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When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in Brazil

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ABSTRACT

Providing food and other products to a growing human population while safeguarding natural ecosystems and the provision of their services is a significant scientific, social and political challenge. With food demand likely to double over the next four decades, anthropization is already driving climate change and is the principal force behind species extinction, among other environmental impacts. The sustainable intensification of production on current agricultural lands has been suggested as a key solution to the competition for land between agriculture and natural ecosystems. However, few investigations have shown the extent to which these lands can meet projected demands while considering biophysical constraints. Here we investigate the improved use of existing agricultural lands and present insights into avoiding future competition for land. We focus on Brazil, a country projected to experience the largest increase in agricultural production over the next four decades and the richest nation in terrestrial carbon and biodiversity. Using various models and climatic datasets, we produced the first estimate of the carrying capacity of Brazil's 115 million hectares of cultivated pasturelands. We then investigated if the improved use of cultivated pasturelands would free enough land for the expansion of meat, crops, wood and biofuel, respecting biophysical constraints (i.e., terrain, climate) and including climate change impacts. We found that the current productivity of Brazilian cultivated pasturelands is 32–34% of its potential and that increasing productivity to 49–52% of the potential would suffice to meet demands for meat, crops, wood products and biofuels until at least 2040, without further conversion of natural ecosystems. As a result up to 14.3 Gt CO_2 Eq could be mitigated. The fact that the country poised to undergo the largest expansion of agricultural production over the coming decades can do so without further conversion of natural habitats provokes the question whether the same can be true in other regional contexts and, ultimately, at the global scale.

1. Introduction

Driven by the global population increase and the concomitant per capita rise in consumption (Godfray et al., 2010), the global demand for agricultural products is projected to rise over the next decades (Alexandratos and Bruinsma, 2012), likely entailing further competition for land (Smith et al., 2010). Competition for land is transboundary (Lambin and Meyfroidt, 2011; Strassburg

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et al., 2014) and although demand increase occurs in one part of the world, pressure to provide commodities may be shifted elsewhere. Lambin and Meyfroidt (2011) show that such displacement, amplified by economic globalization, is driving land conversion in developing countries. Indeed, in the 1980s and 1990s, tropical forests were primary sources of new agricultural land (Gibbs et al., 2010). According to projections from the Food and Agriculture Organization of the United Nations (FAO), land under crop cultivation in developing countries may increase by some 110 million hectares by 2050 (FAO, 2006a,b) while others forecast that as much as one billion additional tropical hectares could be converted into cultivated land by 2050 (Tilman et al., 2001). Moreover, land use and land-use change may contribute to 32% of anthropogenic greenhouse gas emissions (IPCC, 2007) and represent the main driving force behind the extinction of species (Baillie et al., 2004).

Currently, nowhere this conflict over land has the magnitude observed in Brazil. Brazil is the world's second-largest agricultural producer, with the largest forecasted increases in output over the next four decades of any country worldwide (FAO, 2006a). At the same time, Brazil is the first deforesting country (55 million hectares over 1990–2010, versus 24 million hectares in second-place Indonesia) (FAO, 2010), the nation richest in forest carbon (63 billion tonnes, versus 33 billion tonnes in Russia) (FAO, 2010) and the most biodiverse country on the planet (56,000 known plant species, versus 29,375 in Indonesia) (UNEP-WCMC, 2010). Brazilian society is currently discussing its plans for forestry and agriculture, and the government has laid out ambitious plans to reduce deforestation and land-use emissions while simultaneously increasing agricultural output (BMA, 2010). However, there are doubts whether recent reductions in Amazon deforestation can be sustained in the future without further plans that include projected demand (Nepstad et al., 2009; Lapola et al., 2014). In addition, there is evidence of increased pressure elsewhere in Brazil through production displacement, especially the Cerrado savanna (Mesquita, 2009). Cerrado is a global biodiversity hotspot, which over the last 15 years has lost 20% of its area (Mesquita, 2009).

Worldwide, sustainably increasing production on current agricultural lands has been proposed as a solution to the conflict between expanding agricultural production and conserving natural ecosystems (Godfray et al., 2010; Herrero et al., 2010; Phalan et al., 2011, 2013; Foresight, 2011; Mueller et al., 2012; Latawiec et al., 2014). It has been shown (Herrero et al., 2010; Lapola et al., 2010; Tilman et al., 2002; Burney et al., 2010) that it is possible to increase agricultural efficiency and mitigate greenhouse gases through resource conservation and improvements in land management.

In this paper, we hypothesise that Brazil existing agricultural lands are enough to sustain production at levels expected to meet future demand (including both internal consumption and exports) for meat, crops, wood and biofuels until 2040 without further conversion of natural habitats. Increasing productivity of pasturelands has been suggested as a promising resource in reconciling agricultural expansion with the reduction of the environmental impacts of agriculture in Brazil (Arima et al., 2011; Bowman et al., 2012; Bustamante et al., 2012). On account of their low productivity and total area (170 million hectares, versus 60 million hectares for crops) pasturelands indeed present an opportunity for sustainable intensification (producing more food from the same area while reducing the environmental impacts; Royal Society of and London, 2009; Godfray et al., 2010). A recent study estimates that the livestock sector holds the largest mitigation potential in Brazil because the emissions from this sector account for approximately half of all Brazilian GHG emissions (Bustamante et al., 2012).

The extent to which sustainable intensification of current pasturelands in Brazil could contribute to meeting future demands for agricultural products (including for exports) while respecting biophysical constraints has not been tested. Here we, first, show the spatial description of current pasture stocking rates (number of animals per unit of area) for Brazil. Second, we estimated the potential productivity of pasturelands expressed as their potential carrying capacity (the stocking rate at the optimum grazing pressure (Mott, 1960) which is consistent with maintaining the pasture productivity) for two climatic datasets and for Brazil's main types of fodder grass, given edaphoclimatic conditions. Third, we allocated future land uses in order to meet demands until 2040. We finally calculated greenhouse gases mitigation potential from avoided deforestation and from improved livestock management. The results presented here are not only relevant in the Brazilian context, but may also have wider implications for land-use decision-making, especially in the developing world. The analysis presented here may also be repeated at other scales to investigate whether the hypothesis tested here is true globally.

2. Materials and methods

2.1. Current productivity of Brazilian cultivated pasturelands

We used spatial data on current cultivated pasturelands from PROBIO land-use classification project (remote sensing data from TM Sensor onboard Landsat, 30-m resolution) (PROBIO, 2009) for the year 2002. We compiled only the polygons classed as 'Ap', or cultivated pasturelands, which totalled 219,122 polygons with a median area of 13 ha. PROBIO polygons are based on visual identification by experts of blocks of the same land-use category and are therefore of varying size and shapes. This totalled to 115.6 million hectares (Supplementary Material, Fig. S1). We did not include 55 million hectares of additional natural pasturelands, which are not mapped (and the topic of intensification in natural pasturelands may be more technically and ethically complex). We combined this information with census data on total cattle heads per municipality to generate a estimate of the current stocking rates in animal units (AU = 454 kg of animal live weight; The Forage and Grazing Terminology Committee, 1991) per hectare to represent the current productivity of Brazilian pasturelands (Fig. 1a) per municipality (so that all "cultivated pasturelands" polygons in the same municipality had the same value). Current productivity was estimated for all 3308 municipalities where PROBIO identified cultivated pasturelands (PROBIO, 2009).

2.2. Sustainable carrying capacity of cultivated pasturelands

A scientific assessment of our hypothesis that Brazil already has enough land under production to meet future demands includes a 'cap' for the number of animals that can be supported without degrading the pasture or requiring supplementary feed (i.e., a sustainable carrying capacity for extensive systems). This type of estimate has not yet been developed for Brazil.

We produced three independent estimates for sustainable carrying capacity, based on estimates for fodder grass herbage accumulation. Fodder accumulation values for Estimates 1 and 2 were based on Tonato et al. (2010) model (with two extra steps added in order to refine it – explained below), whereas Estimate 3 used fodder accumulation data from the Global Agro-Ecological Zones 2009 project (FAO/IIASA, 2010).

2.2.1. Estimate 1

The Tonato et al. (2010) model estimates the Climatic Potential monthly forage (fodder grass) accumulation rates (kg/ha). It was parameterised using data from five field trials performed in the

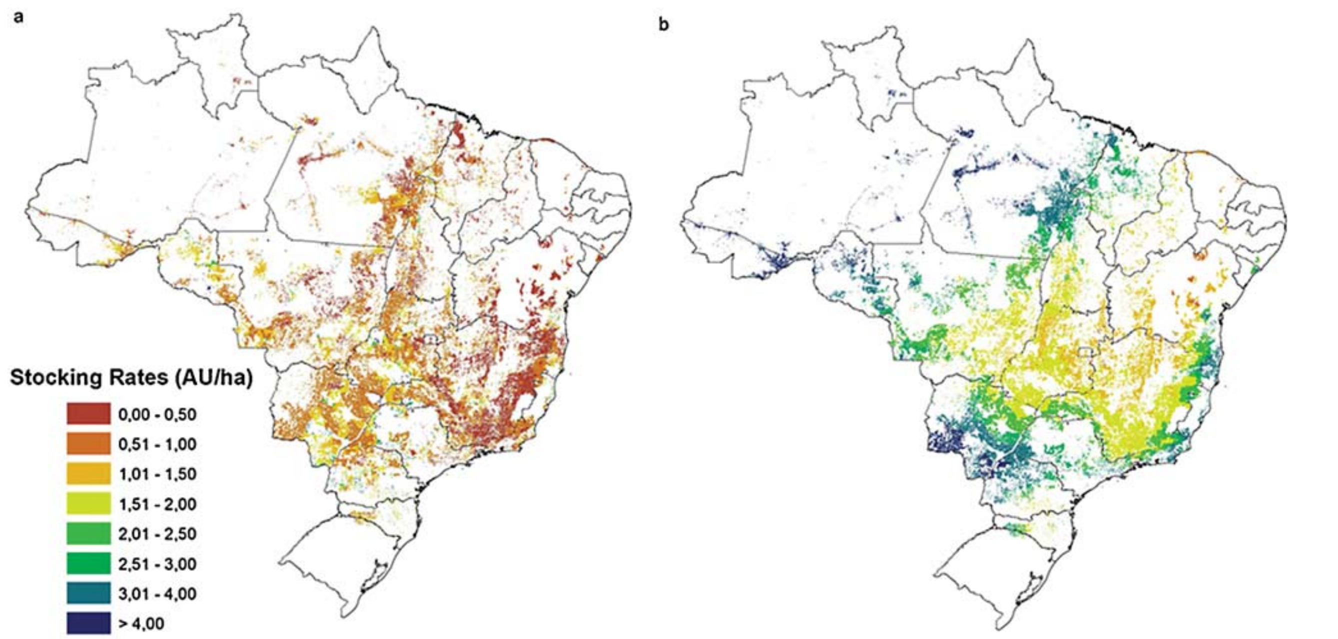

Fig. 1. Current productivity and sustainable carrying capacity of cultivated pasturelands. (a) Current cattle ranching stocking rates in Brazil in Animal Units (AU) per hectare. (b) Potential sustainable carrying capacity for extensive systems in Animal Units (AU) per hectare (Estimate 1). The colour scale, with brown being low (0.00–0.50 AU/ha) and blue being high (>4.00 AU/ha), is the same for both maps. Supplementary Fig. 2 shows two other estimates for sustainable carrying capacity.

state of São Paulo (in Southeastern Brazil) and the state Distrito Federal (in Central Brazil) for Brazil's main tropical (*Urochloa* genus) and subtropical (*Cynodon* genus) grass types. Two additional stages were added into our study to incorporate the impacts of water-deficit stress and seasonal feed deficit, leading to lower (i.e., more conservative) estimates compared to the Tonato et al. (2010) model.

The estimation of the sustainable carrying capacity composed of three steps.

Step 1 – Climatic potential forage accumulation (CPA)

Due to a high positive correlation among climatic variables (average temperature, maximum and minimum temperatures as well as global incident radiation and day of the year for each growth period), a single-variable model was adopted (Tonato et al., 2010). Following Akaike and Bayesian criteria, the monthly average minimum temperature (Tmin) offered the highest explanatory power (Tonato et al., 2010), it was therefore carried towards into our calculations. The standard error of regression was reported to range between 21 and 22 kg of dry matter per day (kg DM/d) for *Urochloa brizantha* cv. Marandu and *Cynodon* spp. cv. Tifton 85 (used in this study) (Tonato et al., 2010). For each polygon we chose one of those grasses, based on its higher climatic potential forage accumulation.

The equation relating forage accumulation potential (CPA) for genotype g and minimum temperature (Tmin) for month i in region (polygon) r is:

$$CPA_{i,r,g} = (\min(\mathrm{Tmin}_{i,r}, \mathrm{Tu}_g) - \mathrm{Tb}_g) \cdot S_g \tag{1}$$

where Tb_g is the base temperature (8.4 °C for *Cynodon* and 12.01 °C for *Urochloa*), and S_g is the productivity response to temperature (7.97 for *Cynodon* and 10.66 for *Urochloa*). Tu is the upper limit for productivity response to temperature, assumed as being 20 °C for both genotypes.

Step 2 – Water-restricted potential forage accumulation (WRA)

To include the negative impact of water deficit on potential forage accumulation, we multiplied, for each month, the climatic potential forage accumulation estimated above by the water requirement satisfaction index (WRSI). Water requirement satisfaction index varies from zero to one and represents the fraction of the water actually consumed by plants by the total amount of water that would be needed by plants to ensure maximum productivity. A water requirement satisfaction index of 1 means there is no water stress. The water requirement satisfaction index is calculated through the evapotranspiration deficit (Allen et al., 1998), i.e., the ratio between the actual evapotranspiration (AETc) and potential crop evapotranspiration (PETc). Evapotranspiration, the sum of evaporation and plant transpiration, was calculated according to the method described in Camargo et al. (1999). Actual pasture evapotranspiration was reduced whenever there was not enough soil water to achieve monthly potential evapotranspiration. Evapotranspiration is here a function of monthly precipitation (R), soil water-holding capacity (WHC), and monthly mean and maximum temperatures. A simplified soil water balance model (one compartment with soil-dependent depth of plant root system) with a one-month time step was used to calculate soil water content throughout the year for normal climate data. Formally:

$$PETc_{i,r} = kc \cdot Q_{0_{i,r}} \cdot \bar{T}_{i,r} \cdot N_i \tag{2}$$

$$PSW_{i,r} = SW_{i-1,r} + R_{i,r} - PETc_{i,r} \tag{3}$$

$$SW_{i,r} = \begin{cases} \max(PSW_{i,r}, WHC_r), & PSW_{i,r} \geq 0 \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$$AETc_{i,r} = \begin{cases} PETc_{i,r}, & PSE_{i,r} \geq 0 \\ SW_{i-1,r} + R_{i,r}, & \text{otherwise} \end{cases} \tag{5}$$

$$WRSI_{i,r} = \frac{AETc_{i,r}}{PETc_{i,r}} \tag{6}$$

where $SW_{i,r}$ is the soil water content for the ith month in region r (mm), $R_{i,r}$ is the rainfall in the ith month (mm) in region r, kc is the single crop coefficient (assumed to be equal to 1.0 for grazed pastures, which is a conservative value within the range of 0.75 to 1.05 recommended for grazing pasture (Allen et al., 1998)), $PETc_{i,r}$ is the potential crop evapotranspiration in the ith month in region r (mm), $AETc_i$ is the actual crop evapotranspiration in the ith month (mm), Q_0 is the global solar radiation, ($T\bar{T}_{i,r}$ and WHC is the soil water-holding capacity (mm)).

Water-restricted pasture forage accumulation (WRA, kg/ha/d) for month i, region r and genotype g was then estimated, in dry-matter basis, as:

$$WRA_{i,r,g} = CPA_{i,r,g} \cdot WRSI_{i,r} \tag{7}$$

Step 3 – Seasonal deficit and the Potential Stocking Rates (PSR)

In Brazil, most of the feed (>95%) consumed by cattle comes from pasture. Therefore, stocking rates were calculated by assuming pastures as the only feed source (again, a conservative approach). Constant stocking rates were assumed throughout the year, as seasonal slaughter and calving are not usual in Brazil. Therefore, daily demand for feed (DDF, kg/ha/d) is calculated as a function of stocking rate, expressed as animal-units per ha, (SR, AU/ha) through Eq. (8).

$$DDF(SR) = \frac{SR \cdot I}{E} \tag{8}$$

where I is the daily feed intake per animal unit (constant, kg/AU/d) and E is the grazing efficiency (dimensionless). We adopted $I = 8$ kg/AU/d, following the Forage and Grazing Terminology Committee (FGTC, 1992). Grazing efficiency (dimensionless) was set at 0.5 (i.e., 50%), considered a realistic value for advanced systems in Brazil (Barioni et al., 2005).

Feed deficits, resulting from year-round grazing with constant daily demand for feed (for a given stocking rate) and pasture forage accumulation (WRA) varying seasonally, may preclude reaching the stocking rates that would be attainable without supplementation, if average pasture production was evenly distributed. Some of the uneven distribution of pasture production can be tolerable because pasture herbage mass can vary within some limits, therefore working as a stock of feed (Santos et al., 2013; Euclides et al., 2007). In our estimate, we constrained stocking rates to not result in more than 1500 kg/ha of accumulated seasonal feed deficit (ASFD, kg/ha) during the year (Eq. (9)).

$$ASFD_{i,r,g}(SR) = \sum_{j=1}^{i} \min(WRA_{j,r,g} - DDF(SR), 0) \tag{9}$$

where j is an auxiliary index to allow computing ASFD.

Sustainable carrying capacity SCC (AU/ha) of pastures of genotype g in a region r is then estimated by maximising the stocking rate, solving the optimisation problem described by Eqs. (10) and (11):

$$SCC_{r,g} = Maximize(SR) \tag{10}$$

Subject to:

$$ASFD_{i,r,g}(SR) \geq -1500, \quad \forall i \tag{11}$$

The potential stocking rate is finally estimated by finding the highest sustainable carrying capacity attainable in the region with any of the genotypes, g = *Cynodon* or *Urochloa* considered in the analysis, i.e.,

$$SCC_r = \max(SCC_{r,g}), \quad \forall g \tag{12}$$

Climate data were obtained from the Climatic Research Unit (University of East Anglia; CRU-UEA) database, available at 5′ by 5′ resolution and we used 1961–1990 averages for all variables. Soil data was obtained from the Brazilian Institute of Geography and Statistics (IBGE, 2001).

2.2.2. Estimate 2

For Estimate 2, we applied the same process as for Estimate 1, but used a Brazilian climatic dataset (data from a network of 3437 meteorological stations in Brazil (Assad and Pinto, 2008), interpolated using the Ordinary Kriging interpolation method, in function of their latitudes and longitudes).

2.2.3. Estimate 3

For Estimate 3, data for pasture forage accumulation was obtained from the Global Agro-Ecological Zones 2009 project (FAO/IIASA, 2010) (Supplementary Material). Sustainable carrying capacity was then obtained through the same process as Estimates 1 and 2 (Fig. 1b and Supplementary Material Fig. S2a and b).

2.2.4. Sustainable carrying capacity in 2040

We also modelled the carrying capacity in 2040 by substituting, in Estimate 1, the current climatic data for those projected for 2040 according to the HadCM3 model using the A2 emissions scenario, also available from the CRU-UEA. To assess the impact of changes in temperature and precipitation, we ran the model three times. First, we kept precipitation at current levels and used 2040 temperature projections (Supplementary Material; Fig. S3a). Then, we kept temperatures constant at current levels and used 2040 precipitation projections (Supplementary Material; Fig. S3b). Finally, we applied 2040 projections for both parameters (Supplementary Material; Fig. S3c).

There were positive impacts due to temperature changes because of increases in minimum temperature, whereas negative impacts arose from heightened water stress due to increased evapotranspiration. Precipitation changes impacted the water deficit, leading to positive impact where precipitation increased and negative impact where it decreased. Both parameters also impacted seasonal deficits. These estimates do not capture the potential impact of an increase in the frequency of extreme events, which might have a substantial negative impact on yields (IPCC, 2007). As the estimated positive impact is largely due to changes in precipitation patterns, and these are highly variable across climate models (Malhi et al., 2009), we opted for a conservative approach of only including negative impacts of climate change on the potential carrying capacity used for the subsequent steps.

Because all analyses were performed independently for each carrying capacity estimate, our results are independently based both on the grass model based on (Tonato et al., 2010) and on Global Agro-ecological Assessment study (GAEZ) data. Comparison of total potential carrying capacity for three different estimates is presented in Appendix A (Table A.1). For further details on modelling please refer to Supplementary Material.

2.3. Future demand for land

We obtained future demand projections for meat, crops and biofuel from the Brazilian Ministry of Agriculture and FAO. The FAO study was a comprehensive modelling effort and included dietary changes, price elasticity feedbacks and a range of policies scenarios (FAO, 2006b). Beef demand, herd productivity and herd necessary to meet demands until 2040 along with areas demanded for crops and planted forest until 2040 are presented in Appendix B. In order to be conservative, for each product and time period, the projected demand in this study was the highest among Brazilian and FAO projections.

2.4. Allocation process and scenarios

We investigated two allocation scenarios for the future land use. In the '*Current Reality*' scenario, crop–livestock and forest–livestock systems are allocated following current production patterns. For each use, suitable polygons in municipalities with higher current production are selected first, then additional polygons are selected until enough land is allocated to produce the necessary outcome in 2040. The rationale is that, given current conditions, it might be easier to expand the production of a given crop or timber production in regions that already have consolidated industries for that product. Cattle productivity is then increased by the same fraction on all polygons with cattle production until enough meat is produced to meet demands in 2040.

In the '*Restoration*' scenario, the goal was to maximise the area liberated for restoration of natural ecosystems. Crops were allocated to suitable polygons with the lowest potential carrying capacity while silvopastoral systems were allocated to polygons with the highest carrying capacity. Stocking rates were then increased to 90% of the sustainable carrying capacity, starting in the polygons where carrying capacity is higher, until enough meat was produced. This extreme scenario provides a theoretical upper limit (with 90% of the carrying capacity) for the area that could be liberated for restoration.

A simple iterative process was applied to spatially allocate different land uses (sugarcane, soybean, maize) and stocking rates across cultivated pasturelands to meet 2040 demands. First, the allocation order of each land use was decided according to the scenario being analysed (see above). Then, 'unrestricted' (given use-specific constraints) polygons are ranked according to criteria pertaining to the use and scenario (Supplementary Material, Figs. S4, S5 and Table S3). In the third step, polygons are selected, beginning with the top-ranking ones and moving downward, until enough land is allocated to meet demand. Finally, the cattle herd necessary to meet projected meat demand is allocated following scenario-specific criteria, always respecting the estimated sustainable carrying capacity (Supplementary Material; Table 4).

Crop and timber production were restricted to pastureland areas free of use-specific constraints. Sugarcane (for consumption and biofuel) was restricted to suitable areas according to the recent sugarcane zoning assessment, which included climate risk (both now and in 2040) and slope constraints (Supplementary Material, Fig. S4c). Crop production (using agropastoral systems) were allocated in areas that presented low climatic risk for each crop both in 2000 and 2040, and steep areas (inclination $>15^{\circ}$) were excluded (Supplementary Material, Fig. S4a–c). Timber production (using silvopastoral systems) was also excluded from steep areas.

2.5. Greenhouse gas mitigation estimate and herd growth constraints

We applied the IPCC Good Practice Guidance (Penman et al., 2003) in order to estimate the mitigation impact of avoided deforestation arising from improving cattle ranching productivity on existing pasturelands. We also investigated whether the projected increase in herd productivity would be feasible given initial conditions and herd growth constraints, applying IPCC Tier 2 guidelines (IPCC, 2009). Detailed methods on greenhouse gases calculations are available online in Supplementary Material.

3. Results and discussion

3.1. Current and potential productivity of Brazilian pasturelands

We found that the current productivity of Brazilian pasturelands (94 million animal units) is 32–34% of their estimated carrying capacity (274–293 million animal units), indicating a substantial potential to increase productivity. The potential carrying capacity of Brazilian pasturelands was found to be 286 million animal units, 293 million animal units and 274 million animal units for Estimates 1, 2 and 3, respectively (Appendix A, Table A.1). Final values for Estimate 1 are shown in Fig. 1b, whereas final values for Estimates 2 and 3 are shown in Fig. S2a and Fig. S2b (Supplementary Material). The proximity among our three estimates (Fig. 2a) suggests that our results are consistent across different fodder grass models and climatic datasets.

The current low productivity of Brazilian pasturelands has multiple causes (Bowman et al., 2012; Bustamante et al., 2012; Macedo et al., 2012; Valentim and Andrade, 2009) including: (i) low technology level characterised by inadequate pasture management (overgrazing and lack of maintenance fertilisation) leading to a widespread degradation and deficient animal management (health, nutrition and breeding) resulting in low animal performance; (ii) land speculation, where cattle ranching is a means to secure land ownership with an aim to sell the land when the cropland frontier advances (in Brazil, farms that are not actively used can be expropriated for land reform, and extensive cattle ranching is among the simplest form of occupation); (iii) insecure tenure, which discourages investments in increased productivity and incentivise an extractivist model that leads to degradation; (iv) lack of long-term credit for the upfront costs of increasing productivity and lack of compliance of the properties with the environmental laws which prevents access to credit; (v) lack of appropriate extension and training services dedicated to cattle ranching productivity.

Pasture degradation is indeed one of the main causes of low productivity of cattle production systems and is driving conversion of native vegetation in the different Brazilian biomes (Fearnside and Barbosa, 1998; Costa and Rehman, 1999; Valentim and Andrade, 2009; Bustamante et al., 2012). It is estimated that more than 50% of the total area of cultivated pastures in the Cerrado (Costa and Rehman, 1999) and more than 60% in the Amazon biome (Dias-Filho and Andrade, 2006) are degraded. In 2010, 39% of the deforested area in the Amazon biome was reported to be either degrading pasture or abandoned area occupied by secondary vegetation (Embrapa and INPE, 2013). More intensive, sustainable pasture and cattle production systems can however be already also found in Brazil (Vosti et al., 2001; Martha et al., 2012; Valentim et al., 2010). These systems are characterised with pastures of higher carrying capacity resulting in more animal products that can be sustained for longer than traditional extensive systems. These higher productivity systems require however more capital and labour to be established and managed (Vosti et al., 2001).

3.2. Meeting future demands on already converted lands

We confirm our hypothesis that Brazil has enough land to meet demand for products analysed here at least until 2040 without further conversion of natural habitats. Under the '*Current Reality* scenario (Fig. 3a), which is keyed to current geographical patterns of production, these needs can be met within this time frame if pasture productivity increases to 49–52% of the carrying capacity and increases in herd productivity follow historical trends (Appendix D). This 53% increase over 30 years would be equivalent to an annual increase of approximately 1.4%. In fact, despite different spatial distributions, our hypothesis is confirmed in every combination of scenarios and carrying capacity estimates (Fig. 3; Appendix C, Fig. C.1, Supplementary Material; Table S.5). This finding suggests that there are several possible alternatives for land allocation able to meet demand in 2040. If, for instance, pasture productivity increases to 70% of its carrying capacity and herd productivity increases according to historical trends (Fig. 3b),

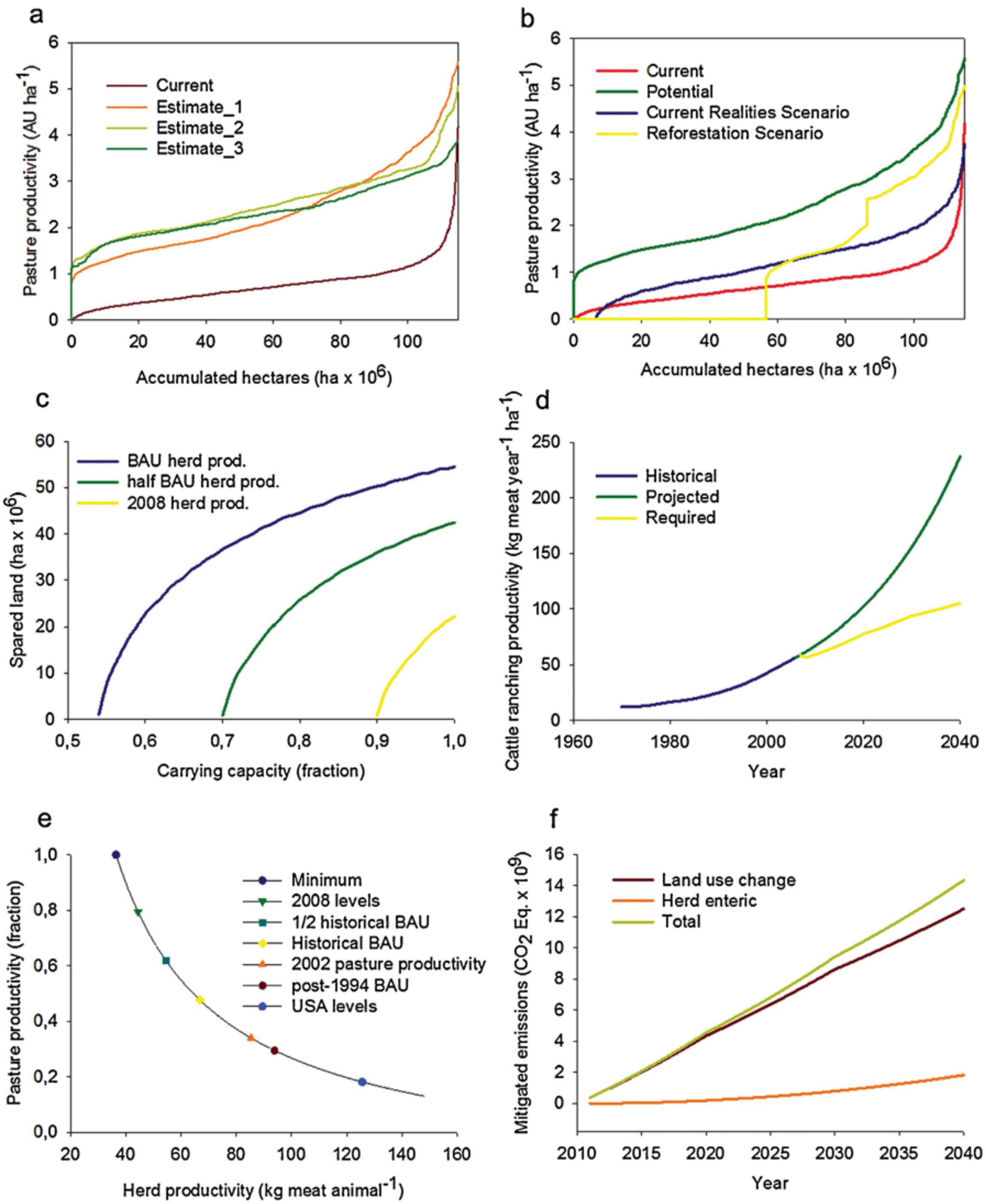

Fig. 2. Relations between productivity increase, land sparing, historical trends and avoided emissions. (a) Distribution of stocking rates across the 115 million hectares of cultivated pasturelands for the current situation, and three estimates for potential carrying capacity. (b) Distribution of stocking rates across the 115 million hectares of cultivated pasturelands for the current situation, Estimate 1 of potential carrying capacity and two scenarios that fulfil demands in 2040. In the reforestation scenario, low productivity pastures are reforested and, as a consequence, their stocking rates equals zero. (c) Relationship between pasture productivity (*x*-axis, in % of carrying capacity) and the extent of land liberated for restoration of native ecosystems (*y*-axis, in million hectares), for three herd productivity levels in 2040 (2008 levels, an annual increase following the historical average and an annual increase that is half of the historical average). (d) Cattle ranching productivity over time: historical productivity, projected productivity assuming that average annual growth remains constant and productivity required to meet all demands on current lands. (e) Relationship between herd productivity levels (*x*-axis) and pasture productivity (in % of carrying capacity) necessary to meet all demands on current lands (highlighted herd productivity levels are: minimum level required, constant at 2008 levels, projected following average historical increase, projected following half the average historical increase and projected following the average increase after the 1994 Brazilian economic stabilisation; also highlighted are the herd productivity necessary to keep pasture productivity at 2002 levels and still meet all demands (84 kg y^{-1}/live animal) and current U.S.A. levels (125 kg y^{-1}/live animal). (f) Mitigated emissions from avoided land use change, reduced enteric herd emissions and total emissions (sum of emissions from land use change and enteric herd emissions) in CO_2 equivalent.

36 million hectares of cultivated pasturelands could be liberated. This area is 70% larger than the estimated 21 million hectares of 'legal deficit' (deforested areas that should be restored so that farmers are in compliance with the environmental legislation) (Soares-Filho, 2013). This '*Restoration*' scenario (Fig. 3b) also illustrates the relation between intensification and land sparing (Fig. 2c). In particular, our results show that there is enough land for a large-scale restoration of the Atlantic Rainforest, the 'hottest

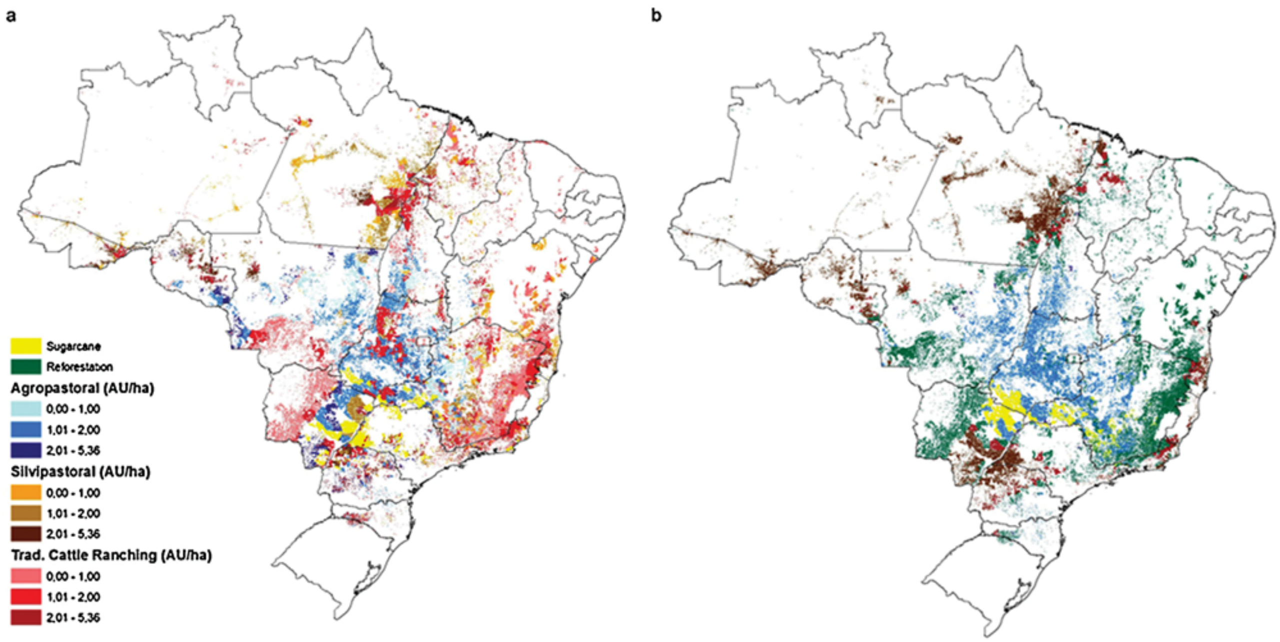

Fig. 3. Possible allocations of land-use systems in 2040 that satisfies demands for land-based products without further conversion of natural ecosystems. Alternative allocations of cattle, sugarcane, crop–livestock (for soybean and maize), silvopastoral (for wood production) and reforestation areas in 2040. Two possible allocations scenarios are presented for Estimate 1, incorporating negative climate change impacts. The '*Current Reality* scenario (a) follows current geographical patterns of production and includes no reforestation. The '*Restoration*' scenario (b) assumes that areas of low potential for cattle production and/or degraded areas will be recuperated for reforestation. As a consequence, cattle required to meet demand in 2040 in the "*Restoration*" scenario was allocated into pastures of high-carrying capacity. Yellow corresponds to sugarcane areas, green to reforestation, shades of blue correspond to mixed cattle–crop systems, shades of brown correspond to mixed cattle–timber systems and shades of red correspond to pure cattle systems. Light shades correspond to low carrying capacity of pastures (0.00–1.00), medium shades to medium carrying capacity (1.01–2.00) and dark shades to high carrying capacity (>2.00).

of hotspots' (Laurance, 2009), where up to 18 million hectares could be restored (Supplementary Material; Table S.6) without impeding national agricultural expansion (Brancalion et al., 2012). This would more than double the remaining area of this biome, slow the massive species extinctions (Strassburg et al., 2012a) and sequester 7.5 billion tonnes of CO_2 Eq.

Notably, the yearly increase in cattle ranching productivity required to meet anticipated demands for meat production while freeing up enough land for other uses is smaller than the average yearly increase in productivity since 1970 (Fig. 2d). In fact, the productivity levels required in 2040 would be similar to what many countries (including developing nations) have already achieved (Supplementary Material, Table S.1).

Indeed, there is already evidence in Brazil of agricultural intensification and land sparing. A comparison of data between the last two Brazilian agricultural censuses show that in the seven states where total cultivated lands remained constant or contracted between 1995 and 2006, an expansion of croplands and planted forests was compensated by a greater contraction of cultivated pasturelands (Fig 4; Appendix D, Table D.1). Furthermore, despite a combined loss of 8.5 million hectares of cultivated pasturelands (and further 7.8 million hectares of natural pasturelands), the combined cattle herd in these states increased by 5.8 million animals. In other words, the recent history in the most developed centre-south of Brazil has showed that when the option of expanding the agricultural frontier is limited, the pressure to improve the use of available land has led to increased productivity in pasturelands, which in turn liberated enough land for the expansion of croplands and planted forests. Here we show that the same could be possible in the rest of the country. Recent observations further suggest an incipient shift in this direction at the Amazon frontier (Macedo et al., 2012).

3.3. How improved cattle ranching productivity can be achieved

The necessary increase in cattle ranching productivity (annual meat production per unit of pasture area) can be met by a combination of pasture productivity (number of animals per unit of pasture area) and herd productivity (annual meat production per total number of animals) increases (Fig. 2e). Pasture productivity can increase through improved fodder grass selection, the incorporation of legumes, tillage reduction, electric fencing, rotational grazing and the introduction of mixed systems (Tilman et al., 2002). Herd productivity can increase for example through improved breed selection, reproductive management and earlier slaughtering.

Transition to improved cattle farming requires however initial financial investment not only to provide fencing or soil enhancers (e.g. lime) and more sophisticated machinery for better pasture management and labour investments from the farmers, but also requires provision of training, extension, market support and marketing organisations, access to roads and relevant policy. This is critical as the capacity of farmers to detect, learn, and adapt to change within complex intensified systems is a key component of successfully functioning pasture and avoiding environmental degradation. In particular, a significant challenge is the training of the personnel from different sectors of the beef supply chain, including those who deal directly with cattle, data collection and health management and also those responsible for the property administration, slaughterhouse companies, distribution and handling and preparation of intermediate and final products (Euclides-Filho, 2004). In order for these changes to gain scale, technology transfer, training services and credit provision would need to be expanded (Van Vliet et al., 2012). The creation of the Low Carbon Agriculture Plan is a first step in addressing

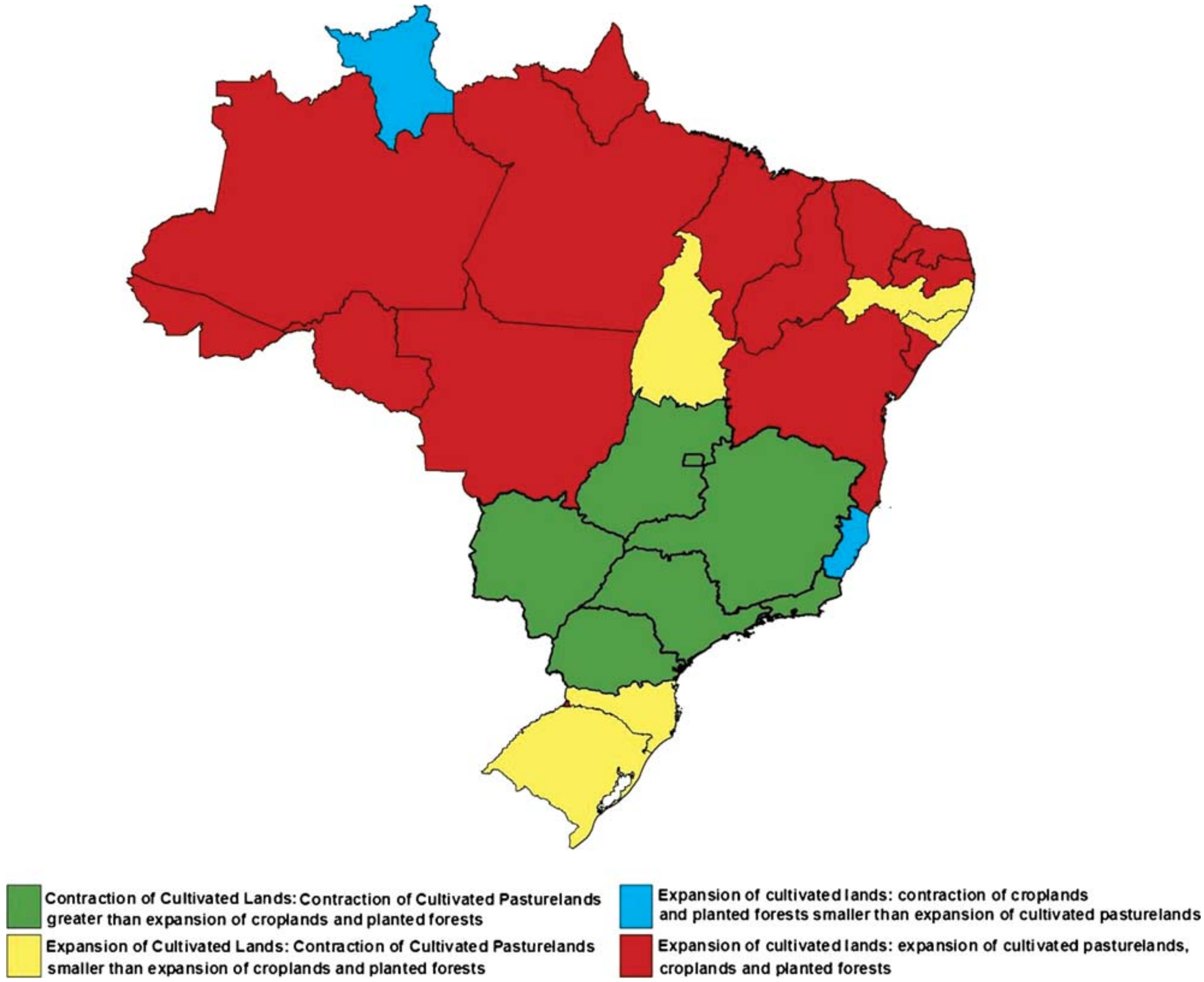

Fig. 4. Recent trends in agricultural lands in Brazil (1995–2006). States in green experienced a contraction of their cultivated land areas. In each of these states, croplands and planted forests expanded, but their expansion was compensated by an even greater reduction in cultivated pasturelands area. This reduction derived from greater productivity, with average stocking rates rising from 0.71 to 0.94 animal units per hectare over the period. States in yellow also experienced increase of croplands and planted forests alongside reduction of cultivated pasturelands, but the latter was smaller than the former, leading to an expansion of cultivated area. States in blue experienced the opposite trend, with pastureland area expanding and croplands and planted forests contracting. States in brown experienced expansion of pasturelands, croplands and planted forests. Calculations by the authors using data from the Brazilian Census Bureau (IBGE), full results shown in Table D1.

the latter (BMA, 2010). Technologies and approaches incentivised by the Low Carbon Agriculture Plan (ABC in Portuguese) include implementation of crop–livestock–forestry systems, recuperation of degraded pasturelands and biological nitrogen fixation. Although the uptake of low-interest loans to apply the Low Carbon Agriculture Plan was very low between 2010 and 2011, it has risen almost by 50% in 2012 (Angelo, 2012).

3.4. Climate change mitigation

Increasing cattle productivity while stopping the conversion of natural environments would be a major contribution to tackling climate change, even without including the mitigation potential from restoration. Indeed, we estimated emissions reductions of 14.3 Gt CO_2 until 2040 (Fig. 2f and Supplementary Material). This mitigation potential stems from a reduction in deforestation (12.5 Gt CO_2) and reduced enteric emissions from the cattle herd due to smaller herd size and earlier slaughtering (1.8 Gt CO_2). The economic value of this mitigation in 2040, if captured via the Reducing Emissions from Deforestation and Forest Degradation (REDD) (Strassburg et al., 2009) or similar mechanisms, could amount to US$ 143–286 billion at carbon prices of US$ 10–20/t CO_2. At the same time, it has been estimated that increasing the productivity of Brazilian pasturelands would require investments of US$ 83 billion (World Bank, 2010), both in-farm and wider policy costs.

Although the establishment of cultivated pastures has been the main driver of conversion of native vegetation in the last decades in Brazil, there is still no clear understanding of the direction of the resulting changes in soil carbon (C) stocks. Soil C dynamics in pastures and whether pastures of increased productivity provide a net C sink or a net source of carbon depends of the soil type, history of land use, amount and distribution of annual precipitation and, most importantly, of pasture management (Fearnside and Barbosa, 1998; Neill and Davidson, 1999; Bustamante et al., 2012). It has however been demonstrated (Vosti et al., 2001; Nepstad et al., 2009; Valentim and Andrade, 2009; Bustamante et al., 2012) that improved pasture management and the adoption of more intensive cattle production systems based on reclamation of degraded and degrading pasture areas, with species of grasses and legumes adapted to the different environmental conditions can contribute to increase soil C stocks. Although aptly performed pasture intensification can lead to increased soil C, there is need for more research on how pastures of increased productivity impact soil C stocks.

3.5. Mitigating risks: the ''rebound effect'' and social considerations

Although an increase in productivity carries the potential for land sparing (Lapola et al., 2010), if complementary policies are not implemented it can unintentionally lead to increased deforestation (Perfecto and Vandermeer, 2010). Since more productive systems are generally more profitable, policies for their implementation on a large scale must be coupled with effective environmental governance to avoid further deforestation for pasture expansion – a ''rebound effect'' (Angelsen, 1999; Bustamante et al., 2012; Nepstad et al., 2009; Vosti et al., 2001; Strassburg et al., 2012a,b). Brazil can take lessons from recent developments in its own soybean industry, where a remarkable increase in productivity made soybean farming much more profitable, transforming it into a leading cause of deforestation (Morton et al., 2006). The moratorium on soy production in areas deforested after 2006 virtually eliminated direct deforestation related to soybean, although indirect deforestation, where soybean expands into pasturelands and pushes ranchers into the forest, remains a challenge (Arima et al., 2011). A proposed approach aimed both at tackling the rebound effect and indirect deforestation and at realising the land-sparing potential of improved cattle ranching is the ''Land Neutral Agricultural Expansion'' mechanism (Strassburg et al., 2012b). There are number of positive outcomes for the farmers resulting from increasing pasture productivity, including increased profits (Strassburg et al., 2012b) and the growing demand for livestock products may also represent an opportunity for livestock enterprises to provide food security and offer pathways out of poverty (Steinfeld and Gerber, 2010). However, transition from extensive systems may also result in loss of traditional agriculture and way of farming (such as slash and burn), although the sustainability of some types of this 'traditional agriculture' can be called into question. In addition, particularly small-scale livestock producers may be disadvantaged by the industrialisation of livestock production. Attention is therefore needed to ensure that improvements in agricultural productivity do not result in negative social consequences. Policies, such as territorial planning (e.g. through Brazil's economic-ecological zoning plans), security of land tenure, incorporating original landowners in any process of technological improvement, improved enforcement of existing environmental regulations, monitoring of land-use practices and other social considerations are paramount to ensuring that increased cattle productivity results in environmental and social benefits in the long-term (Calle et al., 2012).

4. Limitations

The central results of our study are based on two fodder grass biomass models and a range of spatial and climatic datasets, and therefore carry the uncertainties associated to those. We derived three distinct estimates for carrying capacity, one of which was based on a widely-used external database (FAO/IIASA, 2010) and attempted to be conservative in our estimates where possible. There might be biological or chemical factors impacting carrying capacity unconsidered here, for instance prevalence of cattle diseases or extreme soil acidity. Soil acidity would however likely have limited impacts because we are focusing on areas already used as cultivated pasturelands. Our estimates of climate change impacts and mitigation potential are simplified.

The fact that our results indicate a substantial gap between the potential carrying capacity of current pasturelands and the productivity necessary to fulfil all demands additionally gives nevertheless confidence in conclusions drawn here.

The study is limited to examining the biophysical potential of pastureland areas to support the future expansion of Brazilian agriculture. Further research could focus on a range of associated aspects, including economic, social and cultural barriers and opportunities for large scale implementation of improved agricultural systems, developing predictive spatial scenarios and planning to aide policy implementation.

5. Conclusions

The potential for increased productivity in croplands has been previously demonstrated globally (Mueller et al., 2012), but less is known about pasturelands. Pasturelands occupy 2.8 billion hectares globally (compared to 1.5 billion hectares of croplands) and meat consumption is expected to increase more rapidly in the coming decades (Smith et al., 2010; Tilman et al., 2002). In this paper, we demonstrated that Brazil already has enough land under agricultural production in order to meet unprecedented increase in future demand for agricultural products, while sparing land for nature. We explored two scenarios and developed a simple iterative process to allocate land uses and stocking rates, and we estimated sustainable carrying capacity for 2040, incorporating only negative climate change impacts and applying product-specific climatic and terrain constraints, and pasturelands in legally restricted areas. Our results therefore refute the argument often raised by some agricultural stakeholders that there would not be enough land to increase food production and restore illegally deforested areas, often claimed in relation to the revision of the Brazilian agricultural and forest laws (Sparovek et al., 2010). Furthermore, sustainable intensification generates an opportunity to plan and implement 'whole landscape approach' (Defries and Rosenzweig, 2010), combining increased productivity of agriculture with conservation and restoration of natural environments.

Yet, in order to realise the land-sparing potential from increased cattle ranching productivity, complementary policies such as territorial planning, improved law enforcement, monitoring and tenure security must be put in place. Further research could investigate whether our conclusion that Brazil has already enough agricultural lands to support its future needs is true in other regional contexts and, ultimately, at the global level.

The next few decades may see the fastest, largest and perhaps last significant expansion of human demands on land systems since the dawn of agriculture ten thousand years ago. How these demands are met will have profound and lasting impacts on Earth's natural and human systems.

Acknowledgements

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Appendix A. Comparison of total potential carrying capacity for different estimates analysed in this study

See Table A.1.

Table A.1
Comparison of total potential carrying capacity for three different estimates. Estimate 1 is based on EMBRAPA model including CRU climate data, Estimate 2 is based on EMBRAPA model including climatic data from (Pinto and Assad, 2008), Estimate 3 is based on FAO GAEZ model and CRU. Estimates for 2040 were performed using EMBRAPA fodder model and HADCM3 (A2 Scenario) climate change projections also available from CRU. We also produced an estimate for 2040 considering only negative impacts of climate change, which was used in place of Estimate 1 for allocations in 2040 (Fig. 3 in the main text).

Estimate	Total carrying capacity (animal units)
Estimate 1 year 2000	286,038,163
Estimate 2	292,769,702
Estimate 3	273,519,070
Estimate 1 year 2040 – all climate change impacts	377,440,819
Estimate 1 year 2040 – only negative climate change impacts	276,351,928

Appendix B. Areas demanded for meat, crops and planted forest until 2040

See Figs. B.1 and B.2.

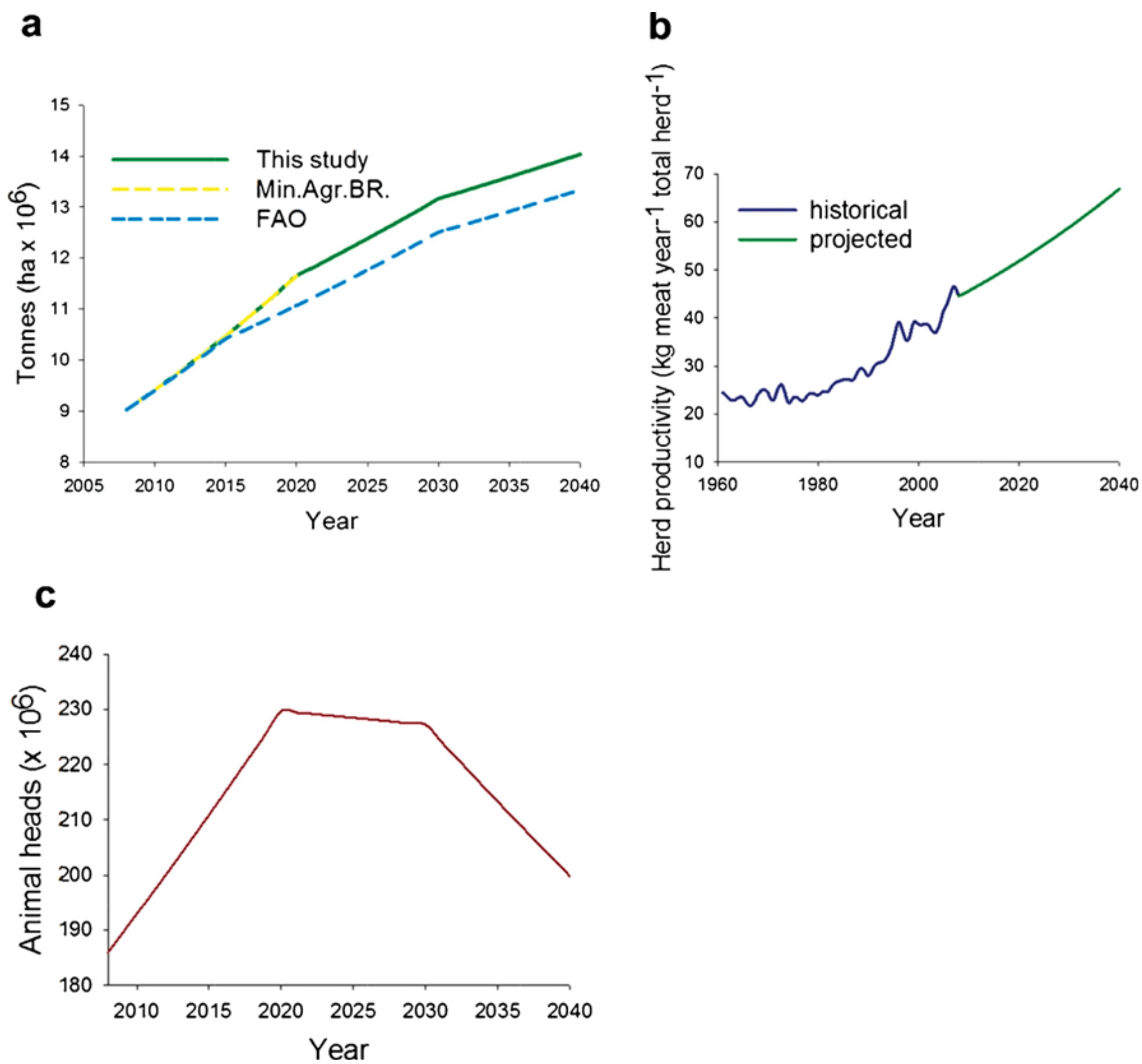

Fig. B.1. Beef demand (a), herd productivity (b) and herd necessary to meet demands until 2040 (c). In order to derive conservative estimates for this study, the highest projected demand for beef was chosen from different future projections. Green line represents values used in this study, yellow dashed line represents estimates from Brazilian Ministry of Agriculture, blue dashed line represents FAO estimates. Herd productivity consists of the slaughter rate (ratio between total animals and slaughtered animals per year) and the meat production per slaughtered animal. Blue line represents historical increase in herd productivity, green line presents future projections of herd productivity increase. Total herd required to meet the projected demand was then calculated based on projected demand and productivity.

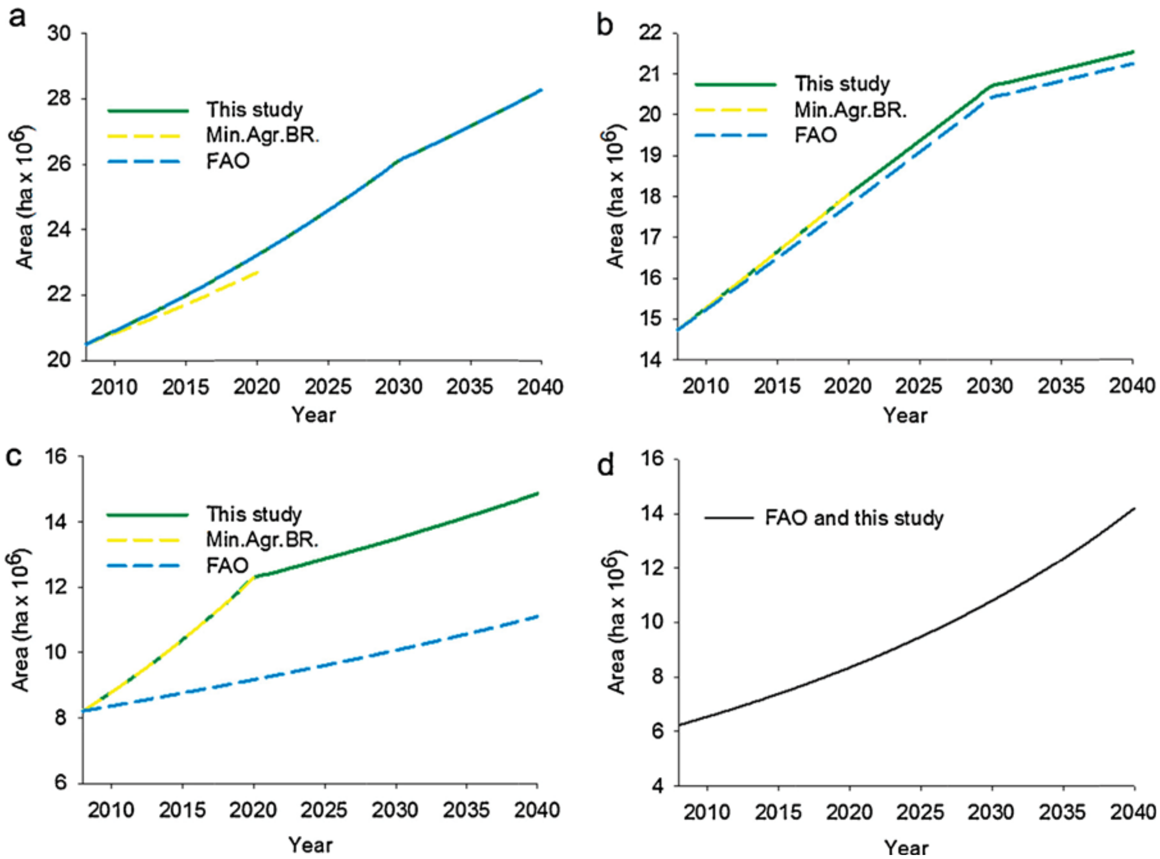

Fig. B.2. Areas demanded for crops and planted forest until 2040. (a) Soybean, (b) maize, (c) sugarcane, (d) planted forest. In order to derive conservative estimates for this study, the highest projected growth rates were adopted from different future projections, thus leading to higher demands in land area. Green line represents values used in this study, yellow dashed line represents estimates from Brazilian Ministry of Agriculture, blue dashed line represents FAO estimates. For planted forest we adopted values from FAO.

Appendix C. Alternative allocations of cattle, sugarcane, crop-livestock (for soybean and maize), silvopastoral (for wood production) and reforestation areas in 2040

See Fig. C.1.

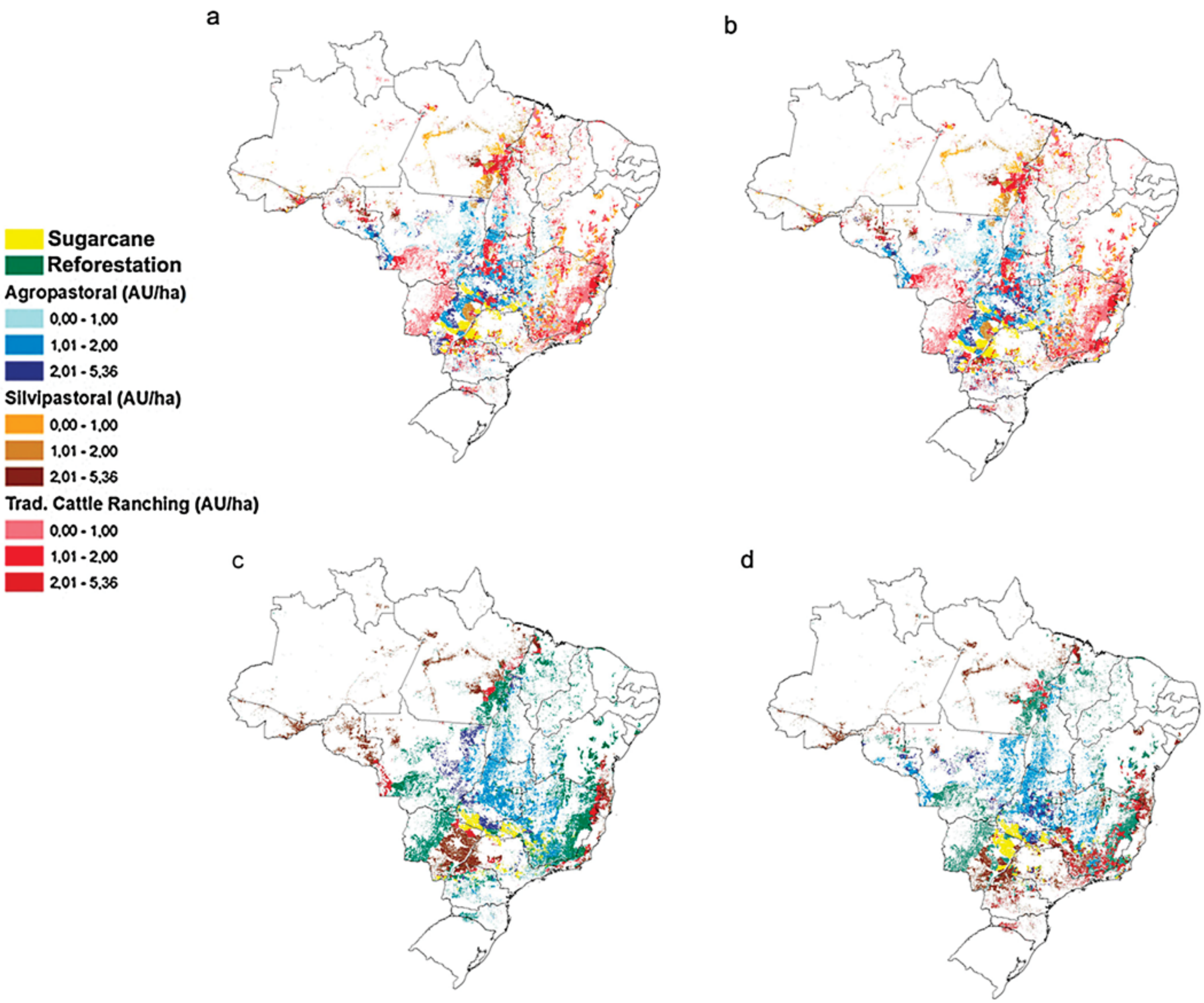

Fig. C.1. Alternative allocations of cattle, sugarcane, crop–livestock (for soybean and maize), silvopastoral (for wood production) and reforestation areas in 2040. Two possible allocations scenarios are presented for Estimates 2 and 3 for carrying capacity of pastures (two scenarios for Estimate 1, incorporating negative climate change impacts, are presented in Fig. 3 in the main text). The '*current reality*' scenario assumes business-as-usual of current geographical patterns of production and no reforestation. The '*Restoration*' scenario assumes that areas of low potential for cattle production and/or degraded areas will be recuperated for reforestation. As a consequence, cattle required to meet demand in 2040 in the "*Restoration*" scenario was allocated into pastures of high-carrying capacity. (a) "*Current reality*" scenario, Estimate 2, (b) "*Current reality*" scenario, Estimate 3, (c) "*Restoration*" scenario, Estimate 2, (d) "*Restoration*" scenario, Estimate 3. Yellow corresponds to sugarcane areas, green to reforestation, shades of blue correspond to mixed cattle–crop systems, shades of brown correspond to mixed cattle–timber systems and shades of red correspond to pure cattle systems. Light shades correspond to low carrying capacity of pastures (0.00–1.00), medium shades to medium carrying capacity (1.01–2.00) and dark shades to high carrying capacity (>2.00).

Appendix D. Trends in total cultivated area, croplands, planted forests, pasturelands area and stocking rates for all Brazilian states between 1995 and 2006

See Table D.1.

Table D.1
Trends in total cultivated area, croplands, planted forests, pasturelands area and stocking rates for all Brazilian states between 1995 and 2006. Own calculations, based on data from the Brazilian Census Bureau (IBGE).

States	Total cultivated area			Croplands and planted forests			Cultivated pasturelands			Stocking rates (AU/ha)		
	1995	2006	% Change	1995	2006	% Change	1995	2006	% Change	1995	2006	% Change
Acre	639	1052	65	87	171	96	552	881	60	0.54	1.65	206
Alagoas	1222	1257	3	850	907	7	373	350	−6	0.68	0.83	22
Amapá	130	202	55	105	158	51	26	44	72	0.27	0.29	7
Amazonas	445	1459	228	236	883	273	208	576	176	1.07	1.08	1
Bahia	10,840	13,157	21	4187	5450	30	6653	7708	16	0.48	0.59	23
Ceará	1591	2249	41	1393	1934	39	197	314	59	0.6	0.63	5
Distrito Federal	149	147	−1	86	101	16	62	47	−25	0.89	0.87	−2
Espírito Santo	2060	2158	5	1001	938	−6	1058	1220	15	0.76	1.11	46
Goiás	16,515	16,263	−2	2248	3687	64	14,267	12,576	−12	0.67	0.92	37
Maranhão	3756	6536	74	850	2518	196	2907	4018	38	0.55	0.81	47
Mato Grosso	18,282	23,809	30	3020	6392	112	15,262	17,417	14	0.46	0.84	83
Mato Grosso do Sul	17,293	17,032	−2	1565	2286	46	15,728	14,747	−6	0.72	0.79	10
Minas Gerais	17,574	17,000	−3	5880	6173	5	11,694	10,826	−7	0.56	0.86	54
Pará	6748	10,983	63	923	1939	110	5825	9043	55	0.76	1.13	49
Paraíba	849	877	3	656	668	2	193	210	9	0.4	0.46	15
Paraná	11,113	10,482	−6	5814	7086	22	5300	3395	−36	0.98	1.45	48
Pernambuco	1947	2380	22	1246	1720	38	700	660	−6	0.45	0.74	64
Piauí	1139	2012	77	679	1386	104	459	626	36	0.62	0.48	−23
Rio de Janeiro	1007	992	−1	363	363	0	644	629	−2	0.86	1.14	33
Rio Grande do Norte	682	773	13	594	685	15	88	88	0	0.41	0.6	46
Rio Grande do Sul	7422	8638	16	6266	7684	23	1157	954	−18	0.85	1.06	25
Rondônia	3052	5048	65	473	514	9	2579	4534	76	0.94	1.67	78
Roraima	430	435	1	134	117	−13	296	318	7	0.13	0.49	277
Santa Catarina	2692	2785	3	2132	2339	10	560	446	−20	0.9	1.42	58
São Paulo	12,909	11,279	−13	5853	7247	24	7056	4032	−43	1.02	1.3	27
Sergipe	811	874	8	282	320	13	529	555	5	0.48	0.79	65
Tocantins	5545	5901	6	267	678	154	5277	5223	−1	0.35	0.67	91
Brazil (total)	146,842	165,781	13	47,190	64,344	36	99,652	101,437	2	0.64	0.91	42

Appendix E. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2014.06.001.

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