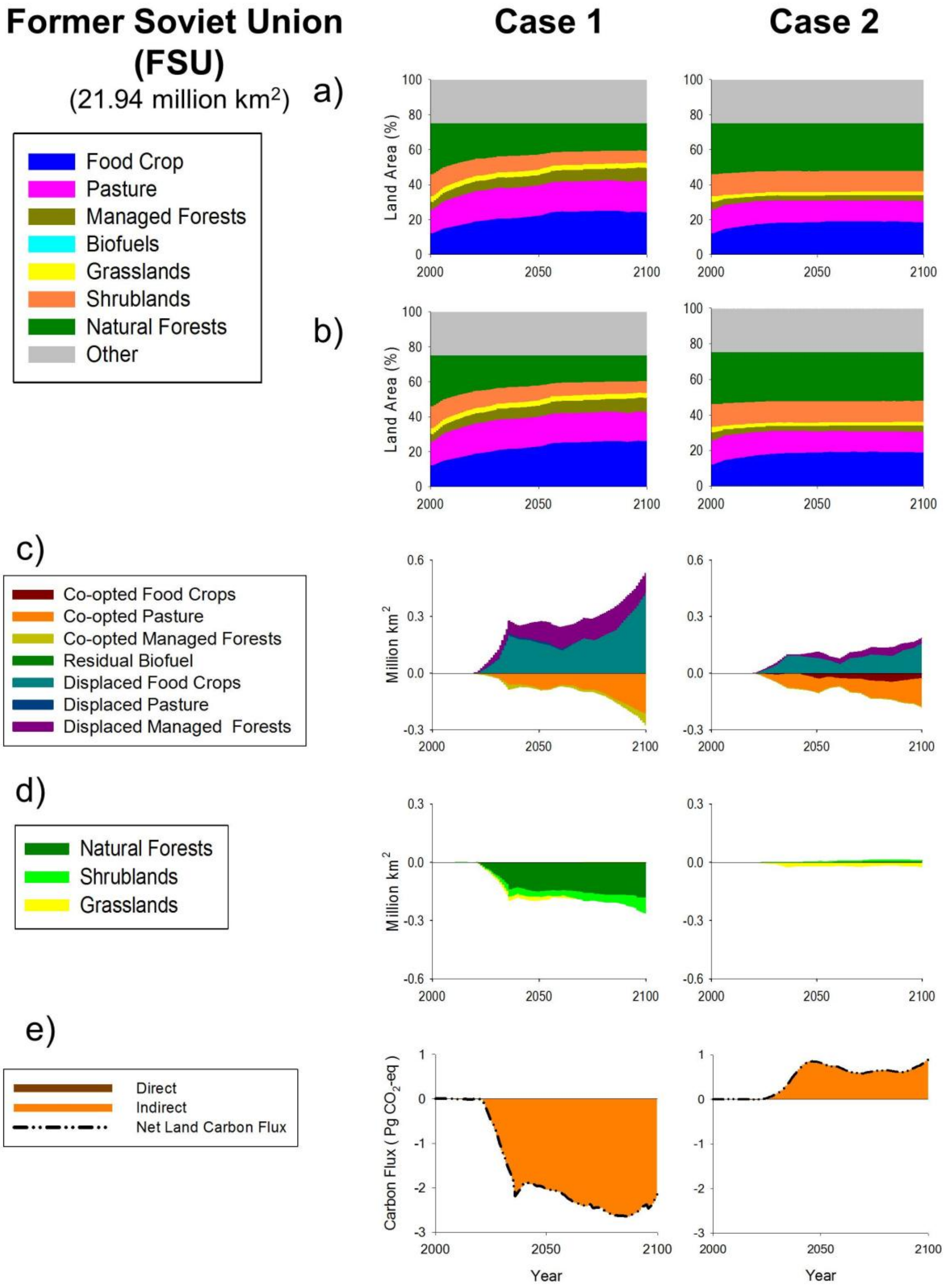


Figure A12. Comparison of temporal variations in land-use characteristics in the Former Soviet Union (FSU) between the Case 1 and Case 2 land-use scenarios.

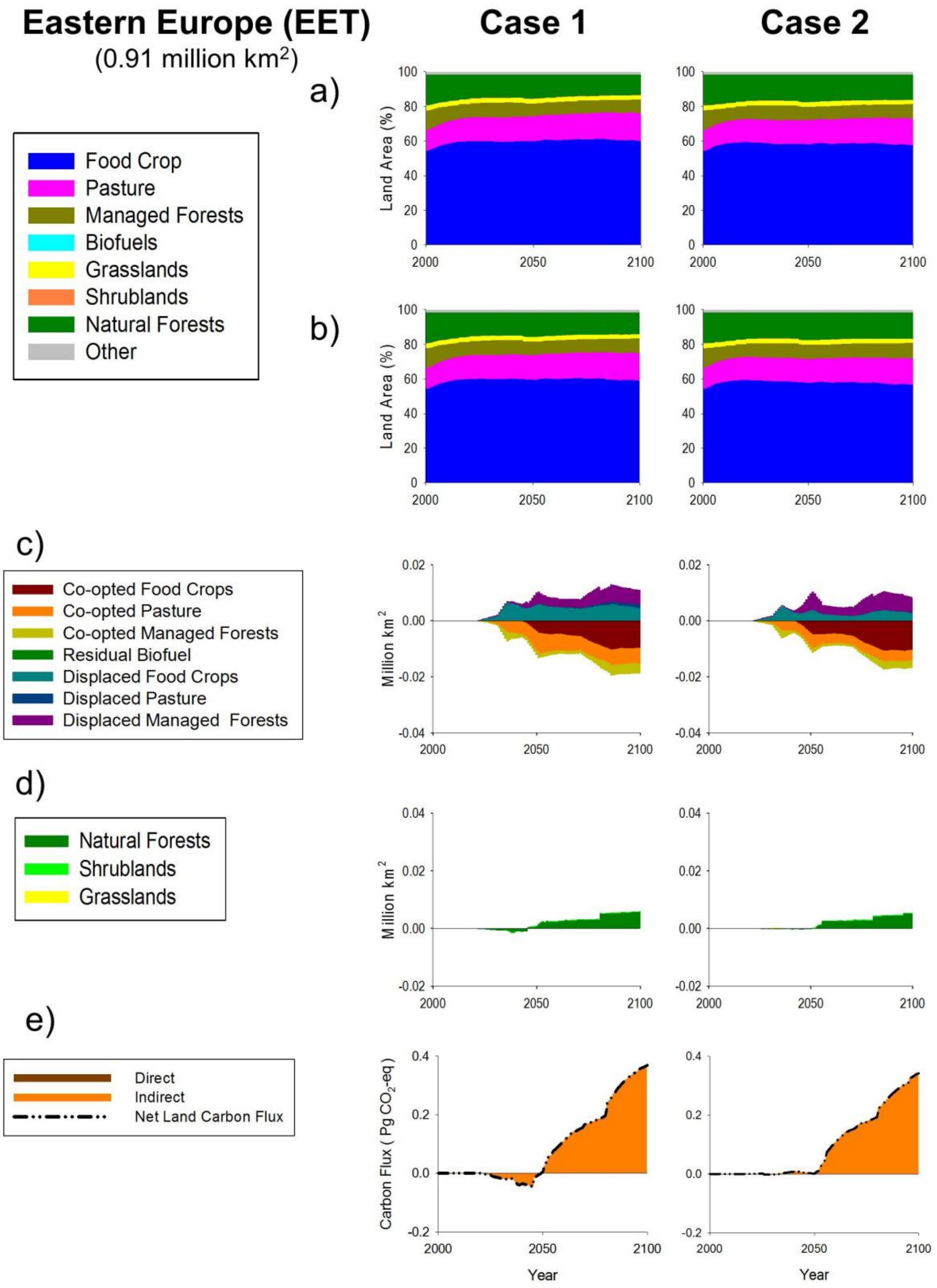


Figure A13. Comparison of temporal variations in land-use characteristics in Eastern Europe (EET) between the Case 1 and Case 2 land-use scenarios.

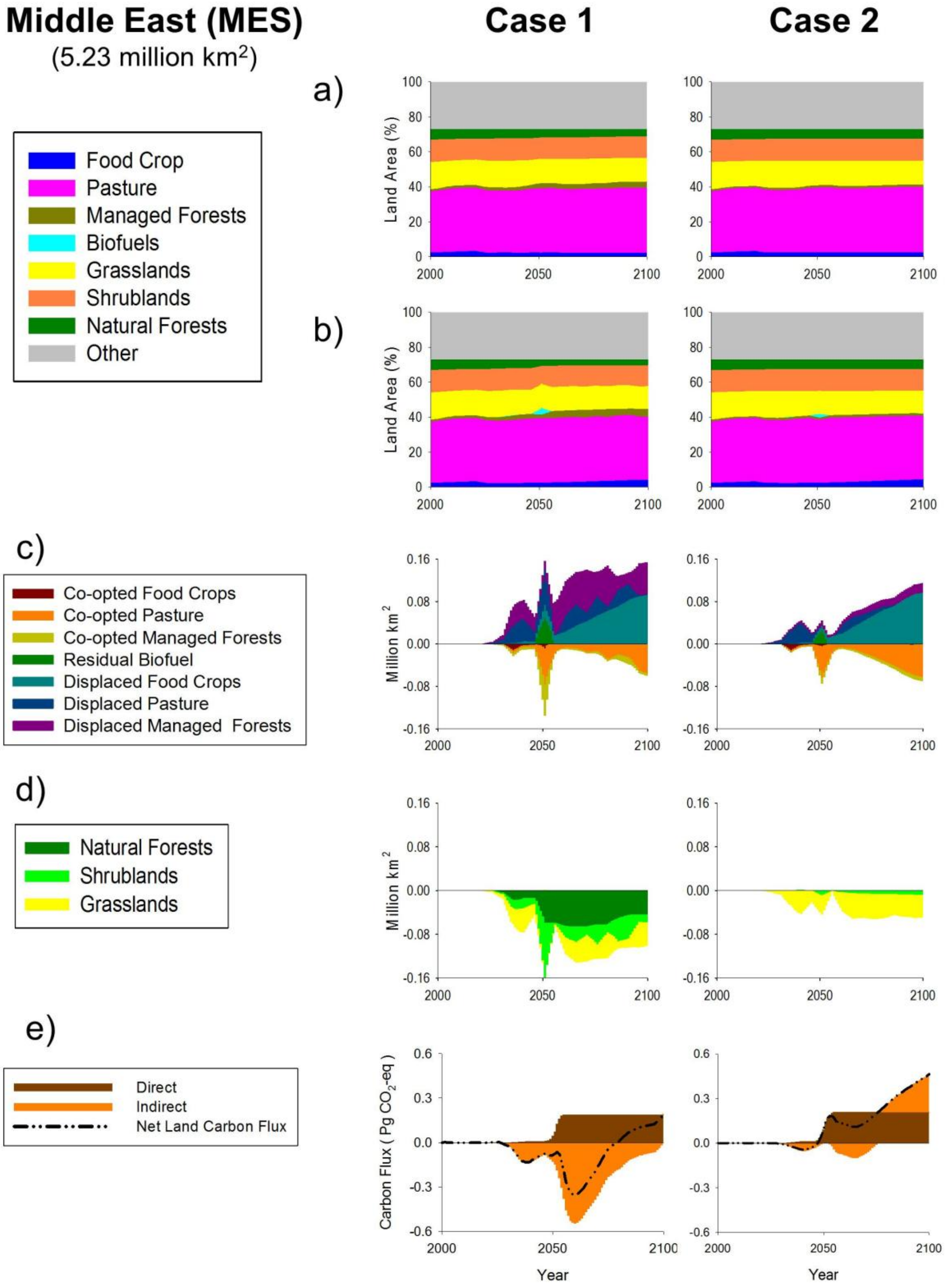


Figure A14. Comparison of temporal variations in land-use characteristics in the Middle East (MES) between the Case 1 and Case 2 land-use scenarios.

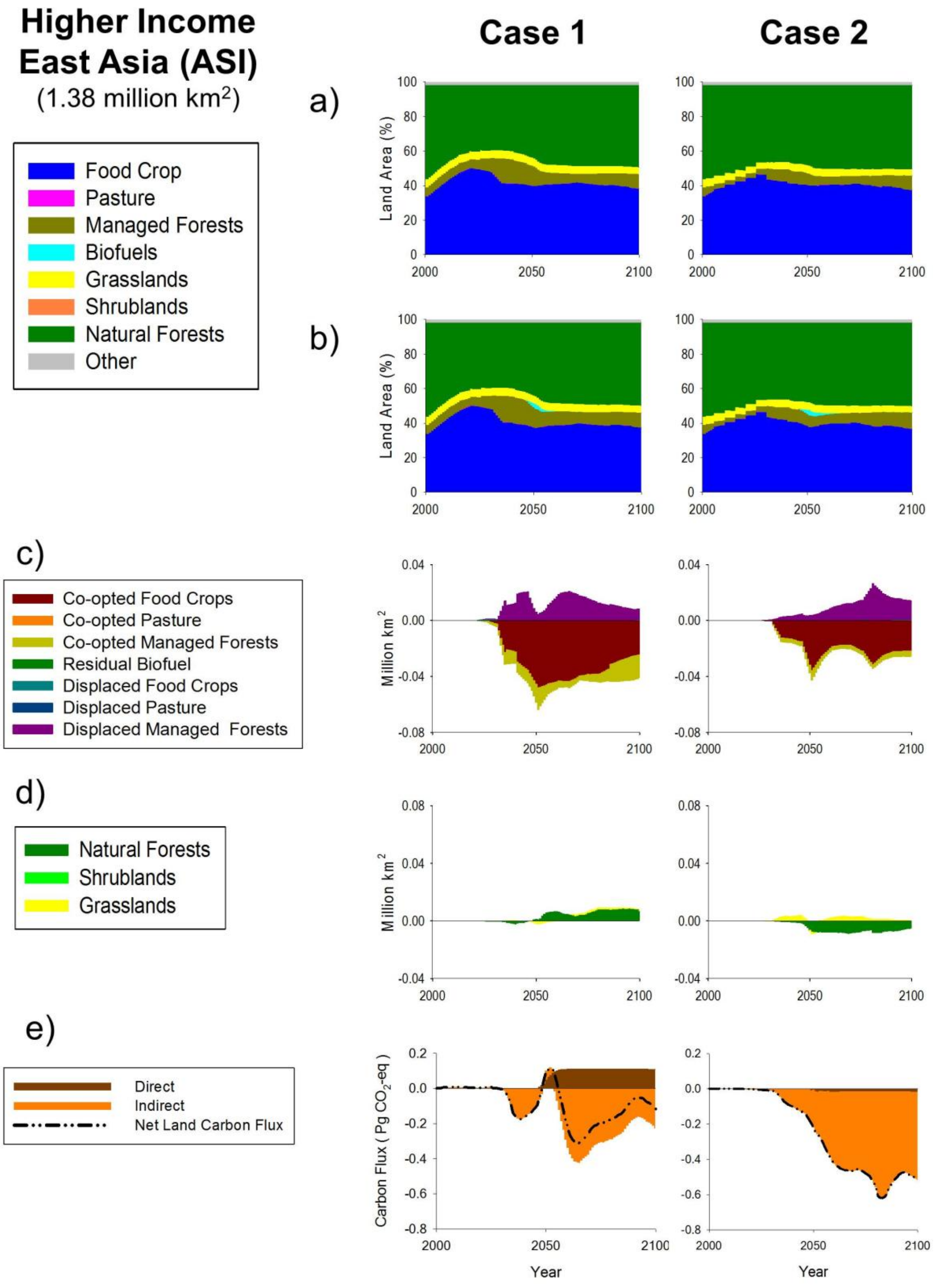


Figure A15. Comparison of temporal variations in land-use characteristics in Higher Income East Asia (ASI) between the Case 1 and Case 2 land-use scenarios.

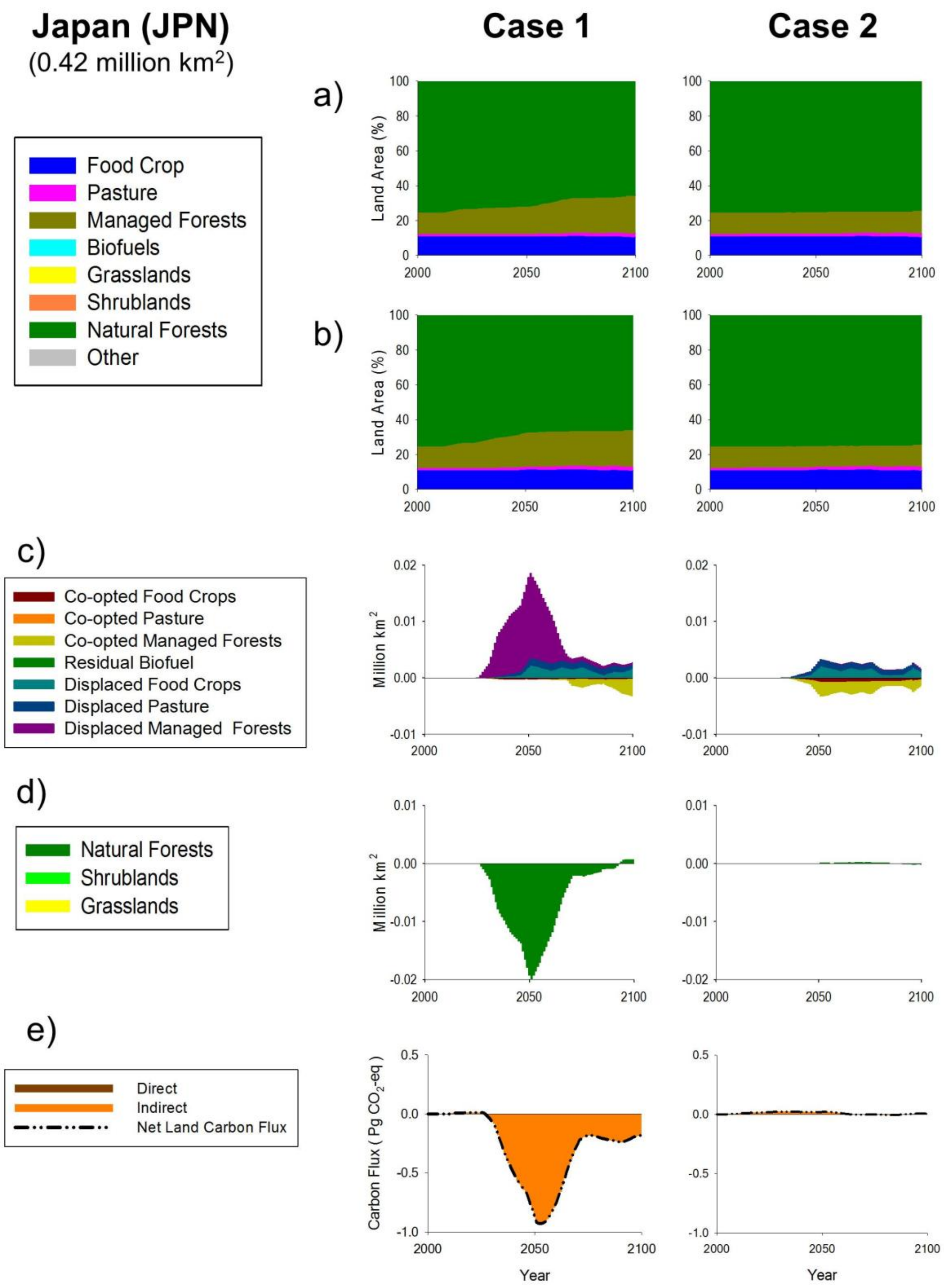


Figure A16. Comparison of temporal variations in land-use characteristics in Japan (JPN) between the Case 1 and Case 2 land-use scenarios.

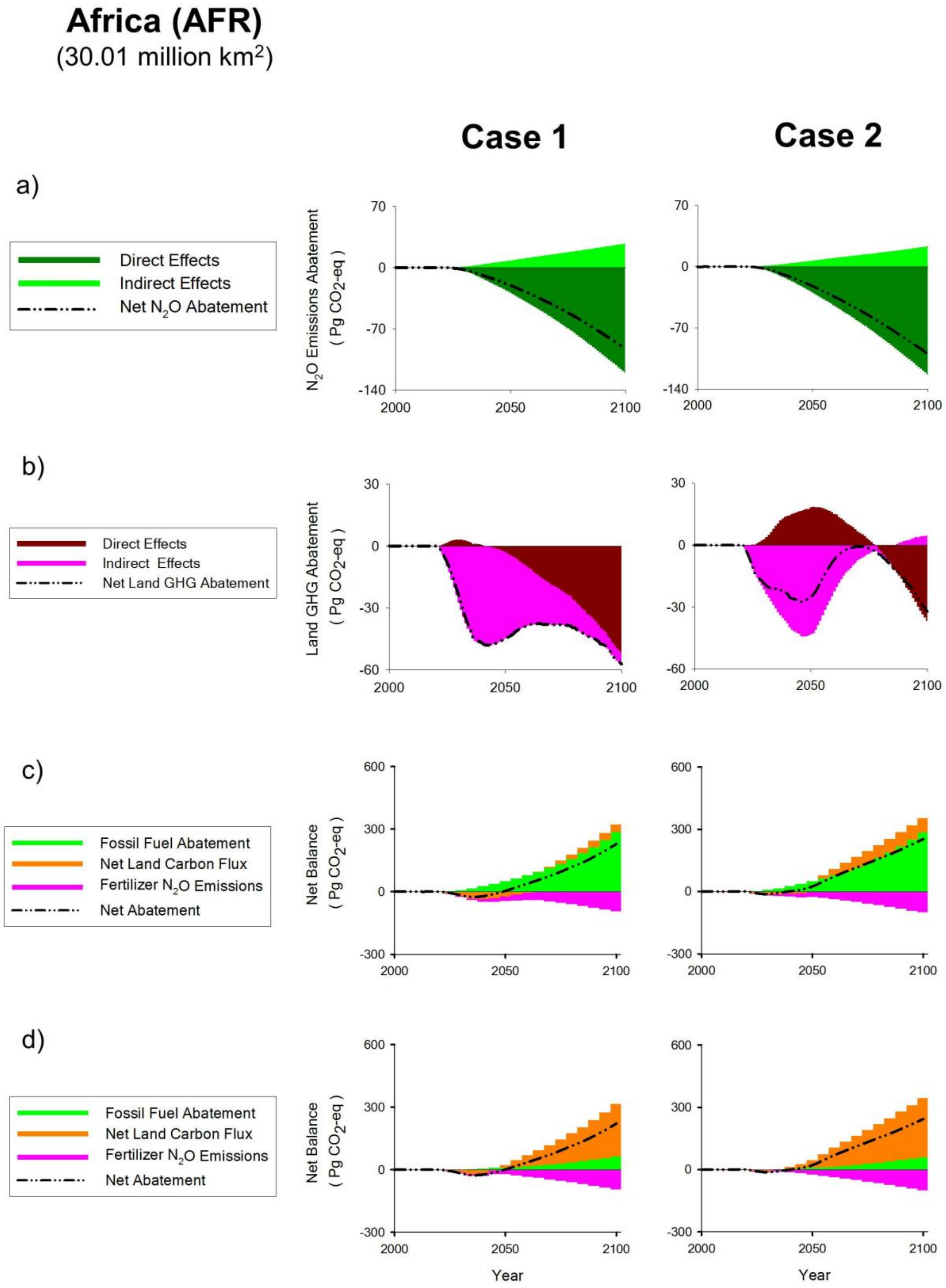


Figure A17. Comparison of temporal variations in additional land-use characteristics in Africa (AFR) between the Case 1 and Case 2 land-use scenarios.

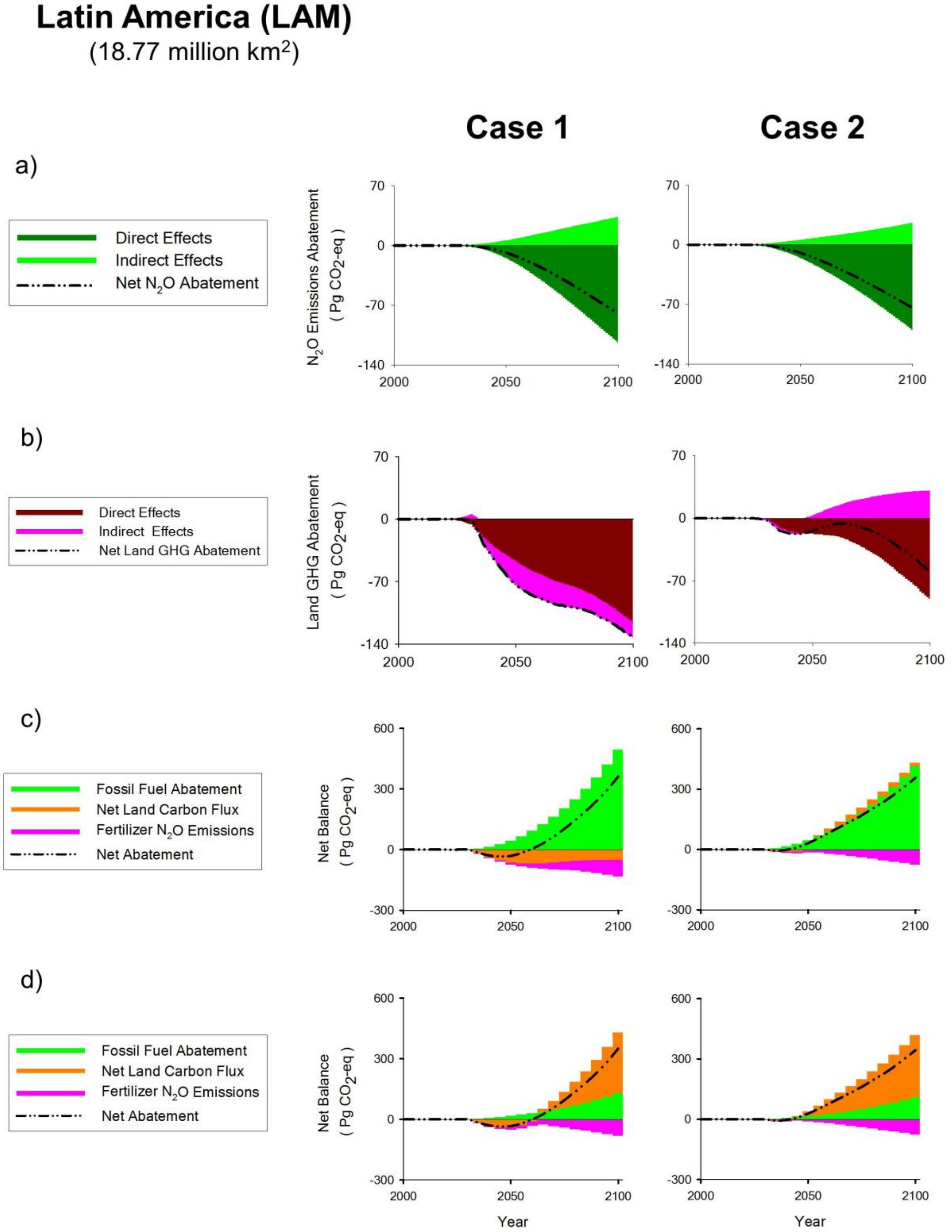


Figure A18. Comparison of temporal variations in additional land-use characteristics in Latin America (LAM) between the Case 1 and Case 2 land-use scenarios.

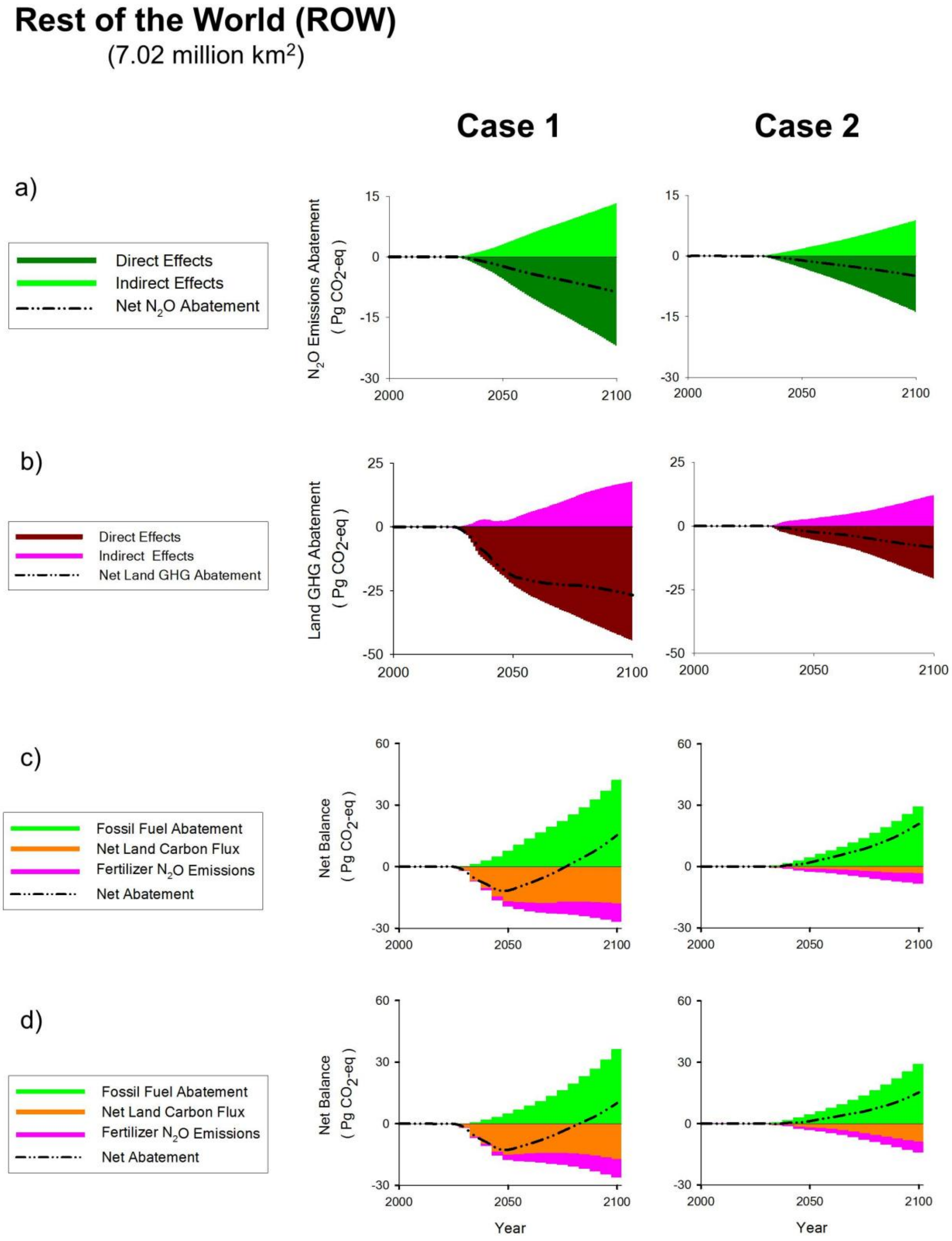


Figure A19. Comparison of temporal variations in additional land-use characteristics in the Rest of the World (ROW) between the Case 1 and Case 2 land-use scenarios.

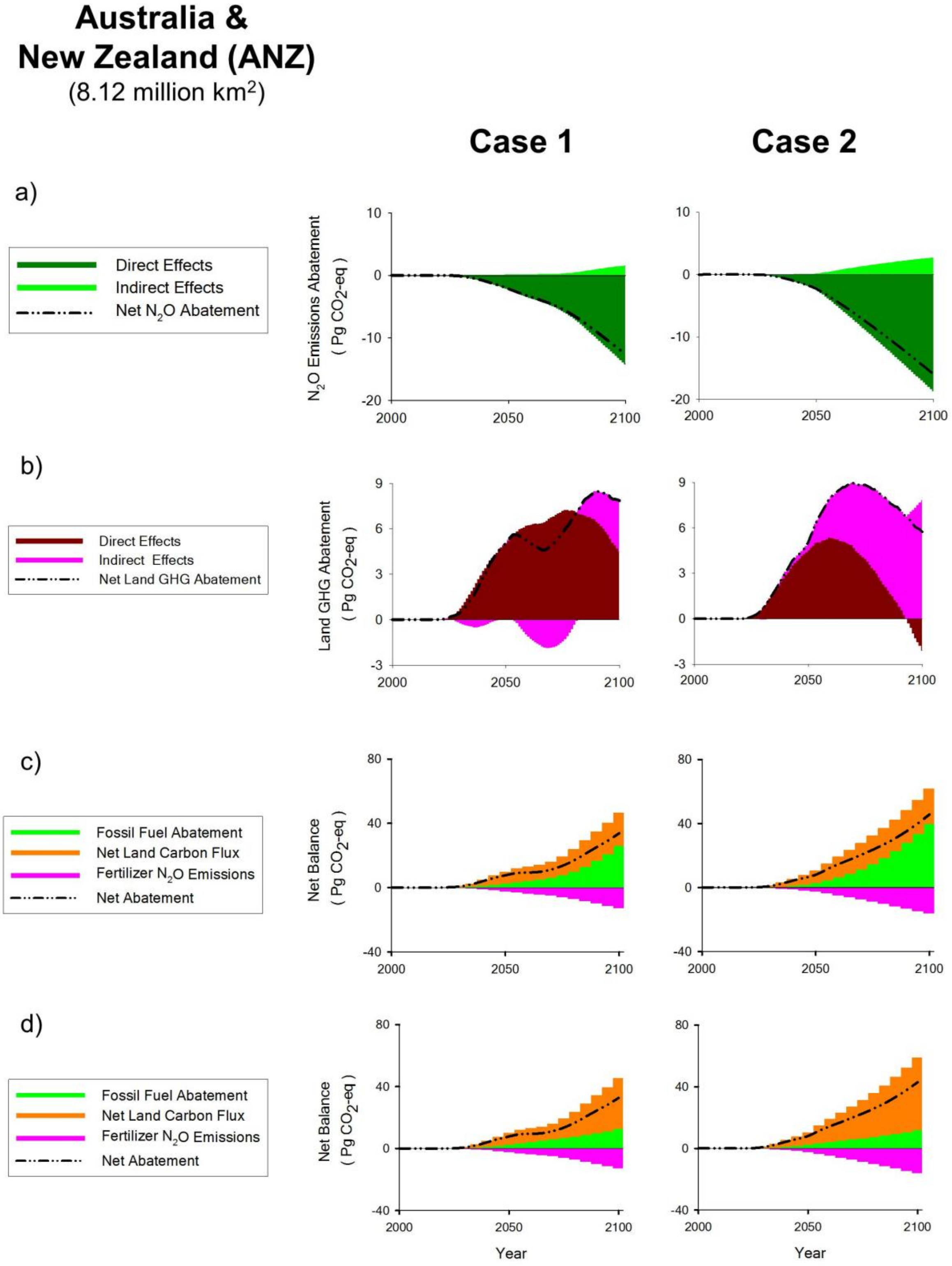


Figure A20. Comparison of temporal variations in additional land-use characteristics in Australia/New Zealand (ANZ) between the Case 1 and Case 2 land-use scenarios.

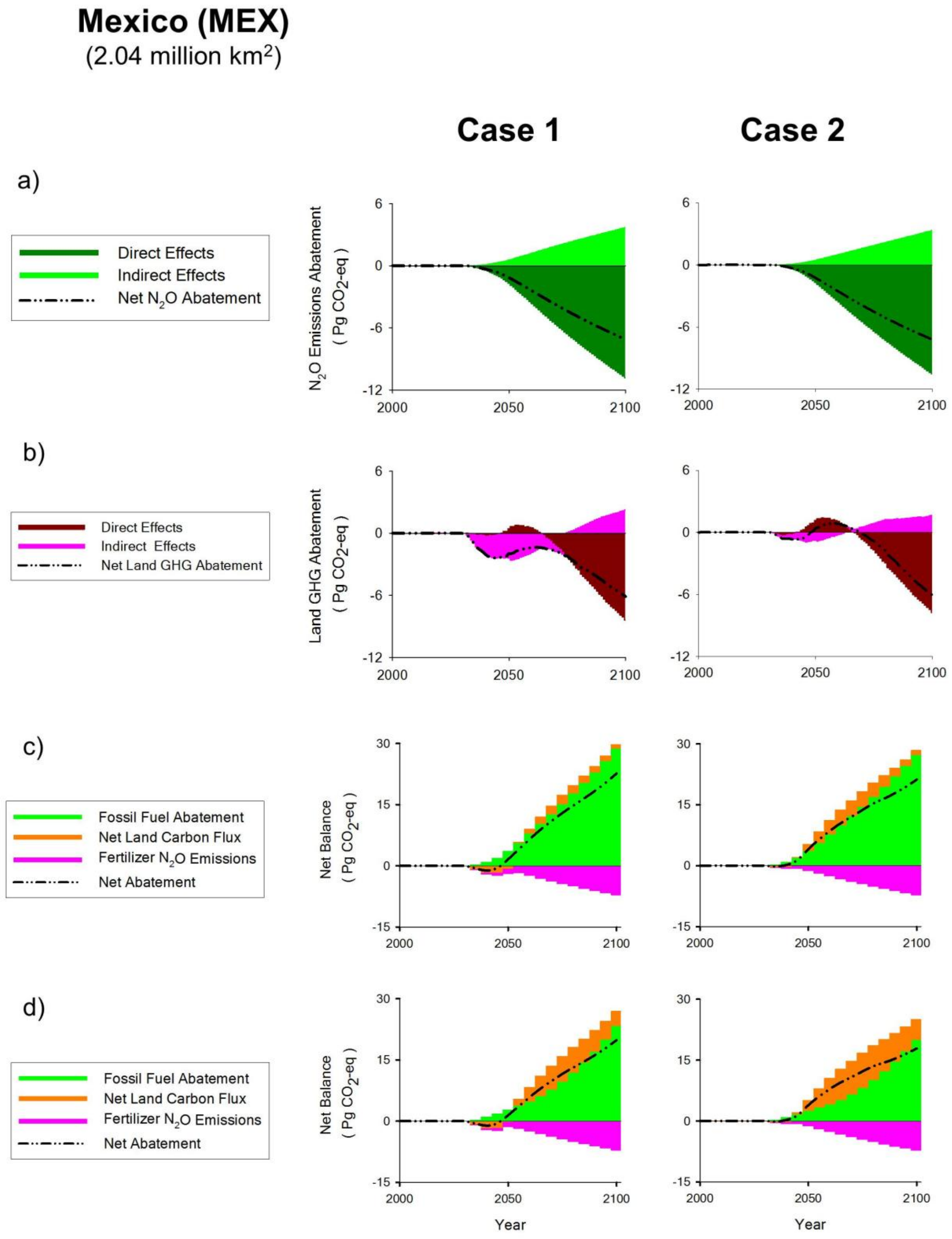
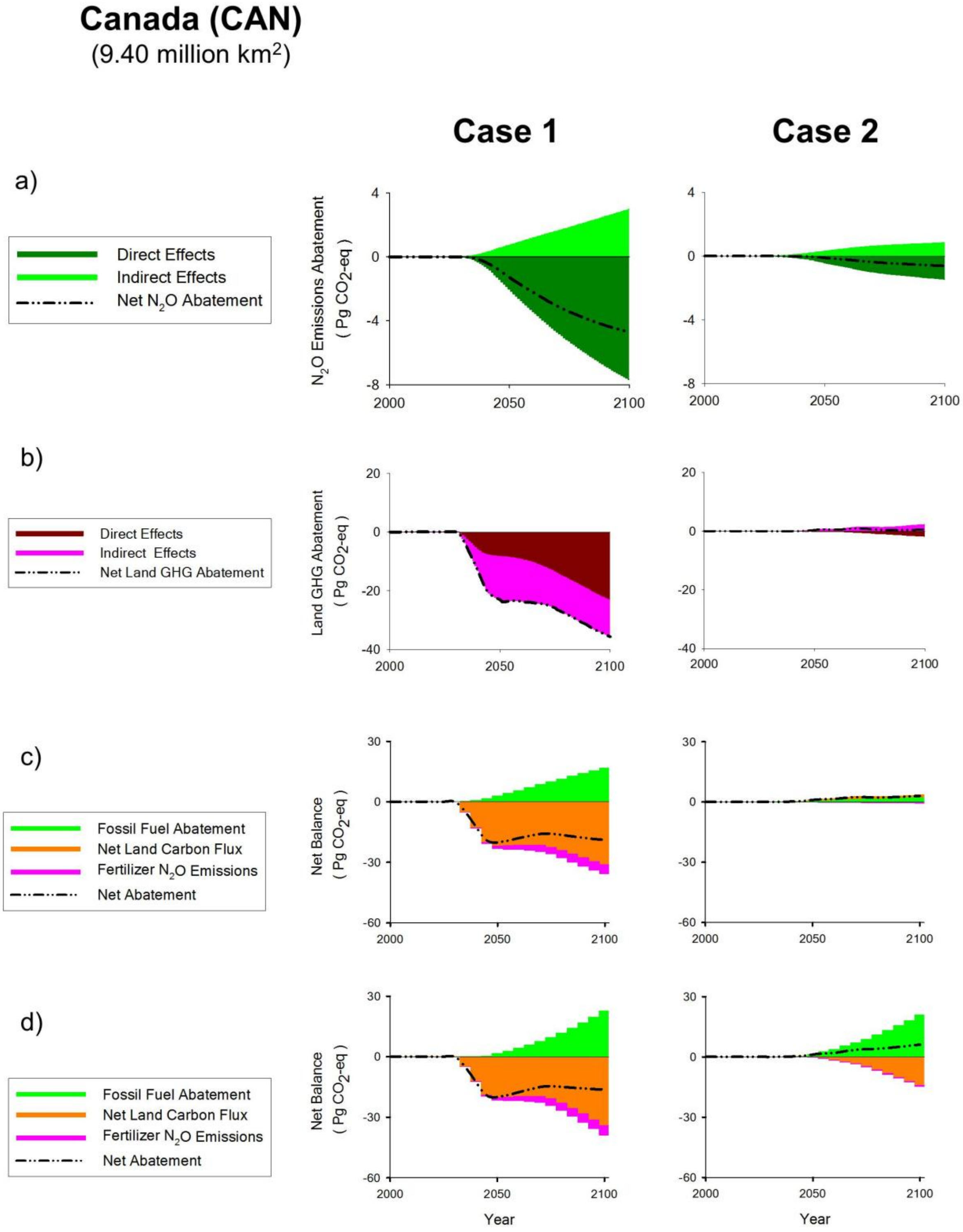


Figure A21. Comparison of temporal variations in additional land-use characteristics in Mexico (MEX) between the Case 1 and Case 2 land-use scenarios.



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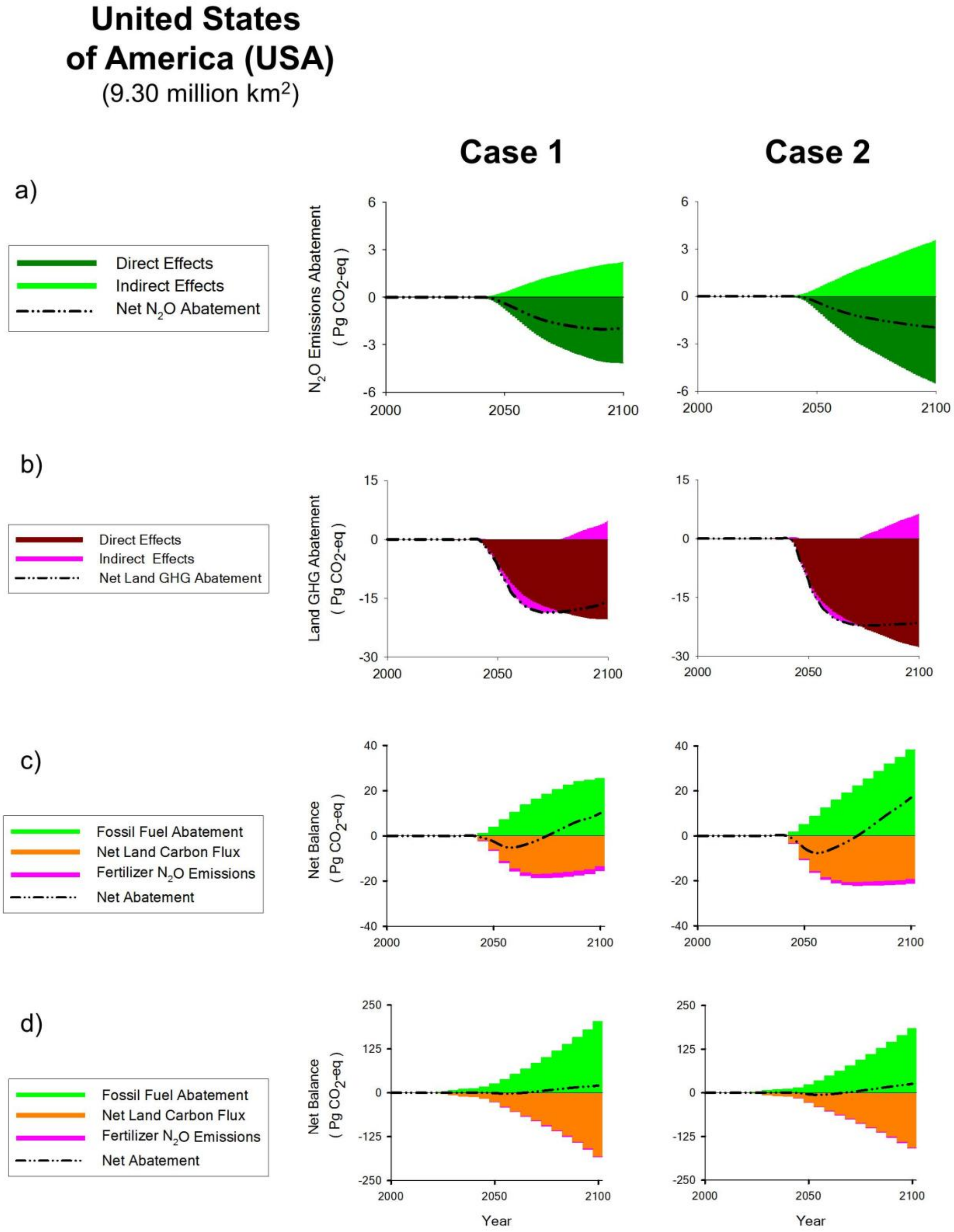


Figure A23. Comparison of temporal variations in additional land-use characteristics in the United States of America (USA) between the Case 1 and Case 2 land-use scenarios.

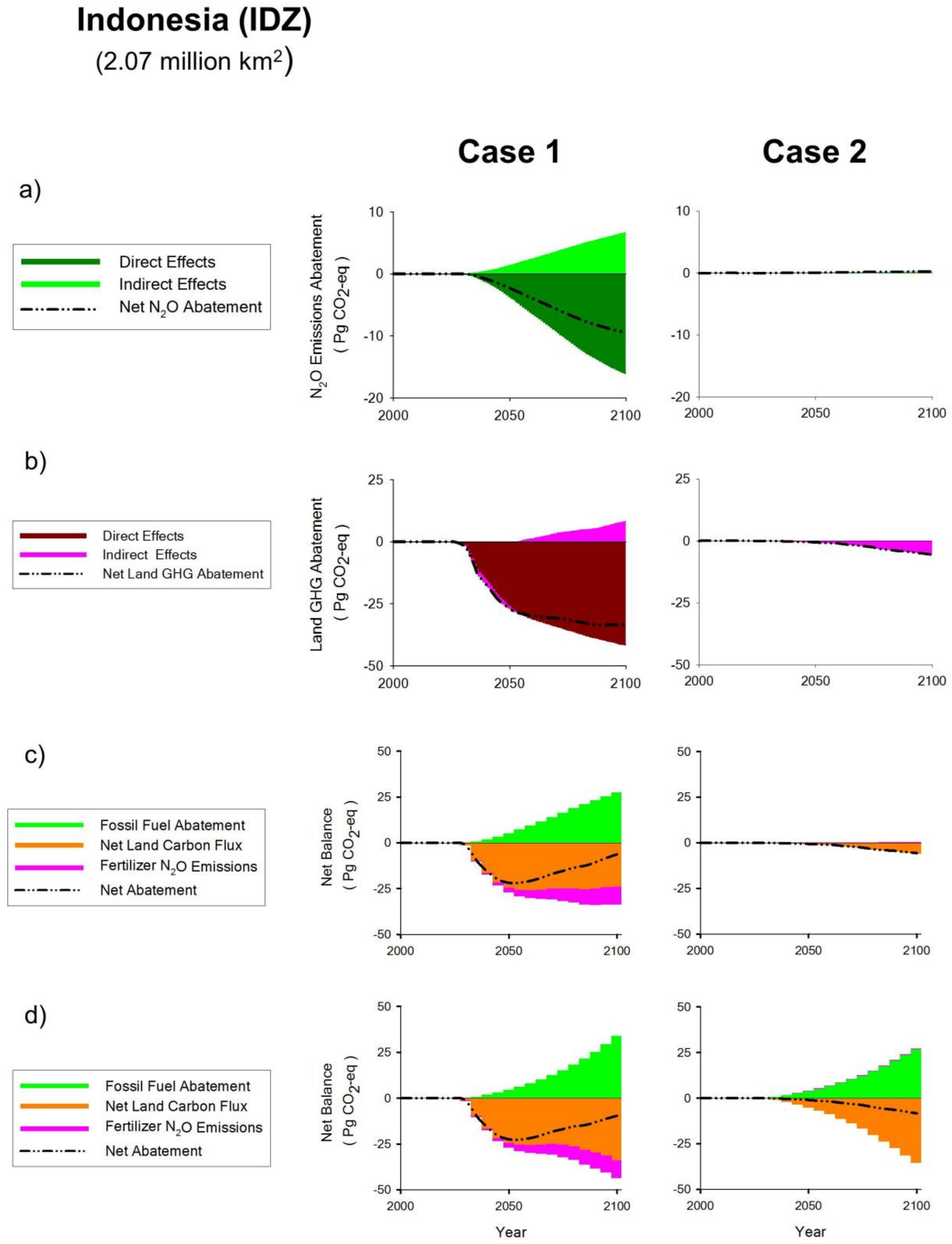


Figure A24. Comparison of temporal variations in additional land-use characteristics in Indonesia (IDZ) between the Case 1 and Case 2 land-use scenarios.

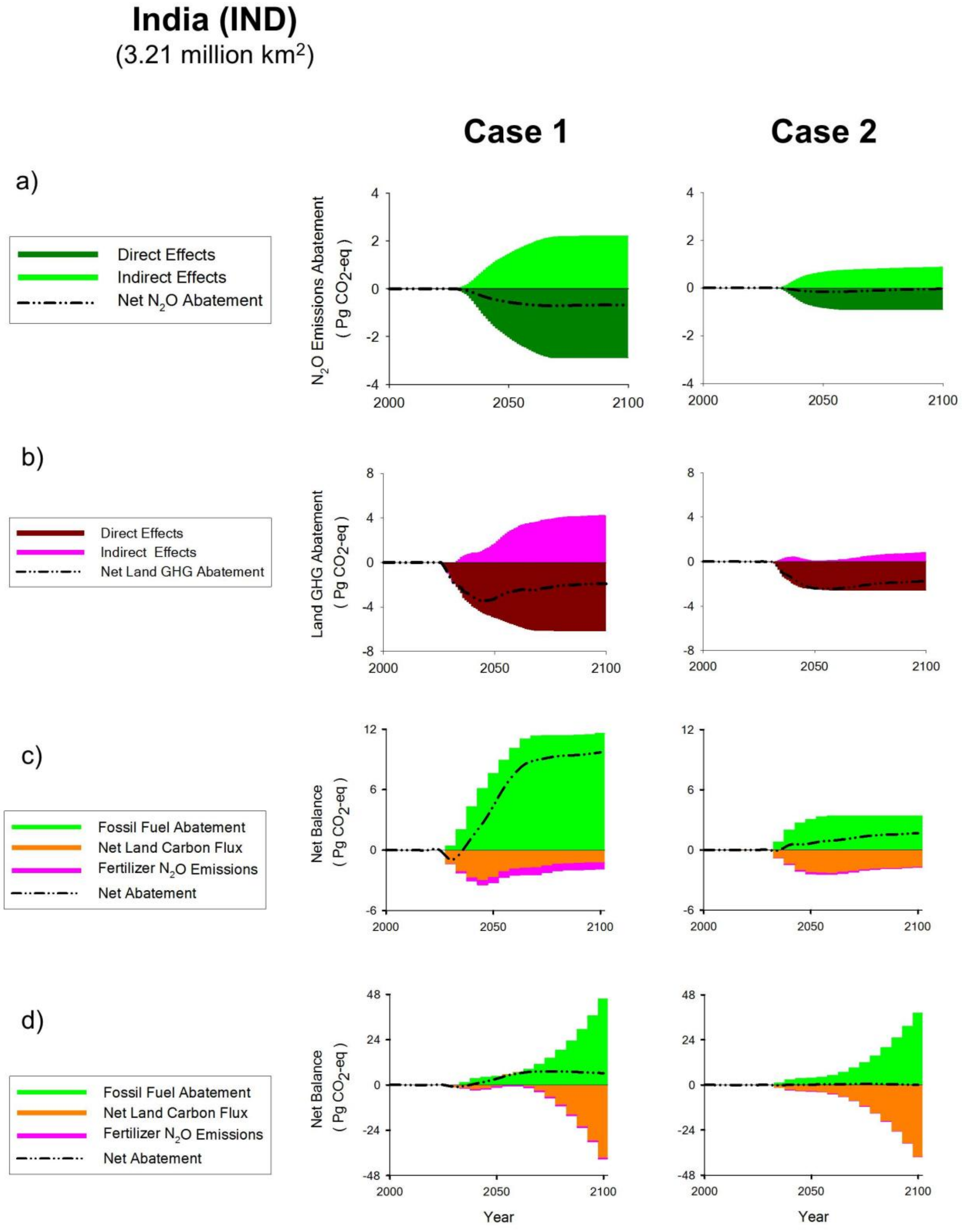


Figure A25. Comparison of temporal variations in additional land-use characteristics in India (IND) between the Case 1 and Case 2 land-use scenarios.

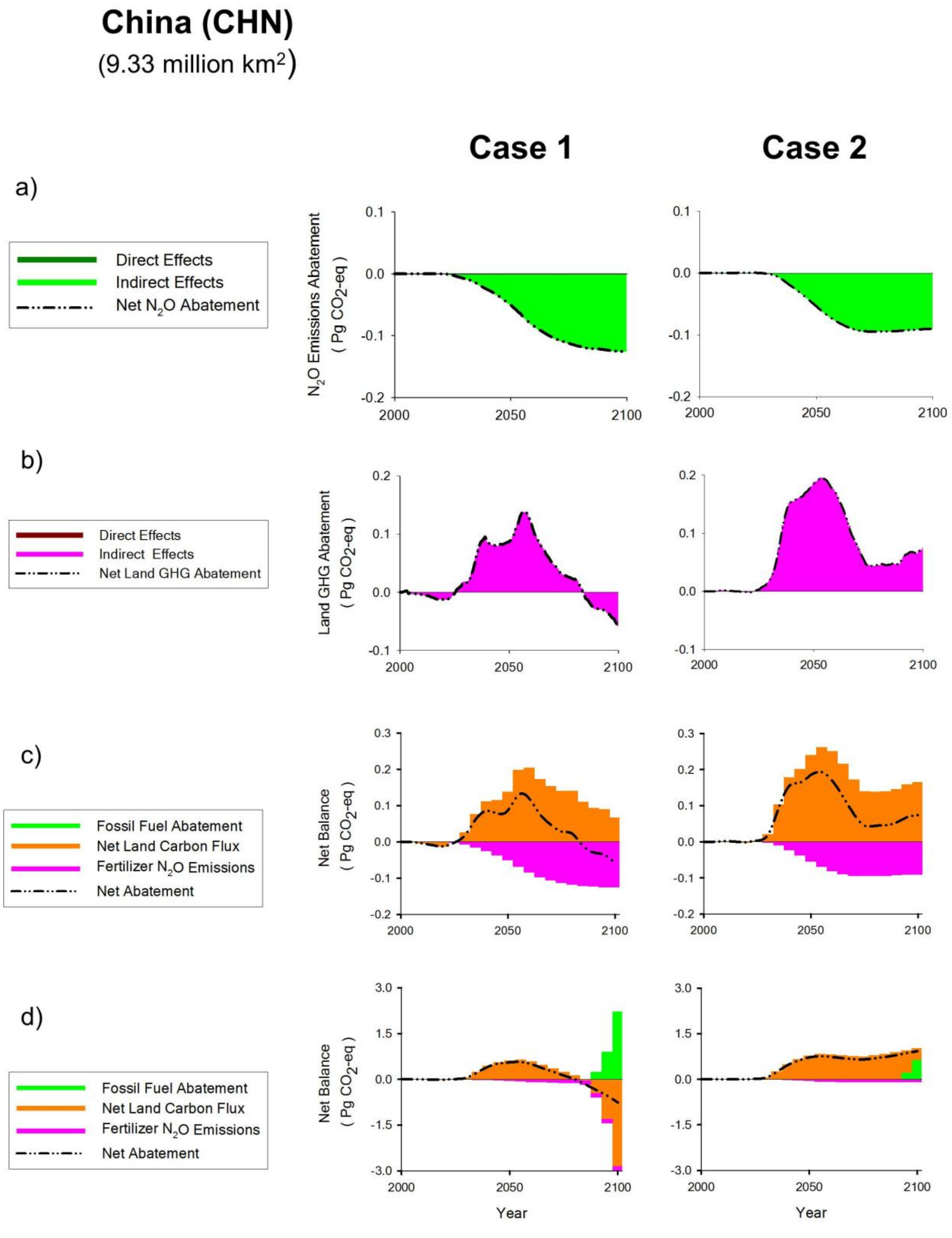


Figure A26. Comparison of temporal variations in additional land-use characteristics in China (CHN) between the Case 1 and Case 2 land-use scenarios.

European Union (EUR)

(3.86 million km^2)

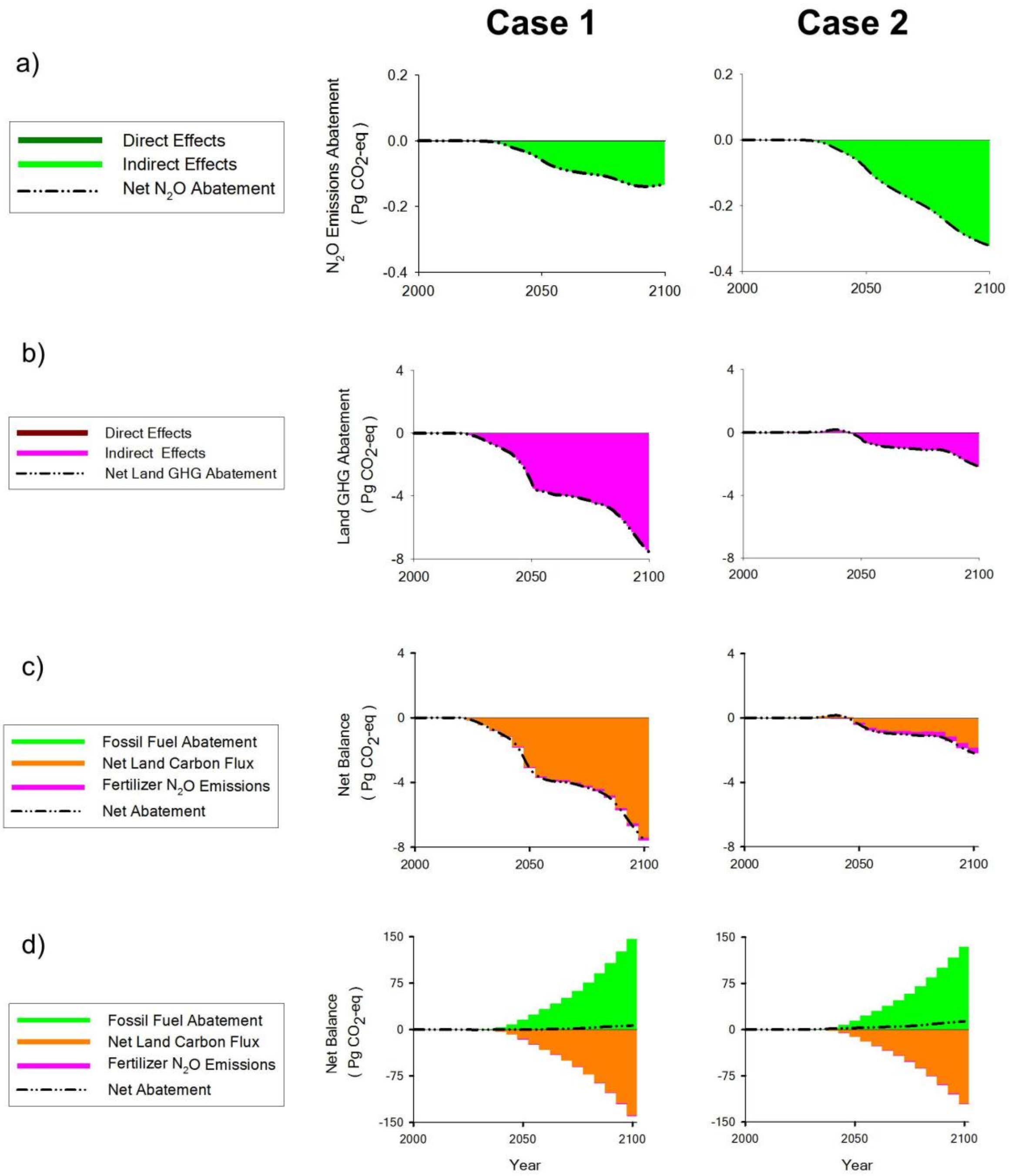


Figure A27. Comparison of temporal variations in additional land-use characteristics in the European Union (EUR) between the Case 1 and Case 2 land-use scenarios.

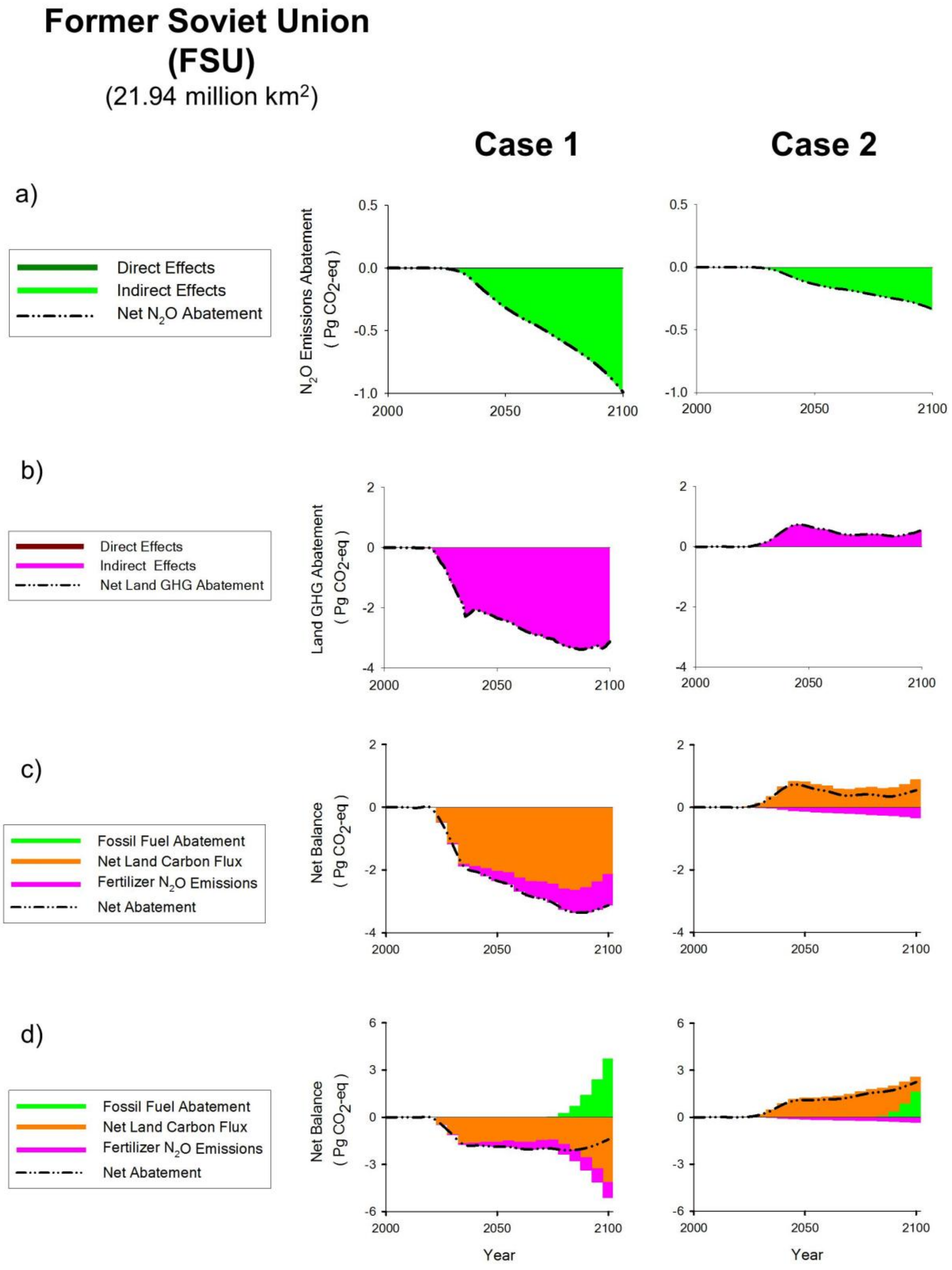
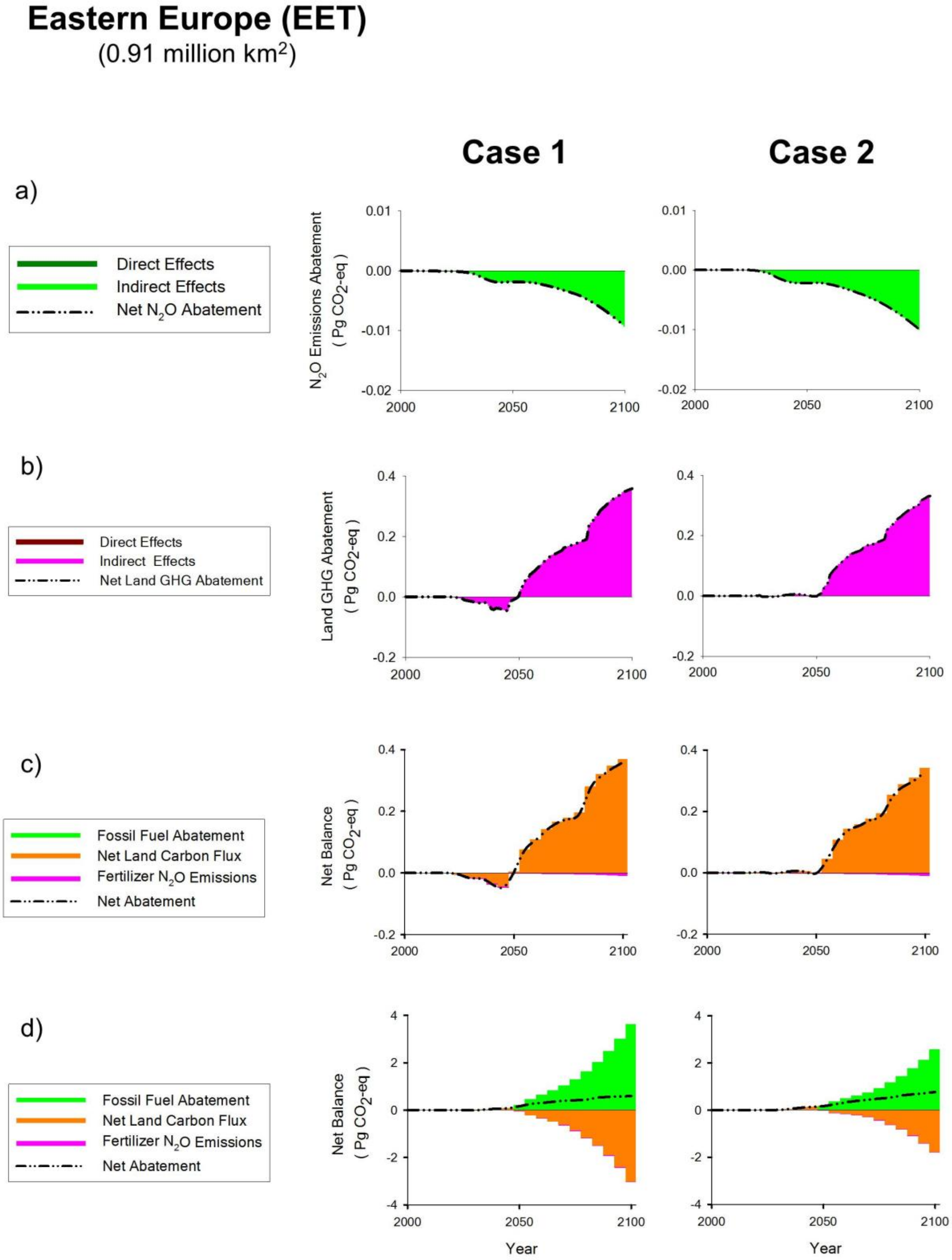


Figure A28. Comparison of temporal variations in additional land-use characteristics in the Former Soviet Union (FSU) between the Case 1 and Case 2 land-use scenarios.



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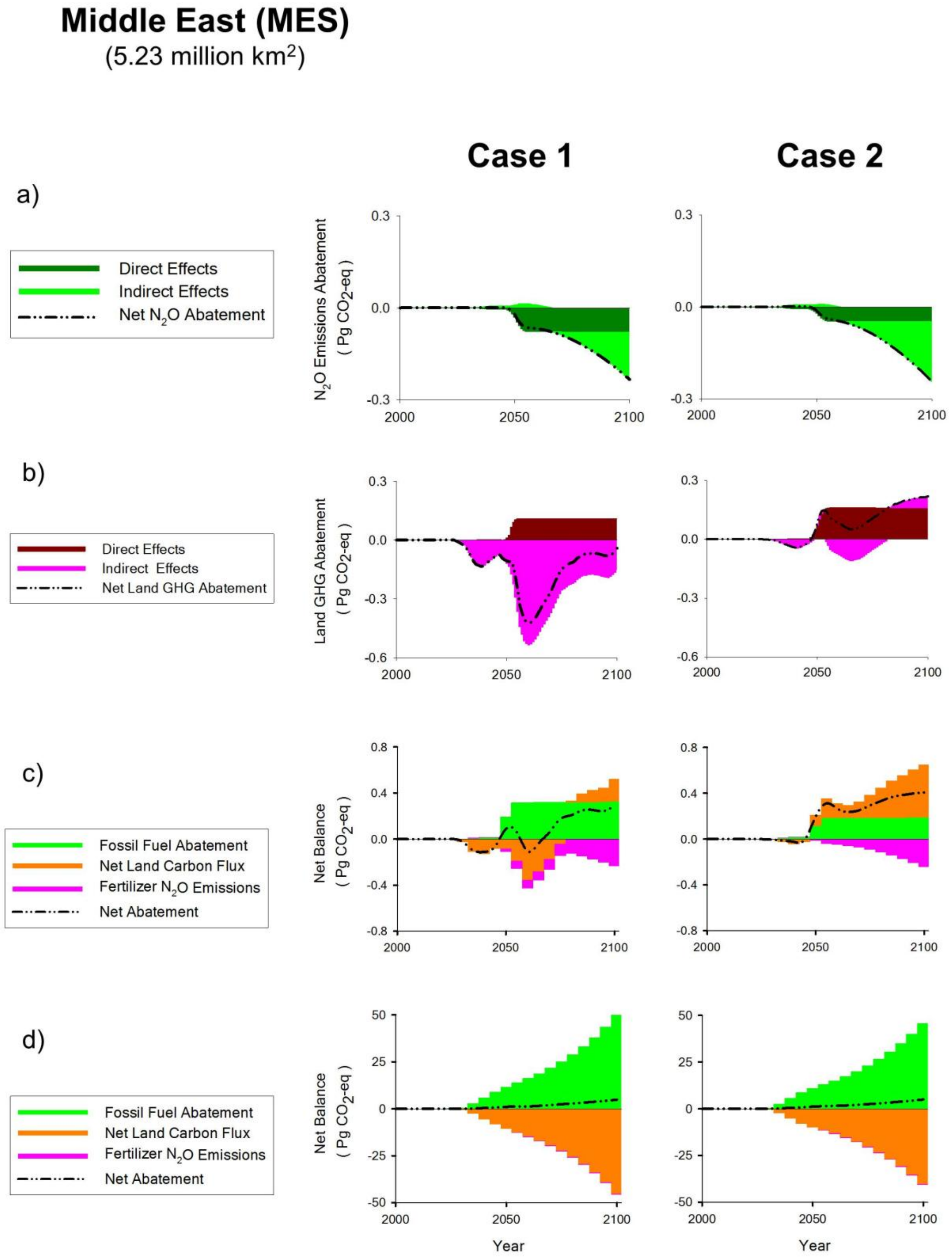

Figure A30. Comparison of temporal variations in additional land-use characteristics in the Middle East (MES) between the Case 1 and Case 2 land-use scenarios.

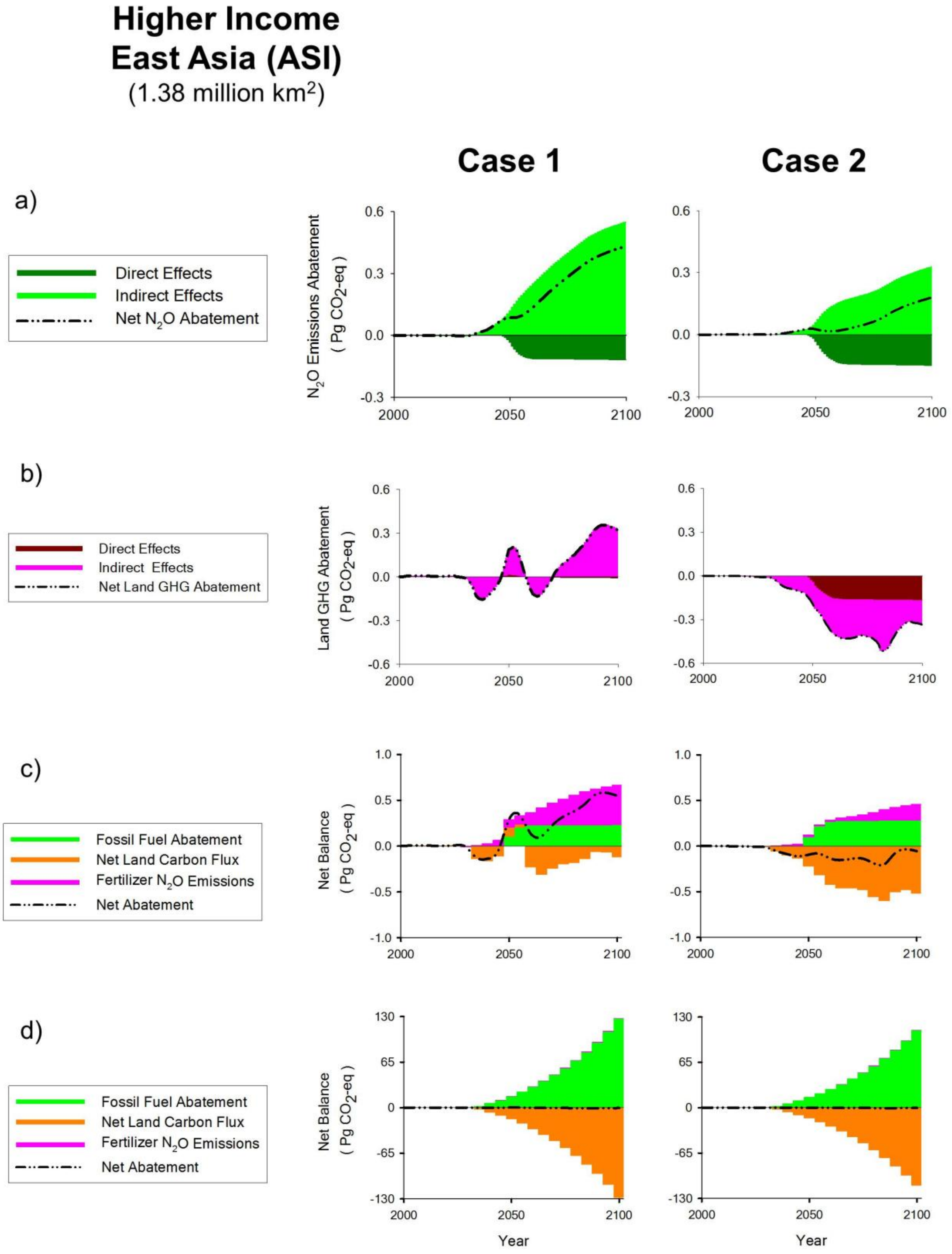

Figure A31. Comparison of temporal variations in additional land-use characteristics in Higher Income East Asia (ASI) between the Case 1 and Case 2 land-use scenarios.

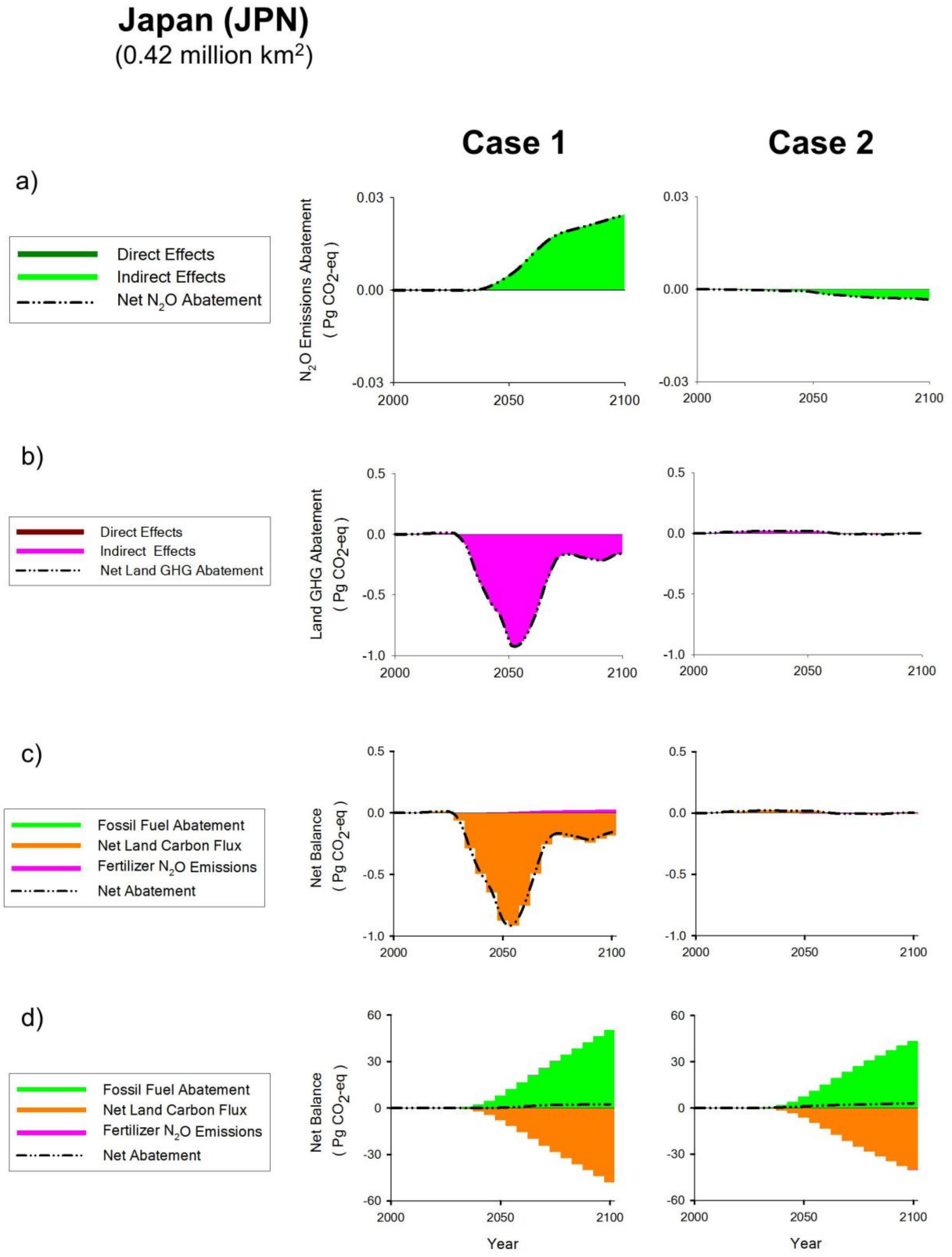

Figure A32. Comparison of temporal variations in additional land-use characteristics in Japan (JPN) between the Case 1 and Case 2 land-use scenarios.

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