Supporting Information for

Indirect land-use changes can overcome carbon savings from biofuels in Brazil

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Determination of the relative importance of p_i factors

The determination of relative importance used in the analytic hierarchy process (AHP) test (RI_{AHP}, ref. (1)) followed four steps: (*i*) determination of the coefficient of variation of the given p_i factor over the entire initial land-use map (CV^1_i); (*ii*) determination of the coefficient of variation of the given p_i factor only over the grid cells covered by cropland in the initial land-use map (CV^2_i); (*iii*) derivation of an empirical index for the p_i factor (EI_i) by CV^1_i/CV^2_i; and (*iv*) determination of RI_{AHP} with a pairwise comparison of EI_i from all p_i factors.

Model Evaluation

Crop/rangeland location. Because crop/rangeland suitability analysis is the central aspect of LandSHIFT, its ability to determine crop/rangeland spatial distribution requires testing. Therefore, we first compared the suitability computed by LandSHIFT against crop and rangeland distribution on an actual land-use map (11, 12). Cropland areas tend to be located where crop suitability is higher, assuming that cropland is given priority over other land uses (besides urban areas) (13). Fig. S3 shows that suitability for cropland and rangeland indeed tends toward higher values in comparison to suitability for other land uses, suggesting that the suitability analysis used in the model is appropriate for determining cropland/rangeland allocation. The suitability frequency distribution of 'other land uses' is significantly different from that of cropland and rangeland (Kolmogorov-Smirnov test, $P<0.01$). There is no significant difference between the suitability distributions for cropland and rangeland. Overall, this analysis suggests a tendency to allocate crops in places with higher suitability. It can be argued that the estimation of the w_i weights (Table S3) using the initial land-use map (which is the same used in this evaluation) may create a spurious dependency between the datasets used for comparison, thus impairing the reliability of this test. Therefore, we performed the same suitability frequency distribution test for cropland with the w_i weights all having the same value of 0.16. This analysis further confirmed what is shown in Fig. S3 because the median suitability for cropland (0.56) differs even more from that of other land uses compared to the analysis in which the weights were determined using the initial land-use map. Moreover, the distribution in which all $w_i = 0.16$ is not significantly different from the distribution for cropland using the pre-determined w_i weights in Table S3. Despite incurring an overlap with 'other land uses' between suitability values of 0.15 and 0.4 (Fig. S3), the latter distribution is preferred over the one in which w_i have all the same values because it better represents the distribution of croplands throughout the whole country and avoids excessive (and erroneous) concentration of cropland in the southern and southeastern states of Brazil.

A second test using the Relative Operating Characteristics (ROC) method (14) makes it possible to assess the degree to which the spatial pattern computed by the model is random or not. This ROC also compares computed suitability to the actual land-use map pattern but relates the proportions of correctly (true positives) and incorrectly (false positives) classified spatial predictions in contingency tables. The resulting curves are shown in Fig. S4. The area under the curve (0.87 for cropland; 0.80 for rangeland) reveals that the spatial pattern of suitability computed by LandSHIFT is not random as exemplified by the 1:1 line, which has an area under the curve of 0.5. This result further confirms that higher suitability values tend to be located in grid cells occupied by cropland and rangeland. Therefore, the ROC method test suggests LandSHIFT is able to represent crop location using suitability analysis. A third analysis regarding crop/rangeland distribution inside major regions in Brazil is presented below.

Crop/rangeland area. We compare crop area modeled by LandSHIFT with reported statistics data (15) for the year 2003. At the country level, modeled crop areas of sugarcane and soybean match FAO data almost perfectly, whereas the area covered by 'other crops' and rangeland (and therefore livestock density, Ld) is overestimated in the model by 13% and 8% respectively. This result suggests the model is able to convert country-scale crop production mass (e.g., Mg) to cropland area (km^2). Model efficiency (18) for the data presented in Fig. S5 is 1.06 (1.0 would represent a perfect match). The overestimation of the 'other crops' area is due to some underestimation of crop yields by LPJmL. However, in the case of rangeland, the area overestimation might also be due to the following reasons: (*i*) the assumption of only one land use per grid cell leads to overestimation of rangeland area, especially in regions where Ld is low, as in Northeast Brazil; and (*ii*) rangeland area might not increase in response to increasing livestock herd in all areas of Brazil, as modeled by LandSHIFT. For example in the Amazon region the farmer's interest is often on guaranteeing ownership over the land rather than on allocating the market demand for livestock on his pastures, and the pasture area may increase not because of increasing livestock demand but because of less obvious reasons like population migration and lack of governance in the region (19, 20).

Distribution of cropland/rangeland inside major regions in Brazil is in good agreement with statistics on a sub-national level (21) weighted by total crop/rangeland area modeled by LandSHIFT (Fig. S6). The underestimation of rangeland area in southern Brazil is corrected if we add 68,000 km^2 of natural grasslands, which are considered in the Brazilian official statistics as 'natural pasture' but are not included in LandSHIFT calculations. The overestimation of rangeland area in Northeast Brazil is explained by two reasons (*i*) the difficulty to deal with the extension of rangeland in areas with low Ld (22), and (*ii*) the rangeland area in Northeast Brazil is overestimated by a factor of 2.3 in the initial land-use map used by LandSHIFT (11, 12). Estimates by Campbell *et al*. (23) suggest that roughly 110,000 km^2 of the rangelands in Northeast Brazil are abandoned (not grazed anymore). These areas are probably not considered as rangeland in the statistics used here for comparison.

Deforestation rates. The modeled annual deforestation rate for the Amazon region for the 1992-2003 period compares well with remote sensing data (LandSHIFT: 16,789 km^2/yr, INPE-PRODES: 18,266 km^2/yr (24)). The shares of this deforestation among states are also comparable with PRODES, though deforestation in Maranhão is overestimated by a factor of 23. That overestimation is due to the denser road network found in this state compared to Mato Grosso, where deforestation is underestimated by a factor of 5.7. Nevertheless, any comparison between different data sets is biased by the different methods used in the construction of a given map. For example, the initial land-use map for the year 1992 used in LandSHIFT has 80% more forest in the state of

Maranhão compared to the dataset used for comparison here (24). Moreover, capturing the exact location of deforestation in the Amazon region, which is not the goal of this study, might involve other factors that are not accounted for in a country-scale simulation program such as LandSHIFT, in which deforestation is mostly caused by increasing crop and/or livestock demand. The deforestation model developed by Soares-Filho *et al*. (25) is focused on the Amazon basin and considers neither the dynamics of land use occurring at deforested sites, nor the teleconnections between land-use changes in Amazonia and other parts of Brazil. Also, the current version of LandSHIFT does not consider forestry activities, which may contribute to deforestation. The modeled deforestation rate in the Cerrado savanna of Central Brazil for the 1992-2003 period is 17,753 km^2/yr. This amount lies within the estimated range (13,100-26,000 km^2/yr) of Cerrado deforestation for the last decade (26). The deforestation of ~5000 km^2 of the Atlantic forest in the 1992-2003 period (27), approximately 55 grid cells in LandSHIFT's resolution, is not captured by the model.

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SI Figures

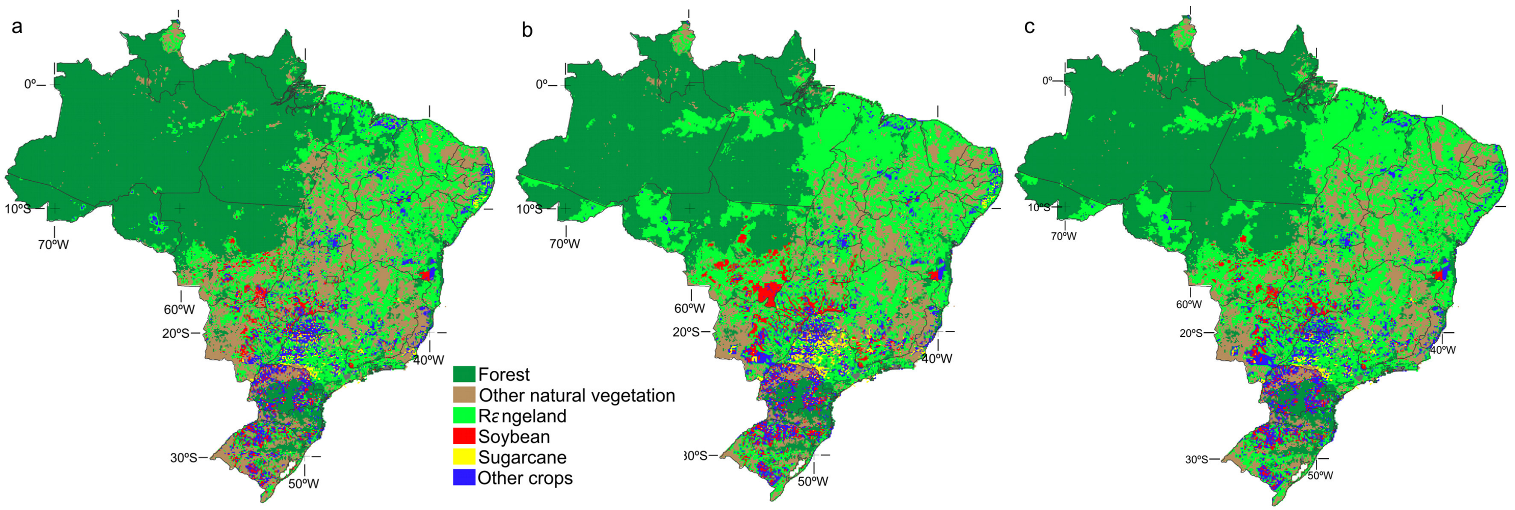

Fig. S1. Modeled land-use maps for (*a*) the year 2003, (*b*) 2020 with fulfillment of Brazil's biofuel target for 2020, and (*c*) 2020 with biofuel production at the same level as in 2003.

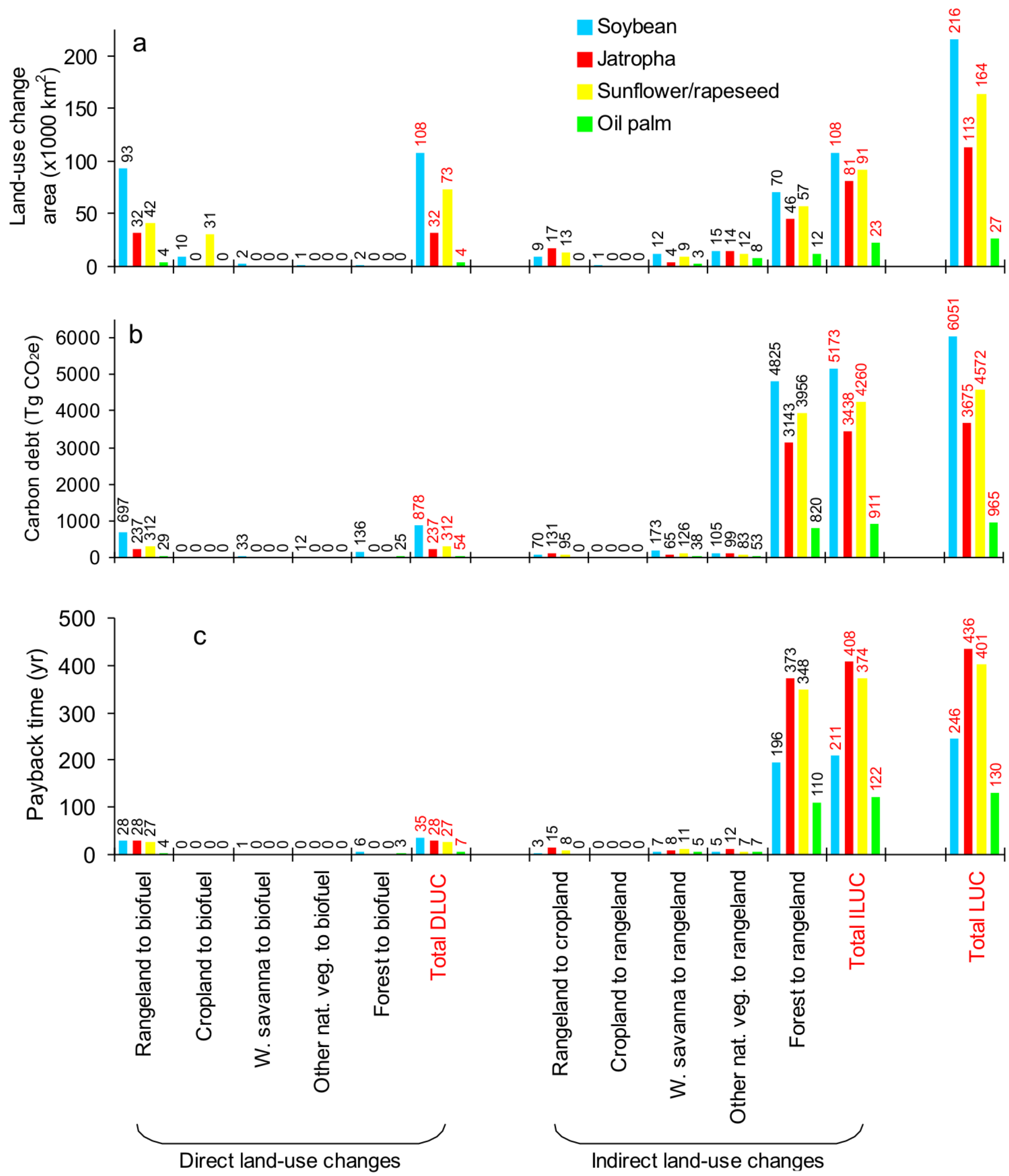

Fig. S2. Land-use changes, carbon debt and time to repay debt for fulfilling Brazil's demand for biodiesel in 2020 with different feedstocks. W.: woody; nat. veg.: natural vegetation.

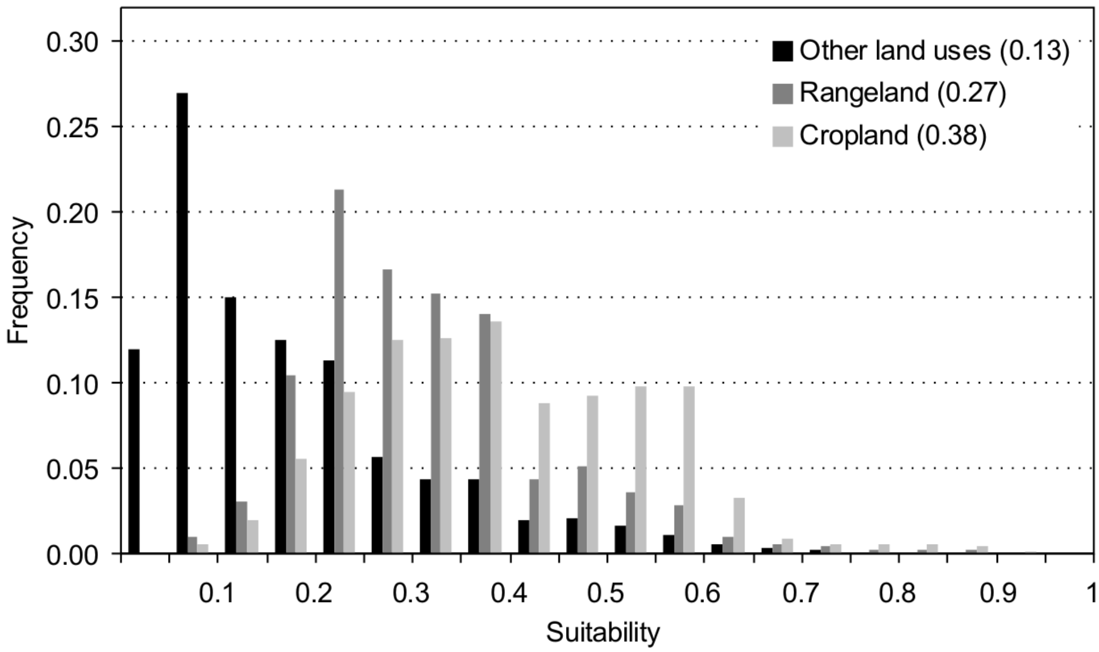

Fig. S3. Frequency distribution of suitability values among different land-use activities: cropland (n = 7436), rangeland (n = 22577), and other land uses (n = 72848). Value in parenthesis indicates the median suitability for the given land use.

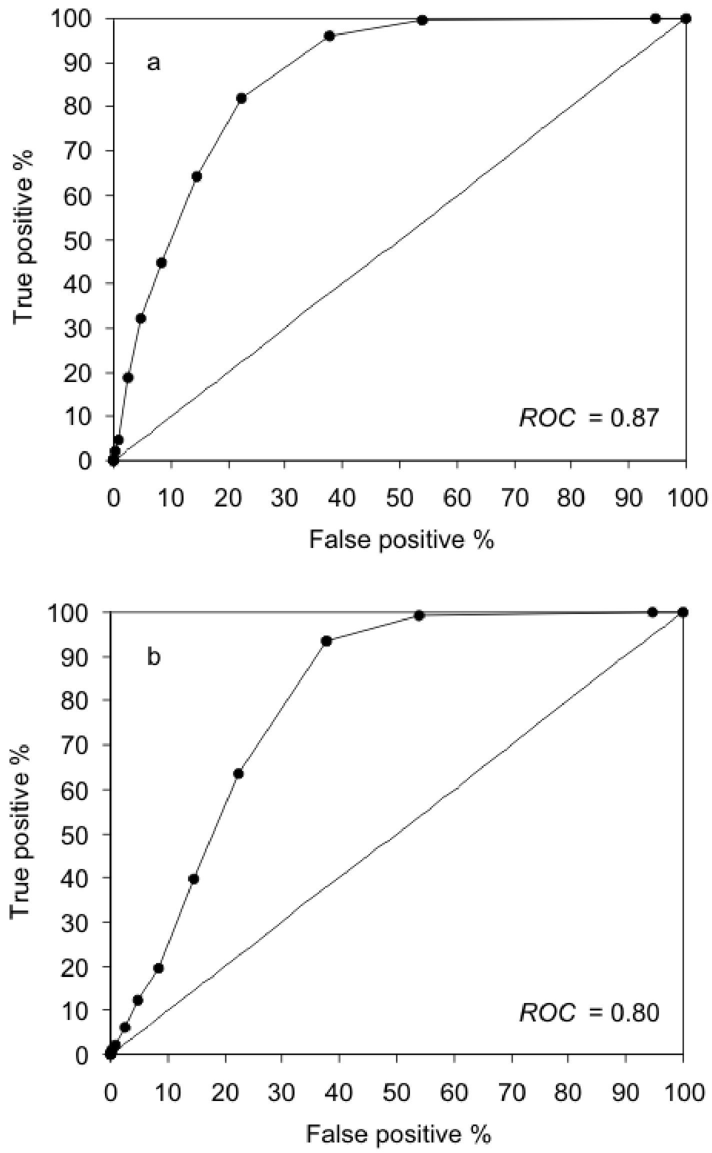

Fig. S4. Relative operating characteristic (ROC) curves for comparison (*a*) between cropland and other land uses excluding rangeland, and (*b*) between rangeland and other land uses excluding cropland.

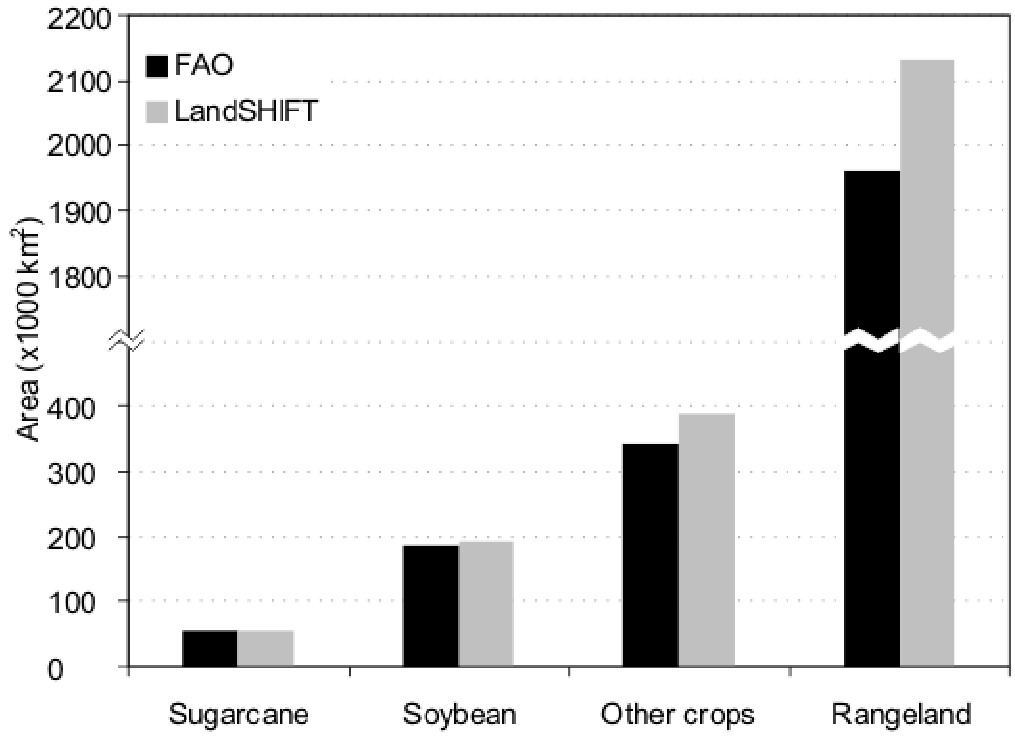

Fig. S5. Comparison of cropland and rangeland area modeled by LandSHIFT against FAO statistics for the year 2003.

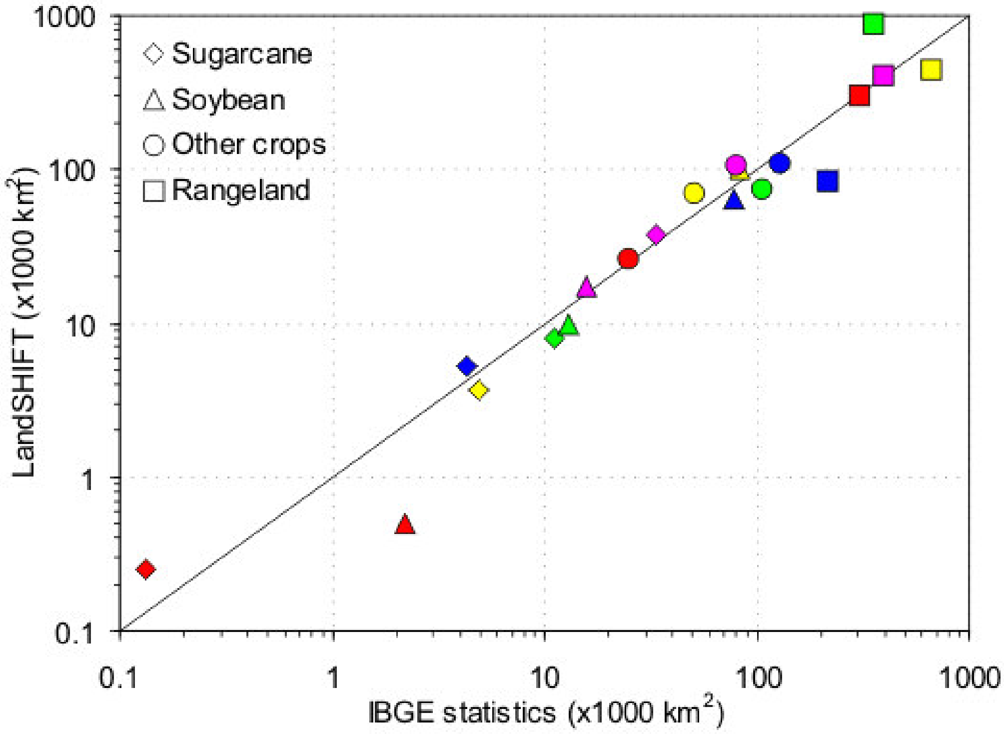

Fig. S6. Comparison of crop/rangeland distribution within major Brazilian regions modeled by LandSHIFT against IBGE subnational statistics (1) weighted by modeled total crop/rangeland area (logarithmic scale). Centre-West: yellow; North: red; Northeast: green; South: blue; Southeast: purple. Centre-West: Distrito Federal, Goiás, Mato Grosso, Mato Grosso do Sul; North: Acre, Amapá, Amazonas, Pará, Rondônia, Roraima, Tocantins; Northeast: Alagoas, Bahia, Ceará, Maranhão, Paraíba, Pernambuco, Piauí, Rio Grande do Norte, Sergipe; South: Paraná, Rio Grande do Sul, Santa Catarina; Southeast: Espírito Santo, Minas Gerais, Rio de Janeiro, São Paulo.

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SI Tables

Table S1. Average actual crop yields modeled by LPJmL compared to FAO statistics for Brazil. To match FAO yields, a management factor is applied to the LPJmL yields before the yields are fed into the LandSHIFT model. Modeled net yield changes are split into changes due to technological improvements such as increased irrigation and plant breeding (1, 2) and changes due to climate change (temperature, precipitation and atmospheric CO_2 concentration) (3, 4) in Brazil. A comparison between projected changes and real yield changes in the last 20 years in Brazil is also shown (5).

	Actual yields*, Mg/ha			2003-2020 yield changes†, Mg/ha			Annual change rate, kg/ha/yr	
Crop type‡	LPJmL	FAO	Management factor	Due to technology	Due to climate	Net	LandSHIFT 2003-2020	FAO 1986-2006
Sugarcane	67.9	66.4	1.0	26.9	4.5	31.4	1850	632
Soybean	1.2	2.1	1.8	0.6	0.2	0.8	46	39
Sunflower/Rapeseed	1.4	1.3	0.9	0.4	0.1	0.5	31	46
Oil palm§	13.2	10.0	0.8	4.1	6.1	10.2	600	-26
Jatropha curcas	3.7¶	-	1.0	1.5	0.1	1.6	95	-
Maize	3.1	2.5	0.8	1.5	0.1	1.6	94	78
Pulses	2.5	0.6	0.2	0.2	0.0	0.2	13	21
Rice	5.2	2.6	0.5	1.4	0.4	1.8	108	93

* For the 1991-2000 period (see ref. 3).

† All 2020 yields are below maximum theoretical yields (ref. 6; see also ref. 1 and 2 for assumptions used by the IMPACT model for the 'GEO4-Sustainability First' scenario).

‡ More than 90% of the cultivated area in Brazil is comprised by these crop types.

§ Oil palm yields, which are not modeled by the LPJmL model, are derived by applying a factor of 6.0 to the tropical roots crop functional type.

¶ In fact this is the potential yield (average yield of every grid cell) since there is no consistent information on the location and extension of actual *Jatropha curcas* plantations in Brazil.

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Table S2. Crop production in 2003 (1) and 2020 (2), and 2003-2020 changes in Brazil.

Crop type	2003, Gg	2020, Gg	Δ, %
Wheat	5033	8741	73.7
Other temperate cereals	744	1402	88.6
Rice	11343	17619	55.3
Maize	41928	73640	75.6
Tropical cereals	1560	2831	81.5
Pulses	54831	105172	91.8
Temperate roots	3022	5447	80.3
Tropical roots	23811	33775	41.8
Other annual oil crops	443	717	61.8
Soybeans	47604	77756	63.3
Sugarcane	388184	763493	96.7
Permanent crops / Vegetables	53486	88349	65.2
Total	631989	1178942	86.5

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Table S3. Weights w_i for factors p_i used in LandSHIFT's cropland module for this study.

p_i **factor**	w_i **weight**
Potential crop yield	0.23
Proximity to cropland	0.08
Proximity to settlements	0.04
Road network	0.13
Slope	0.23
Soil fertility	0.29

Table S4. Land-use transition constraints (c_i) used in this study. Transition to forest or other native habitat is not modeled.

From \ To	Urban	Cropland	Rangeland	Set-aside
Urban	-	0.0	0.0	0.0
Cropland	1.0	-	0.5	1.0
Rangeland	1.0	1.0	-	1.0
Forest	1.0	0.5	0.5	0.0
Other native habitat	1.0	0.5	0.5	0.0
Set-aside	1.0	1.0	1.0	-

Table S5. Biofuel production in Brazil in 2003 and projections for 2020 (1, 2). Sources for biofuel yields: (2-6).

Biofuel	Year	Volume, ($x10^9$ liter)	Feedstock	Biofuel yield, (liter/Mg)	Production, (Tg)
Ethanol	2003	14.5	sugarcane	85	170.59
Ethanol	2020	50.03	sugarcane	85	588.53
Biodiesel	2003	0.5	soybean	200	2.50
Biodiesel	2020	4.47	soybean	200	22.33
Biodiesel	2020	4.47	jatropha	278	16.07
Biodiesel	2020	4.47	sunflower/rapeseed	448	9.97
Biodiesel	2020	4.47	oil palm	490	9.12

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Table S6. Carbon debt estimates (CO_2 emissions from soils and aboveground and belowground biomass caused by land-use change) used in this study.

Previous land-use (from)	To cropland $MgCO_2e./ha$	To rangeland* $MgCO_2e./ha$	To well-managed rangeland† $MgCO_2e./ha$	Source ref.
Cropland	0	0	0	1
Rangeland	75	0	0	2
Other natural vegetation	85	69	13	1
Woody savanna	165	145	60	1
Tropical forest	737	690	572	1

* Soil carbon emissions are 20% lower (see ref. 3).

† Soil carbon emissions are hypothetically reduced to zero (see main text's Discussion)

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Table S7. Proportion of total land-use change carbon debt (see Table S6) allocated to biofuel production, and estimates of annual life-cycle GHG reduction from biofuels (including displaced fossil fuels, soil carbon storage and fertilizer use, but not land-use change emissions) used in this study.

Biofuel	Debt allocated to biofuel* %	Source ref.	Annual GHG offset $MgCO_2e$./Gg of harvested feedstock	Source ref.¶
Sugarcane ethanol	100	1	162	1, 5
Soybean biodiesel	39	1	429	1
Sunflower/Rapeseed biodiesel	82†	2	935	6
Jatropha biodiesel	72‡	3, 4	378	7
Oil palm biodiesel	87	1	710	1

* See ref. 1 for definition.
† Considering 2007 prices of $1.26 for oil and $0.2 for seed cake
‡ Considering 2007 prices of $0.5 for oil and $0.2 for seed cake
¶ Where more than one reference is cited, average value was used

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