IOPscience iopscience.iop.org

Home Search Collections Journals About Contact us My IOPscience

Large-scale expansion of agriculture in Amazonia may be a no-win scenario

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2013 Environ. Res. Lett. 8 024021

(http://iopscience.iop.org/1748-9326/8/2/024021)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 129.2.12.97
The article was downloaded on 15/05/2013 at 15:12

Please note that terms and conditions apply.

OPEN ACCESS
IOP PUBLISHING
ENVIRONMENTAL RESEARCH LETTERS
Environ. Res. Lett. **8** (2013) 024021 (10pp)
doi:10.1088/1748-9326/8/2/024021

Large-scale expansion of agriculture in Amazonia may be a no-win scenario

Leydimere J C Oliveira[1,2], Marcos H Costa[1], Britaldo S Soares-Filho[3] and Michael T Coe[4]

[1] Federal University of Viçosa, Avenue P H Rolfs s/n, Viçosa, MG, 36570-000, Brazil
[2] Federal University of Pampa, R Luiz Joaquim de Sá Britto s/n, Itaqui, RS, 97650-000, Brazil
[3] Federal University of Minas Gerais, Avenue Antônio Carlos 6627, Belo Horizonte, MG, 31270-901, Brazil
[4] The Woods Hole Research Center, 149 Woods Hole Road, Falmouth, MA 02540-1644, USA

E-mail: leydimereoliveira@unipampa.edu.br, mhcosta@ufv.br, britaldo@csr.ufmg.br and mtcoe@whrc.org

Received 27 August 2012
Accepted for publication 22 April 2013
Published 9 May 2013
Online at stacks.iop.org/ERL/8/024021

Abstract
Using simplified climate and land-use models, we evaluated primary forests' carbon storage and soybean and pasture productivity in the Brazilian Legal Amazon under several scenarios of deforestation and increased CO_2. The four scenarios for the year 2050 that we analyzed consider (1) radiative effects of increased CO_2, (2) radiative and physiological effects of increased CO_2, (3) effects of land-use changes on the regional climate and (4) radiative and physiological effects of increased CO_2 plus land-use climate feedbacks. Under current conditions, means for aboveground forest live biomass (AGB), soybean yield and pasture yield are 179 Mg-C ha^{-1}, 2.7 Mg-grains ha^{-1} and 16.2 Mg-dry mass ha^{-1} yr^{-1}, respectively. Our results indicate that expansion of agriculture in Amazonia may be a no-win scenario: in addition to reductions in carbon storage due to deforestation, total agriculture output may either increase much less than proportionally to the potential expansion in agricultural area, or even decrease, as a consequence of climate feedbacks from changes in land use. These climate feedbacks, usually ignored in previous studies, impose a reduction in precipitation that would lead agriculture expansion in Amazonia to become self-defeating: the more agriculture expands, the less productive it becomes.

Keywords: Amazonia, no-win scenario, ecosystem services, carbon storage, agriculture, land-use change, climate change

S Online supplementary data available from stacks.iop.org/ERL/8/024021/mmedia

1. Introduction

Ecosystem services significantly contribute to human welfare, both directly and indirectly (Costanza *et al* 1997). Through changes in land-use humans have appropriated a larger than ever share of the planet's resources. In the process, humans also potentially undermine the capacity of natural ecosystems to sustain food production, maintain freshwater and forest resources, regulate climate and air quality, and ameliorate infectious diseases. As a result, we face the great challenge of balancing immediate human needs and the capacity of the biosphere to provide goods and services over the long term (Foley *et al* 2005).

If on the one hand, agriculture is essential to sustain food production, on the other hand it can degrade the ecosystems and their services upon which it relies (Foley *et al* 2005). Brazil faces this challenge as pressure to convert

Content from this work may be used under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Figure 1. The Brazilian Legal Amazon.

forestlands to croplands and cattle pasturelands in the Legal Amazon continues (figure 1) (Nepstad *et al* 2008, Galford *et al* 2008, Soares-Filho *et al* 2010, Macedo *et al* 2012). In addition to providing agricultural and timber commodities, Amazon landscapes also sequester and store carbon, regulate freshwater and river flows, and influence the regional climate (Foley *et al* 2007, Davidson *et al* 2012).

Another driver of environmental changes in the Amazon is the change in atmospheric composition, which may cause changes in the global climate. Most global climate models predict that greenhouse gas accumulation and associated increases in the radiative forcing of the atmosphere will cause a substantial (more than 20%) decline in rainfall in eastern Amazonia by the end of the century, with the steepest decline occurring during the dry season (Malhi *et al* 2008).

In addition to the radiative effect of CO_2 as a greenhouse gas, atmospheric CO_2 has a physiological effect on vegetation canopy processes; higher partial pressure of CO_2 in the atmosphere often stimulates canopy photosynthesis and decreases stomatal conductance, increasing the water-use efficiency of plants, in particular of C3 plants (Sellers *et al* 1996).

Here, we focus on the three major services provided by the Amazon ecosystems: climate regulation, carbon storage, and agriculture production. Our study evaluates how local climate patterns are modified under different deforestation scenarios, and the role of radiative and physiological effects of CO_2 on these ecosystem services. In doing so, we aim to assess the resilience of the primary forests and productivities of soybean and pastures in the Amazon under scenarios of deforestation and increased CO_2 concentration.

We evaluate the carbon storage of the primary forests and the productivity of soybean and pasture in the Amazon under several scenarios of regional deforestation and increased CO_2 using a simplified model that represents the interactions between climate and land use. We analyze four different scenarios for 2050, considering: (1) radiative effects of increased CO_2, (2) radiative and physiological effects of increased CO_2, (3) effect of changes in land use on the regional climate and (4) radiative and physiological effects of increased CO_2 plus the effect of changes in land use on climate. In all cases, the 2050 climate is the average of the period 2041–2060.

2. Productivity models

The primary forest, soybean and pasture productivity models were implemented using Dinamica EGO, an environmental modeling platform for the design of analytical and space–time models (Soares-Filho *et al* 2013)). Figure 2 shows the basic structure of the model developed.

Primary forest productivity is simulated using the CARLUC model (carbon and land-use change) designed by Hirsch *et al* (2004). During each monthly time step, the model assumes that wood, leaf, and root carbon pools increase by an overall amount equal to the Net Primary Productivity (NPP), given by:

$$\mathrm{NPP} = \mathrm{cue} \times \mathrm{qe} \times \mathrm{PAR} \times f_{\mathrm{APAR}} \times f_{\mathrm{Temp}} \times \min(f_{\mathrm{SW}}, f_{\mathrm{VPD}}). \quad (1)$$

This formulation is based on the 3-PG model by Landsberg and Waring (1997). NPP is driven by photosynthetically active radiation (PAR, moles of photons m^{-2} $month^{-1}$), and modified by four dimensionless functions representing vapor pressure deficit (f_{VPD}, 0–1); temperature (f_{Temp}, 0–1); soil water (f_{SW}, 0–1); and fraction of absorbed photosynthetically active radiation (f_{APAR}, 0–1) (Hirsch *et al* 2004). The carbon-use efficiency (cue, ratio of NPP to Gross Primary Productivity) and quantum efficiency (qe, mol-C mol-PAR^{-1}) parameters convert photons to net carbon stored (Hirsch *et al* 2004).

Soybean daily dry mass (DM) production is determined by the intensity of radiation and average temperature according to Costa *et al* (2009). Carbon assimilation is simulated using the concept of light-use efficiency (Monteith 1977). The physiological process is based on two specific parameters: thermal time to flowering and to seed maturation (Costa *et al* 2009). Total assimilation is allocated to different plant parts, depending on the stage of development (Costa *et al* 2009). Yield is estimated based on the percentage of dry matter allocated to reproductive organs as a function of growth stage (Costa *et al* 2009). The simulation is completed when the crop reaches physiological maturity (Costa *et al* 2009). The model that describes the dynamics of soybean daily dry matter accumulation is as follows:

$$\frac{\mathrm{dDM}}{\mathrm{d}t} = \mathrm{qe} \times \mathrm{PAR} \times f_{\mathrm{APAR}} \times f_{\mathrm{Temp}} \times f_{\mathrm{SW}}. \quad (2)$$

Pasture dry mass accumulation is calculated as a dynamic system consisting of live (green) and dead tissues according to McCall and Bishop-Hurley (2003). Live tissue enters the system as a result of photosynthesis (McCall and Bishop-Hurley 2003). If not consumed, live tissue eventually senesces and flows into the dead pool (McCall and Bishop-Hurley 2003):

$$\frac{\mathrm{dDM}}{\mathrm{d}t} = \mathrm{PAR} \times \mathrm{qe} \times f_{\mathrm{APAR}} \times f_{\mathrm{Temp}} \times f_{\mathrm{SW}} - \sigma_t \times f_{\mathrm{SE}} \times \mathrm{DM}. \quad (3)$$

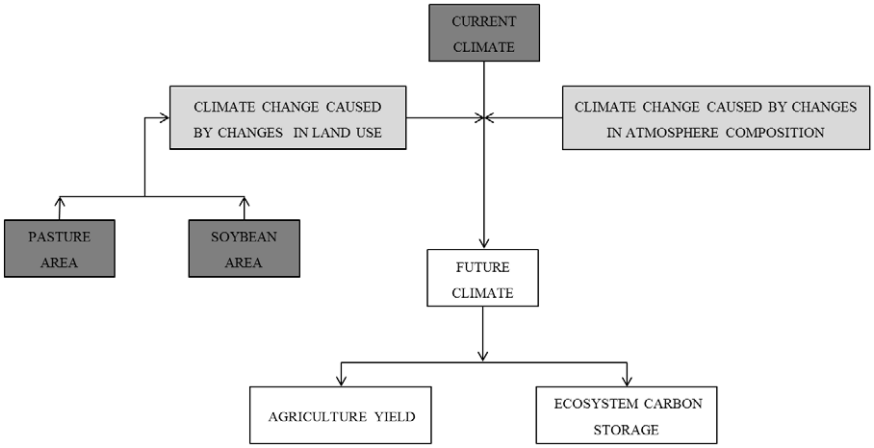

Figure 2. Block diagram of the model developed.

Senescence is proportional to the amount of live green mass (DM). The base senescence rate (σ_t) varies seasonally, assuming greater values in the post-reproductive period of grasses (McCall and Bishop-Hurley 2003). Senescence rate is also determined as a function of the available water content (f_{SE}) (McCall and Bishop-Hurley 2003). At low levels of available soil water, senescence increases above base levels (McCall and Bishop-Hurley 2003).

In all three models, temperature affects net carbon assimilation penalizing it when it is outside the range of optimum temperature. Optimum temperature range for primary forest is from 25 to 29 °C, for pasture is from 30 to 35 °C and for soybeans is from 28 to 32 °C.

Validation of the productivity models is presented in the online supplementary material (available at stacks.iop.org/ERL/8/024021/mmedia).

3. Climate datasets and experiment design

To evaluate the productivity of primary forests, soybeans and pastures, we conduct five sets of simulations that represent the present climate and climate change due to changes in atmospheric composition and Amazon deforestation, as follows:

(a) Control run: to estimate the current productivity of agricultural crops and primary forests, we used the climate database developed by Sheffield *et al* (2006) for the period between 1971 and 2000. This database is constructed by combining a suite of global observation-based datasets, disaggregated to 3-hourly time intervals using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis. The variables used are precipitation, air temperature, downward shortwave radiation, surface pressure and specific humidity. A comparison of the simulated productivity values against the observations is presented in the online supplementary material (available at stacks.iop.org/ERL/8/024021/mmedia).

(b) Radiative effects of CO_2: these simulations consider only climate predictions for the IPCC A2 scenario for the 2041–2060 period. This scenario, published in 2000 and initially considered pessimistic, has become the most realistic CO_2 scenario for the period 2001–2010 (Van der Werf *et al* 2009). As the IPCC AR4 report shows, there is much less climate difference for the period 2020–2050 between emissions scenarios than between climate models for the same scenario. To avoid individual model biases, we used the climate anomalies simulated by seven AR4 IPCC models and added these to the climatology used in the control run. The seven models employed are (1) the NCAR CCSM3 (National Center for Atmospheric Research, USA); (2) CNRM CM3 (Centre National de Recherchés Météorologiques, France); (3) GISS ER (NASA/Goddard Institute for Space Studies, USA); (4) INM CM3.0 (Institute for Numerical Mathematics, Russia); (5) IPSL CM4 (Institute Pierre Simon Laplace, France); (6) MRI CGCM2.3.2 (Meteorological Research Institute, Japan) and (7) MIROC3.2 (Center for Climate System Research, National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan). The average of the climate anomalies from these seven climate models is likely to be more representative than the climate anomaly of any individual model.

(c) Radiative and physiological effects of CO_2: in addition to future climate conditions as described in (b), this set of simulations also considers the physiological effect of elevated CO_2 concentration on carbon assimilation by primary forests and agricultural crops. For primary forests, Lloyd and Farquhar (2008) found that, for a 170 ppm increase in CO_2 concentration, there was a 30% increase in the assimilation of carbon by tropical forests. For simplicity, we assumed that the response is linear (0.18% ppm^{-1}). For crops, Tubiello *et al* (2000) found that, for an increase of 350 ppm in the CO_2 concentration, there was a crop yield increase of 25% in C3 crops, and 10% in C4 crops. Again, assuming that this increase is linear, we used 0.0714% ppm^{-1} for soybean (C3 crop) and 0.029% ppm^{-1} for the C4 pastures that dominate in Amazonia. For the A2 scenario, the IPCC (2007) predicts 559 ppm for 2050. For the control simulation, we use 380 ppm.

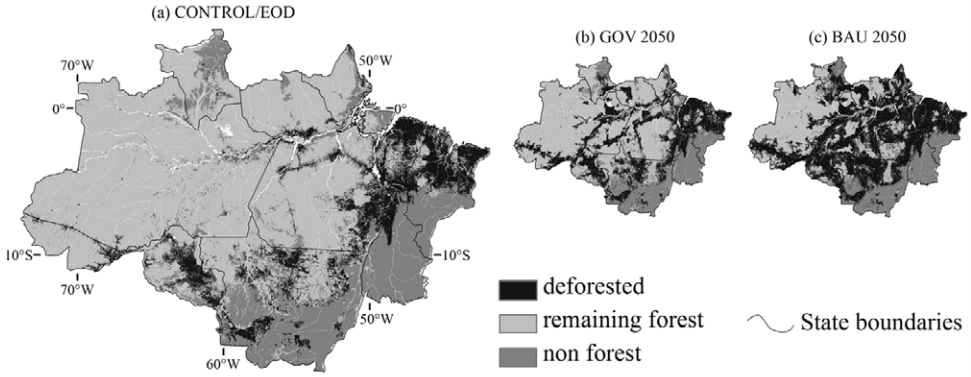

Figure 3. Scenarios of deforestation from Soares-Filho *et al* (2006) (a) control/EOD (deforested area 1.496 M km^2), (b) GOV 2050 (deforested area 2.201 M km^2) and (c) BAU 2050 (deforested area 3.623 M km^2). Reprinted by permission from Macmillan Publishers Ltd: *Nature* **440** 520–3, copyright 2006.

(d) Effect of land use on the regional climate: we considered three land-use scenarios.

(i) First, the control scenario, which is based on the 2002 deforestation map (figure 3(a)), and is just slightly different from the end-of-deforestation (EOD) land-use scenario from (Nepstad *et al* 2009). The end-of-deforestation scenario is plausible given the reversal of Amazon deforestation trend that occurred after 2004 (an accumulated decline by 2011 of 68% from the historical 1996–2005 baseline of 19 600 km^2 per year). However, there is significant pressure to expand agricultural production in Brazil to meet domestic and global demands. Brazil's powerful agricultural sector hopes to double agricultural and livestock output by 2020. The Brazilian government's Growth Acceleration Plan, for example, is a heavily capitalized, inter-ministerial program that has few environmental safeguards and will increase the profitability of deforestation-dependent activities by lowering the costs of transportation, storage, and energy (Nepstad *et al* 2011). Thus the profitability of deforestation is rising, and could remain high for many years or decades given the global outlook for continued growth in agricultural commodity prices (Grantham 2011). As a result, high rates of return to agriculture will put more pressure on the Brazilian government to soften environmental laws, such as the recent revision of the Brazilian Forest Code. In light of these events, a reversal of the trend toward decreasing deforestation in Brazil appears plausible (Soares-Filho *et al* 2012). To include these opposing trends, we included two other deforestation scenarios, the business as usual and the governance by 2050 from Soares-Filho *et al* (2006) (figure 3), described below.

(ii) The business-as-usual scenario for 2050 (BAU) assumes that: (1) recent deforestation trends will continue; (2) highways currently scheduled for paving will be paved; (3) compliance with legislation requiring forest reserves on private land will remain low; and (4) new protected areas (PAs) will not be created or not enforced. The BAU scenario assumes that as much as 40% of the forests inside of PAs are subject to deforestation, climbing to 85% outside.

(iii) The governance scenario for 2050 (GOV), assumes that Brazilian environmental legislation is implemented across the Amazon basin through the refinement and multiplication of current experiments in frontier governance. These experiments include enforcement of mandatory forest reserves on private properties through a satellite-based licensing system, agro-ecological zoning of land use, and the expansion of the PA network (Amazon Region Protected Areas Program), which has already occurred (Soares-Filho *et al* 2010). Their final product includes annual maps of simulated future deforestation under user-defined scenarios of highway paving, protected area networks, protected area effectiveness, deforestation rates and legal deforestation constraints.

These three land-use scenarios, regardless of their likelihood, cover a wide range of deforestation extents for 2050, thus allowing us to assess the effects of basinwide land-use changes on climate and the modeled ecosystem services. For analyzing the effects from climate feedbacks only, we then assume that, in the BAU and GOV scenarios, all deforested cells are either occupied by soybean crops or by pasture, totaling then five land-use scenarios. To convert land-use change to anomalies in climate, we use the semi-empirical climate model of Zeng and Neelin (1999), who demonstrate that the anomaly in precipitation (P′, in mm d^{-1}) after deforestation is proportional to the anomaly in the reflected surface radiation (Sr′, in W m^{-2}), or the incoming surface radiation multiplied by the anomaly in albedo (α'). Yanagi (2006) calculated empirical coefficients for the Zeng and Neelin model for trimester time scales (equations (4)–(7)):

$$\mathrm{P}' = -0.0527 \cdot \mathrm{Sr}' + 0.20, \qquad r^2 = 0.30, \quad \text{for Jan–Mar} \tag{4}$$

$$\mathrm{P}' = -0.0451 \cdot \mathrm{Sr}' + 0.62, \qquad r^2 = 0.43, \quad \text{for Apr–Jun} \tag{5}$$

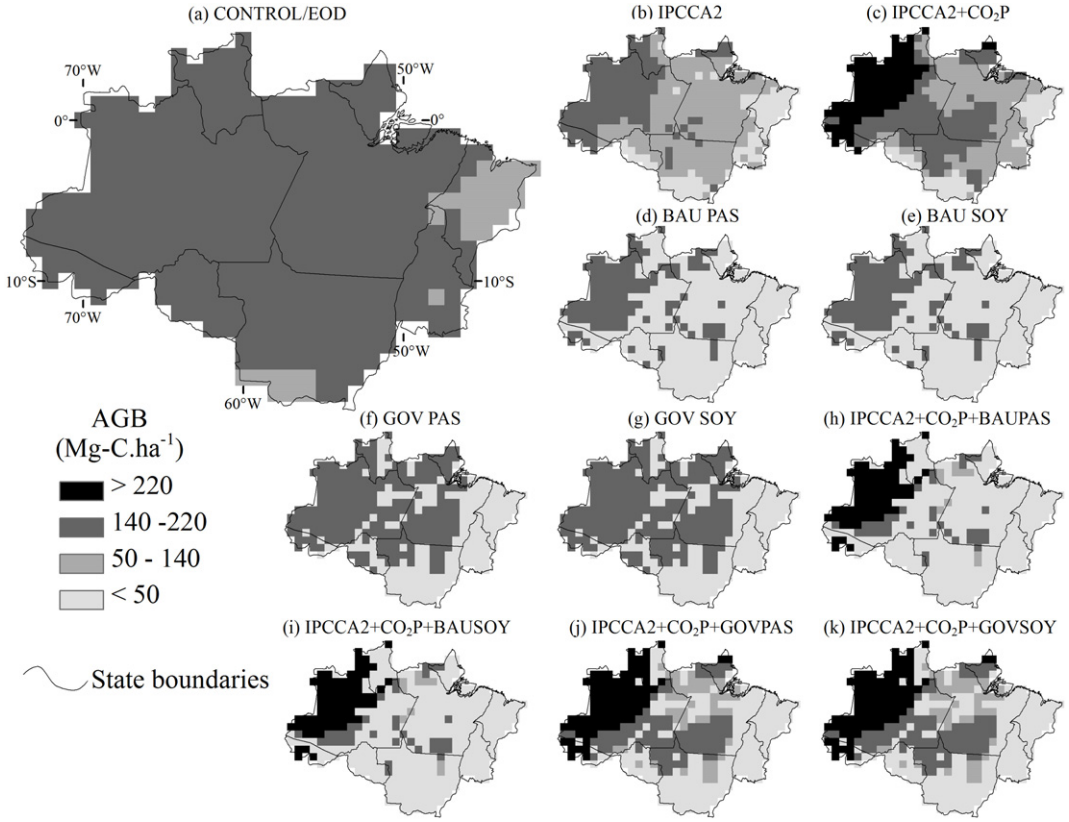

Figure 4. Spatial distribution of living aboveground biomass (Mg-C ha^{-1}) for the control/EOD scenario (a), IPCC A2 climate scenario (b), IPCC A2 climate scenario plus physiological effects of CO_2 (c), BAU deforestation scenario in which cells deforested were occupied by pasture (d), BAU deforestation scenario in which cells deforested were occupied by soybean (e), GOV deforestation scenario in which cells deforested were occupied by pasture (f), GOV deforestation scenario in which cells deforested were occupied by soybean (g), IPCC A2 climate scenario plus physiological effect of CO_2 plus BAU deforestation scenario in which cells deforested were occupied by pasture (h), IPCC A2 climate scenario plus physiological effect of CO_2 plus BAU deforestation scenario in which cells deforested were occupied by soybean (i), IPCC A2 climate scenario plus physiological effect of CO_2 plus GOV deforestation scenario in which cells deforested were occupied by pasture (j), IPCC A2 climate scenario plus physiological effect of CO_2 plus GOV deforestation scenario in which cells deforested were occupied by soybean (k) for the period 2041–2060.

$$P' = -0.0444 \cdot Sr' + 0.03, \qquad r^2 = 0.37, \quad \text{for Jul–Sep} \tag{6}$$

$$P' = -0.1266 \cdot Sr' + 1.29, \qquad r^2 = 0.29, \quad \text{for Oct–Dec.} \tag{7}$$

The surface albedo in each land-use scenario is calculated as a weighted average of the different types of land cover (13% for the forest, and 11% for bare land). For pastures and soybeans, albedo depends on LAI, reaching a maximum of 20% for pastures and 26% for soybeans (Costa *et al* 2007). Finally, we use equations (1)–(3) to calculate productivity of primary forests and agriculture and compare simulations outputs for the year 2050 with those of the control run. We also perform simulations with the land-use scenarios but without the climate model, i.e., climate feedbacks are not included.

(e) Radiative and physiological effects of CO_2 plus the effects of changes in land use: to evaluate the combined effect of all factors on the primary forests, soy and pastures, our model adds projections of climate change calculated by different IPCC AR4 models and the physiological effect of CO_2 (item c) to the climate change induced by land-use change (item d). The simulated yields for the 2041–2060 period are compared to those of the control run.

To assess the response of primary forests and agricultural systems, we compared simulated productivity of the primary forests, crops and pastures under scenarios of climate and deforestation to those simulated under current conditions. The statistical significance of differences was evaluated using the test *t* of Student. When the output mean from the modeled scenario was not different from the control (current climate) at 5% level of significance, the system is considered resilient.

4. Results

4.1. Resilience of carbon storage

Simulated values of AGB for current conditions are presented in figure 4(a). Total AGB in primary forest in the Legal Amazon is 91.5 Pg-C, with an average of 179 Mg-C ha^{-1} (table 1), which is in the range of 85–140 Pg-C estimated by an interpolation of field estimates (Malhi *et al* 2006).

Table 1. Mean values of living aboveground biomass in each scenario (Mg-C ha^{-1}), % variation from the control, *P* values and total living aboveground biomass in Legal Amazon (Pg-C, uncertainties are reported as the 95% confidence range) for the 2041–2060 period. NF indicates simulations without climate feedback. Calculations of total AGB consider the area of the rainforest in the legal Amazon (5.119 M km^2).

Scenario	AGB per unit area			Total AGB in Legal Amazon (Pg-C)
	Mean values (Mg-C ha^{-1})	Variation %	*P*	
Control/EOD	179			91.5 ± 15.7
IPCC A2	109	−39.1	<0.01	55.7 ± 12.7
IPCC A2 + CO_2P	145	−19.0	<0.01	74.4 ± 13.6
BAU_PAS$_{NF}$	74	−58.6	<0.01	38.2 ± 12.2
BAU_SOY$_{NF}$	59	−67.0	<0.01	30.2 ± 13.9
GOV_PAS$_{NF}$	118	−34.1	<0.01	60.3 ± 14.1
GOV_SOY$_{NF}$	110	−38.6	<0.01	56.4 ± 11.5
BAU_PAS	69	−61.5	<0.01	35.6 ± 13.9
BAU_SOY	59	−67.0	<0.01	30.2 ± 14.3
GOV_PAS	117	−34.6	<0.01	59.8 ± 14.2
GOV_SOY	110	−38.6	<0.01	56.4 ± 14.5
IPCC A2 + CO_2P + BAU_PAS	74	−58.7	<0.01	37.9 ± 14.5
IPCC A2 + CO_2P + BAU_SOY	64	−64.3	<0.01	32.5 ± 14.8
IPCC A2 + CO_2P + GOV_PAS	112	−37.4	<0.01	57.5 ± 14.6
IPCC A2 + CO_2P + GOV_SOY	105	−41.3	<0.01	54.0 ± 14.9

Climate warming alone leads to simulated reductions in the ecosystem carbon storage of 39% for the 2041–2060 period (table 1, figure 4(b)). This decline in biomass occurs mainly in the eastern Amazon, because the projected climate is +2.3 °C warmer on average and drier in these regions. When including the physiological effect a different pattern emerges, with significant increases in biomass in western Amazonia for the period 2041–2060 (figure 4(c)). The physiological effect of CO_2 in this region plays an important role in increasing ecosystem productivity despite warmer conditions due to increased water-use efficiency (figures 4(b) and (c)). Legal Amazonia AGB changes in the scenario IPCC A2 + CO_2P is about −34 Pg-C, or −19%, in the range of +3% to −28% change in carbon storage found by Galbraith *et al* (2010) in their three Dynamic Global Vegetation Model intercomparison study for the scenario A2. In BAU 2050 scenario when the deforested areas are converted to soy, AGB declines by 67% compared to the control (table 1, figure 4(e)). The decline is the same in the simulations with and without climate feedbacks. When the deforested land is replaced by pasture, AGB decreases by 62% in the simulation with climate feedbacks and 59% in the simulation without climate feedback. (table 1, figure 4(d)). This decrease is a combination of the forest biomass removal itself, and the resulting climate change, which feeds back on the ecosystem productivity. When all the effects are analyzed together, AGB declines by up to 65% for the period 2041–2060 (table 1 and figure 4(i)).

In summary, for all 2041–2060 scenarios, the live AGB was significantly lower than that obtained in the control simulation, 179 Mg-C ha^{-1} (table 1). These results indicate that, under all modeled scenarios, the live carbon stored by the forest is not resilient to changes in climate and land use.

4.2. Resilience of pasture yield

Pasture productivity for the year 2050 is reduced, only in Tocantins and Maranhão states, mainly as a result of decreased precipitation (figure 5(b)). Increased temperature is not a significant factor because the optimal growth range of C4 pasture is 30–35 °C, which is well below the average Amazon temperature of 25 °C. Significant differences in the spatial distribution of simulated pasture productivity do not occur when the physiological effect of CO_2 is considered (figure 5(c)). In response to expansion of the area cleared (no climate feedbacks), the results suggest a 4% decrease in average values of pasture productivity for BAU scenario (figure 5(d)) and 2% for GOV scenario (figure 5(e)). Although no climate feedbacks are included, these small yield reductions are explained by the expansion of agriculture land to areas where present climate supports less photosynthesis (e.g. higher cloudiness, lower incoming PAR at surface). Simulations considering the climate effects of land-use change on pasture productivity show very low productivity in the northern states of Maranhão and Pará. An important result of this simulation is the suggestion that the expansion of pasturelands to these regions decreases simulated precipitation and pasture yields to a point that cattle ranching becomes unviable in regions where it occupies today, such as eastern Pará and northern Maranhão (figures 5(f) and (g)). With all the effects combined together, regional pasture productivity declines by up to 33% by 2050 (table 2).

For the period 2041–2060, pasture productivity shows resiliency at the 95% confidence level only under the scenario where the physiological effects of CO_2 offsets the radiative induced climate change (IPCC A2 + CO_2P) (table 2). However, climate feedbacks from deforestation cause a reduction in precipitation that reduces pasture productivity by 28–33% compared to the control.

4.3. Resilience of soybean yield

Mean productivity of soybean for the control/EOD scenario is 2.7 Mg-grains ha^{-1}, (table 3), with highest productivities simulated in Mato Grosso and Tocantins (figure 6(a)).

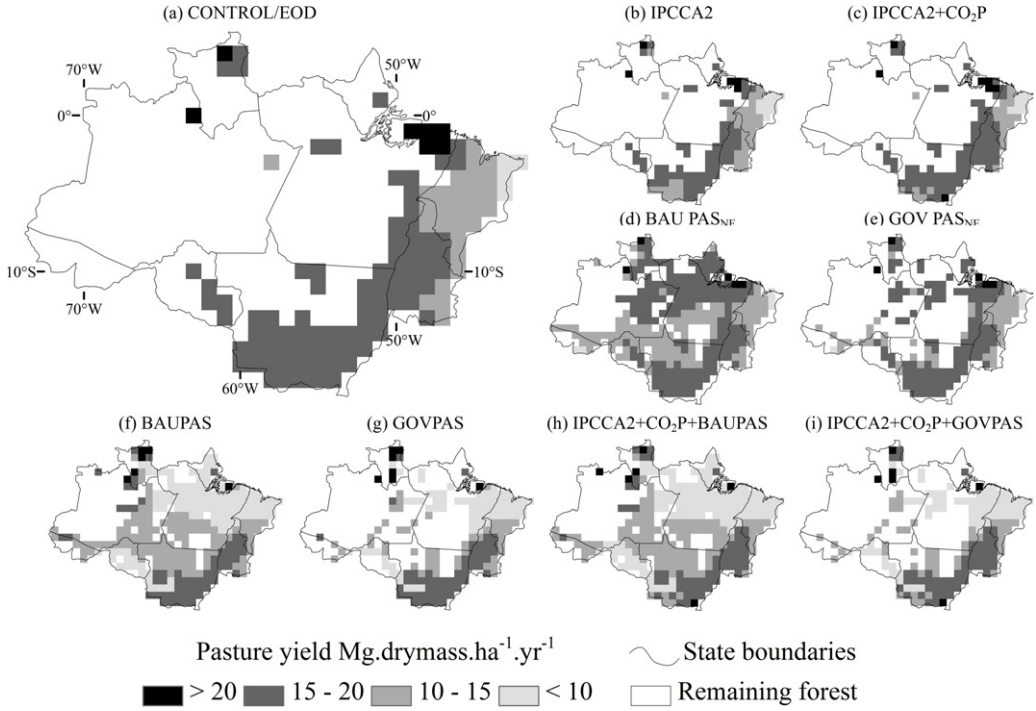

Figure 5. Spatial distribution of pasture yield (Mg-dry mass ha^{-1} yr^{-1}) for the control/EOD scenario (a), IPCC A2 climate scenario (b), IPCC A2 climate scenario plus physiological effect of CO_2 (c), BAU deforestation scenario without climate feedback (d), GOV deforestation scenario without climate feedback (e), BAU deforestation scenario with climate feedback (f), GOV deforestation scenario with climate feedback (g) IPCC A2 climate scenario plus physiological effect of CO_2 plus BAU deforestation scenario (h) and IPCC A2 climate scenario plus physiological effect of CO_2 plus GOV deforestation scenario (i) for the period 2041–2060.

Table 2. Mean values of pasture yield in each scenario (Mg-dry mass ha^{-1} yr^{-1}), % variation from the control, *P* values and total pasture production in Legal Amazon (Pg-dry mass yr^{-1}, uncertainties are reported as the 95% confidence range) for the 2041–2060 period. NF indicates simulations without climate feedback.

Scenario	Pasture yield per unit area			Pasture planted area (M km^2)	Total pasture production (Pg-DM yr^{-1})
	Mean values (Mg-DM ha^{-1} yr^{-1})	Variation %	*P*		
Control/EOD	16.2			1.496	2.42 ± 0.08
IPCC A2	15.0	−7.4	<0.01	1.496	2.25 ± 0.08
IPCC A2 + CO_2P	16.3	0.6	0.95	1.496	2.44 ± 0.09
BAU_PAS_{NF}	15.5	−4.3	0.01	3.623	5.62 ± 0.23
GOV_PAS_{NF}	15.9	−1.8	0.36	2.201	3.50 ± 0.16
BAU_PAS	11.0	−32.1	<0.01	3.623	3.99 ± 0.21
GOV_PAS	11.6	−28.4	<0.01	2.201	2.56 ± 0.19
IPCC A2 + CO_2P + BAU_PAS	10.8	−33.3	<0.01	3.623	3.91 ± 0.22
IPCC A2 + CO_2P + GOV_PAS	11.4	−29.6	<0.01	2.201	2.51 ± 0.19

Table 3. Mean values of soybean yield in each scenario (Mg-grains ha^{-1}), % variation from the control, *P* values for the 2041–2060 period. NF indicates simulations without climate feedback.

Scenario	Soybean yield		
	Mean values (Mg-grains ha^{-1})	Variation %	*P*
Control/EOD	2.7		
IPCC A2	2.0	−25.9	<0.01
IPCC A2 + CO_2P	2.5	−7.4	0.20
BAU_PAS_{NF}	2.3	−14.8	<0.01
GOV_PAS_{NF}	2.3	−14.8	<0.01
BAU_SOY	2.0	−25.9	<0.01
GOV_SOY	2.2	−18.5	<0.01
IPCC A2 + CO_2P + BAU_SOY	1.8	−33.3	<0.01
IPCC A2 + CO_2P + GOV_SOY	1.9	−29.6	<0.01

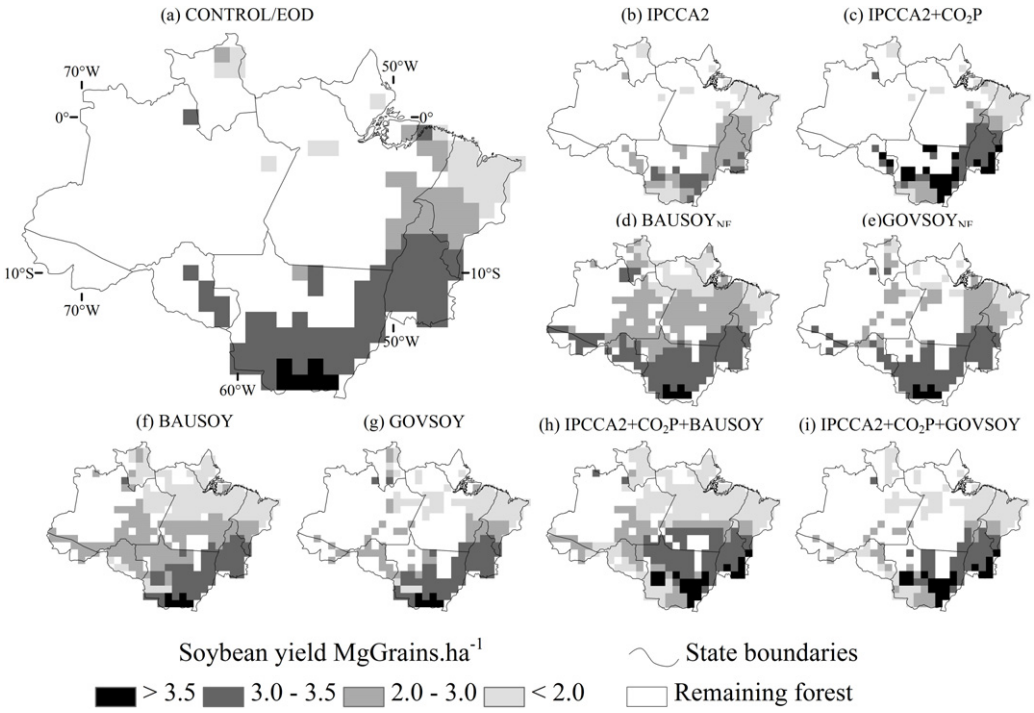

Figure 6. Spatial distribution of soybean yield (Mg-grains ha^{-1}) for the control/EOD scenario (a), IPCC A2 climate scenario (b), IPCC A2 climate scenario plus physiological effect of CO_2 (c), BAU deforestation scenario without climate feedback (d), GOV deforestation scenario without climate feedback (e), BAU deforestation scenario with climate feedback (f), GOV deforestation scenario with climate feedback (g) IPCC A2 climate scenario plus physiological effect of CO_2 plus BAU deforestation scenario (h) and IPCC A2 climate scenario plus physiological effect of CO_2 plus GOV deforestation scenario (i) for the period 2041–2060.

Reductions in soybean yields are predicted in response to future modeled climates for the 2041–2060 period. The reduction is greatest in the states of Maranhão and southern Mato Grosso (figure 6(b)). The decrease in soybean yield is associated with the shortening of the phenological phase due to changes in the growing-degree days in a warmer climate. Moreover if temperatures are above optimum range for soybean, the f_{Temp} function in the model penalizes the carbon assimilation. The sowing date considered is 15 October, well into the rainy season in most of Amazonia; decreases in rainfall projected by the IPCC models or due to changes in land-use affect only the most arid regions in the borders of the Amazon. Therefore, the simulated productivity decrease is not associated with rainfall changes. For soybeans, the physiological effect of CO_2 is sufficient to mitigate the effects of future climate conditions on productivity, except in southern Mato Grosso (figure 6(c)). For the year 2050 (figures 6(f) and (g)), results indicate that the climatic effects of soybean expansion northward of latitude 5°S may decrease soy productivity in these regions. Soybean yield simulated under all combined scenarios is greater than 2.0 Mg-grains ha^{-1} in 55% of the soybean area in the scenario GOV and in 62% of the soybean acreage in the scenario BAU, respectively. However in the region northward of 5°S, representing 35% of the cultivated area in the two scenarios, yield is lower than 1.2 Mg-grains ha^{-1} (figure 6(h)).

Mean soybean yield under all scenarios is lower than that of the control simulation (table 3). However, for the scenarios that consider only the radiative and physiological effects of CO_2, we verified that the averages for the year 2050 are not significantly different than that of the control simulation. For all other scenarios, the *t*-test was significant ($P < 0.01$). We also observed that the lowest productivity occur in the scenarios in which climate change due to changes in atmospheric composition and deforestation are evaluated together.

5. Discussion and conclusions

Three important results from our analysis stand out:

First, in nearly every scenario considered, both carbon storage and agriculture yield decrease in Amazonia in the first half of the 21st century. Loss of carbon storage from the primary forests is a consequence of a relatively drier and warmer Amazon climate in the first half of the 21st century, although this effect is partially compensated by the physiological effects of rising CO_2. Moreover, expansion of agriculture land (scenarios GOV and BAU) introduces climate feedbacks that reduce rainfall in all the seasons, thereby affecting the yield in all land uses. Considering all the effects, individually and combined, carbon storage decreases in every modeled scenario, while pasture and soybean yields are resilient only in scenarios in which there is no expansion of agriculture land and subsequent climate feedback.

Second, our results indicate that trading carbon storage in Amazon ecosystems for alleged increases in agriculture output could be a no-win scenario (lose–lose situation). Carbon storage in 2050 decreases from 145 Mg-C ha^{-1} (IPCC

A2 + CO_2P) to 105–112 Mg-C ha^{-1} under the governance scenarios (a reduction of 23–27%), and 64–74 Mg-C ha^{-1} in the business-as-usual scenarios (a reduction of 49–56%). Similarly, pasture productivity in 2050 decreases from 16.3 Mg-dry mass ha^{-1} yr^{-1} (end-of-deforestation scenario), to 11.4 Mg-dry mass ha^{-1} yr^{-1} in the GOV scenario (a reduction of 30%), and to 10.8 Mg-dry mass ha^{-1} yr^{-1} in the BAU scenario (a reduction of 34%), a consequence of the climate feedbacks. Similarly, soybean yield in 2050 decreases from 2.5 Mg-grains ha^{-1} (no additional deforestation scenario), to 1.9 Mg-grains ha^{-1} in the GOV scenario (a reduction of 24%), and to 1.8 Mg-grains ha^{-1} in the BAU scenario (a reduction of 28%).

In sum, an increase in agriculture area of 47% (2.201/1.496, these values refers to deforested area in GOV2050 scenario and in the EOD scenario, respectively, see figure 3 and table 2) under the 2050 GOV scenario is offset by a decrease of 24–30% in agriculture yield, resulting in a net change of pasture output of only 3% ($1.47 \cdot 0.70 = 1.03$, the value 1.47 refers to the 47% expansion of the deforested area and the 0.70 refers to 30% decrease in agricultural productivity). If the entire new deforested land were occupied by soybeans (a somewhat unrealistic scenario) the net change of soybean output would be 12% ($1.47 \cdot 0.76 = 1.12$, the value 1.47 refers to the 47% expansion of the deforested area and the 0.76 refers to 24% decrease in agricultural productivity) in the GOV scenario. This would be the best situation in terms of total soybean output for the region. In a more realistic soybean expansion scenario, in which soybean area expands by 10% (Gouvello *et al* 2010), and the remaining deforested area is occupied by pasturelands, total soybean output would decrease by 16% ($1.10 \cdot 0.76 = 0.84$, the value 1.17 refers to the 10% expansion of the deforested area and the 0.76 refers to 24% decrease in agricultural productivity) under the GOV scenario, again a consequence of regional climate change due to deforestation.

In the 2050 BAU scenario, an increase in agriculture area of 142% (figure 3) is offset by a decrease of 33–34% in agriculture yield (table 3), leaving a net change of pasture output of 60% ($2.42 \cdot 0.66 = 1.60$, the value 2.42 refers to the 142% expansion of the deforested area and the 0.66 refers to 34% decrease in agricultural productivity). In the more realistic soybean expansion scenario (10% soybean expansion and the remaining deforested area occupied by pasturelands), total soybean output would decrease by 26% ($1.10 \cdot 0.67 = 0.74$, the value 1.10 refers to the 10% expansion of the deforested area and the 0.67 refers to 33% decrease in agricultural productivity).

To summarize our second point, agriculture expansion in Amazonia may impose a large loss of several ecosystem services. One of the services quantified here, carbon storage, would decrease from 23% to 56% depending on the land-use scenario. Other losses in ecosystem services, although not quantified here, will most likely ensue, including biodiversity loss and spread of infectious diseases (Foley *et al* 2007). Yet the expected increase in agriculture output that would compensate (and justify) such losses may not occur. In our simulations, pasture production may increase by only 3%, and soybean production may decrease by 16% in the governance land-use scenario. In BAU scenario (142% increase in Amazon agriculture area), pasture output may increase by 60%, and soybean output may actually decrease by 26%. In all cases, a no-win situation is realized: the loss of ecosystem services is associated with a loss in soybean productivity and total Amazon soybean production. In turn, pasture total output would be much lower than that expected from pasture expansion. This unexpected no-win scenario arises as a consequence of the climate feedbacks introduced from changes in land use, which were usually ignored in previous studies.

This leads to our third conclusion: large-scale expansion of agriculture in Amazonia may be self-defeating. This is particularly worrisome for eastern Pará and northern Maranhão, where local precipitation appears to depend strongly on forests, and changes in land cover would drastically affect the local climate, maybe, to a point that agriculture becomes unviable.

Our results are subject to a number of caveats. First, we used simple linear models that, although representing the most relevant processes involved, may miss second order processes or feedbacks. Nevertheless, our climate feedback results are comparable, both in the direction and magnitude of the response, to the results of more sophisticated global climate models used by Sampaio *et al* (2007) and Costa and Pires (2010), who investigated the effects of the same land-cover change scenarios on the climate of Amazonia.

Second, model bias can never be eliminated, regardless of model complexity. We can only overcome this limitation by using multiple model ensembles, which lies beyond the scope of this study. On the other hand, we avoided single model bias in the future climate scenarios by using future climate results from seven different IPCC models.

Third, uncertainties in the future scenarios cannot be eliminated, either in predicted climate (IPCC A2) or land-use trajectories. A steep decline in deforestation rates in the Brazilian Amazon in recent years demonstrates that land-use trajectories can change drastically in a short period of time (Soares-Filho *et al* 2012). However, future efforts to reduce deforestation will need to address the increasing global demand for food production (especially protein from cattle and soy) that will build up pressure to expand the agriculture frontier, especially in southern and eastern Amazon (Lapola *et al* 2011).

Fourth, the scenarios used here do not consider possible agriculture land abandonment, and subsequent forest regrowth, and thus these effects are not included in the carbon storage calculations. If these effects were included, the results would be intermediate between the control and each deforested scenario.

As a final word, large-scale agriculture expansion in Amazonia may introduce climate feedbacks that would reduce precipitation, leading agriculture expansion in Amazonia to become self-defeating: the results of this study suggest that the more agriculture expands, the less productive it becomes. This would be a no-win situation, in which we all lose. Therefore, agriculture expansion in Brazil should prioritize land already

converted and must be accompanied with comprehensive forest conservation to counteract externalities of this process.

Acknowledgments

This research had support from the Brazilian agencies CNPq and CAPES, NSF grant DEB0743703, NASA grant NNX11AE56G, The Gordon and Betty Moore Foundation, and Climate and Land Use Alliance.

References

Costa L C, Justino F, Oliveira L J C, Sediyama G C, Ferreira W P M and Lemos C F 2009 Potential forcing of CO_2, technology and climate changes in maize (Zea mays) and bean (Phaseolus vulgaris) yield in southeast Brazil *Environ. Res. Lett.* **4** 014013

Costa M H and Pires G F 2010 Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation *Int. J. Climatol.* **30** 1970–9

Costa M H, Yanagi S N M, Souza P J O P, Ribeiro A and Rocha E J P 2007 Climate change in Amazonia caused by soybean cropland expansion, as compared to caused by pastureland expansion *Geophys. Res. Lett.* **34** L07706

Costanza R *et al* 1997 The value of the world's ecosystem services and natural capital *Nature* **387** 253–60

Davidson E A *et al* 2012 The Amazon Basin in transition *Nature* **481** 321–8

Foley J A *et al* 2005 Global consequences of land use *Science* **309** 570–4

Foley J A *et al* 2007 Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin *Front. Ecol. Environ.* **5** 25–32

Galbraith D, Levy P E, Sitch S, Huntingford C, Cox P, Williams M and Meir P 2010 Multiple mechanisms of Amazonian forest biomass losses in three dynamic global vegetation models under climate change *New Phytol.* **187** 647–65

Galford G L, Mustard J F, Melillo J, Gendrin A, Cerri C C and Cerri C E P 2008 Wavelet analysis of MODIS time series to detect expansion and intensification of row-crop agriculture in Brazil *Remote Sens. Environ.* **112** 576–87

Gouvello C, Soares-Filho B, Nassar A, Schaeffer R, Jorge F and Nogueira W 2010 *Brazil Low-Carbon Country Case Study* (Washington, DC: World Bank) (http://siteresources.worldbank.org/BRAZILEXTN/Resources/Brazil_LowcarbonStudy.pdf)

Grantham J 2011 Time to wake up: days of abundant resources and falling prices are over forever *GMO Quarterly Letter* April 2011 (available at www.theravinaproject.org/JGLetterALL_1Q11.pdf)

Hirsch A I, Little W S, Houghton R A, Scott N A and White J D 2004 The net carbon flux due to deforestation and forest re-growth in the Brazilian Amazon: analysis using a process-based model *Glob. Change Biol.* **10** 908–24

IPCC 2007 Summary for policymakers *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed M L Parry, O F Canziani, J P Palutikof, P J van der Linden and C E Hanson (Cambridge: Cambridge University Press) pp 7–22

Landsberg J J and Waring R H 1997 A generalized model of forest productivity using simplified concepts of radiation use efficiency, carbon balance and partitioning *For. Ecol. Manag.* **95** 209–28

Lapola D M *et al* 2011 Impacts of climate change and the end of deforestation on land use in the Brazilian legal Amazon *Earth Interact.* **15** 16

Lloyd J and Farquhar G D 2008 Effects of rising temperatures and $[CO_2]$ on the physiology of tropical forest trees *Phil. Trans. R. Soc.* B **363** 1811–7

Macedo M N, DeFries R S, Morton D C, Stickler C M, Galford G L and Shimabukuro Y E 2012 Decoupling of deforestation and soy production in the southern Amazon during the late 2000s *Proc. Natl Acad. Sci. USA* **109** 1341–6

Malhi Y *et al* 2006 The regional variation of aboveground live biomass in old-growth Amazonian forests *Global Change Biol.* **12** 1107–38

Malhi Y, Roberts J T, Betts R A, Killeen T J, Li W and Nobre C A 2008 Climate change, deforestation, and the fate of the Amazon *Science* **319** 169–72

McCall D G and Bishop-Hurley G J 2003 A pasture growth model for use in a whole-farm dairy production model *Agric. Syst.* **76** 1183–205

Monteith J L 1977 Climate and the efficiency of crop production in Britain *Phil. Trans. R. Soc. Lond.* B **281** 227–94

Nepstad D C, McGrath D and Soares-Filho B S 2011 Systemic conservation, REDD, and the future of the Amazon Basin *Conserv. Biol.* **25** 1113–6

Nepstad D C, Stickler C M, Soares-Filho B and Merry F 2008 Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point *Phil. Trans. R. Soc.* **363** 1737–46

Nepstad D C *et al* 2009 The end of deforestation in the Brazilian Amazon *Science* **326** 1350–1

Sampaio G, Nobre C, Costa M H, Satyamurty P, Soares-Filho B S and Cardoso M 2007 Regional climate change over eastern Amazonia caused by pasture and soybean cropland expansion *Geophys. Res. Lett.* **34** L17709

Sellers P J *et al* 1996 Comparison of radiative and physiological effects of doubled atmospheric CO_2 on climate *Science* **271** 1402–6

Sheffield J, Goteti G and Wood E F 2006 Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling *J. Clim.* **19** 3088–111

Soares-Filho B S *et al* 2010 Role of Brazilian Amazon protected areas in climate change mitigation *Proc. Natl Acad. Sci.* **107** 10821–6

Soares-Filho B S, Lima L, Bowman M, Viana L and Gouvello C 2012 *Challenges for a Low Carbon Agriculture and Forest Conservation in Brazil* (Washington, DC: IADB) (www.iadb.org/sustainability/soares)

Soares-Filho B S, Nepstad D C, Curran L M, Cerqueira G C, Garcia R A, Ramos C A, Voll E, McDonald C, Lefebvre P and Schlesinger P 2006 Modelling conservation in the Amazon basin *Nature* **440** 520–3

Soares-Filho B S, Rodrigues H O and Follador M 2013 A hybrid analytical-heuristic method for calibrating land-use change models *Environ. Modelling Softw.* **43** 80–7

Tubiello F N, Donatelli M, Rosenzweig C and Stockle C O 2000 Effects of climate change and elevated CO_2 on cropping systems: model predictions at two Italian locations *Eur. J. Agron.* **13** 179–89

Van der Werf G R, Morton D C, DeFries R S, Olivier J G J, Kasibhatla P S, Jackson R B, Collatz G J and Randerson J T 2009 CO_2 emissions from forest loss *Nature Geosci.* **2** 737–9

Yanagi S N M 2006 Albedo of an Amazon tropical rainforest: field measurements, remote sensing, modeling, and its influence on the regional climate *PhD Thesis* Federal University of Viçosa, Brazil (available at www.tede.ufv.br)

Zeng N and Neelin J D 1999 A land–atmosphere interaction theory for the tropical deforestation problem *J. Clim.* **12** 857–72