Brazilian Agriculture and Environmental Legislation: Status and Future Challenges

GERD SPAROVEK,*,† GÖRAN BERNDES,‡ ISRAEL L. F. KLUG,† AND ALBERTO G. O. P. BARRETTO†

"Luiz de Queiroz" College of Agriculture, Department of Soil Science, University of São Paulo, Av de Pádua Dias, 11, Piracicaba (SP), Brazil, 13418-900 and Chalmers University of Technology, Department of Energy and Environment, Division of Physical Resource Theory, SE-412 96 Göteborg, Sweden

Received March 10, 2010. Revised manuscript received June 15, 2010. Accepted June 30, 2010.

Brazilian agriculture covers about one-third of the land area and is expected to expand further. We assessed the compliance of present Brazilian agriculture with environmental legislation and identified challenges for agricultural development connected to this legislation. We found (i) minor illegal land use in protected areas under public administration, (ii) a large deficit in legal reserves and protected riparian zones on private farmland, and (iii) large areas of unprotected natural vegetation in regions experiencing agriculture expansion. Achieving full compliance with the environmental laws as they presently stand would require drastic changes in agricultural land use, where large agricultural areas are taken out of production and converted back to natural vegetation. The outcome of a full compliance with environmental legislation might not be satisfactory due to leakage, where pristine unprotected areas become converted to compensate for lost production as current agricultural areas are reconverted to protected natural vegetation. Realizing the desired protection of biodiversity and natural vegetation, while expanding agriculture to meet food and biofuel demand, may require a new approach to environmental protection. New legal and regulatory instruments and the establishment of alternative development models should be considered.

Introduction

Brazilian agriculture, presently covering about one-third of the Brazilian land area, has expanded substantially during recent decades and is expected to expand further in response to growing demand for food products and biofuel feedstocks (*1*). Recent decade's expansion has resulted in a large increase in output but also substantial loss of natural ecosystems and negative impacts for biodiversity and soil and water resources (*2–5*). The impacts however vary with crop type. For instance, during the period 1996–2006 sugar cane plantations were mainly established on existing croplands and pastures and did not in general contribute to direct deforestation in the traditional agricultural region where most of the expansion took place (*6*). In contrast, soybean production has during recent decades expanded in the Cerrado, replacing natural grassland ecosystems (*7, 8*)

Studies that consider environmental consequences of Brazilian agricultural expansion report seemingly contrasting results. Some point to risks of further ecosystem conversion, large greenhouse gas emissions, biodiversity loss, and resource degradation (*9–16*), while others stress that productivity increases and good agricultural practices can reduce agricultural land expansion requirements and mitigate negative impacts (*15–19*). Reasons for the diverging conclusions include differences in scope and applied methodology and variation of empirical data used. In Brazil, the primary data required for modeling and quantification are distributed over several sources and institutions, limiting data access and restricting comprehensive national modeling. There is also in general limited knowledge about the land-use dynamics (including underlying drivers) in possible agriculture expansion regions such as woodland and savanna regions (*20, 21*). A large volume of case studies exists that can give authoritative accounts of land use change in particular places, but their validity outside the location of study is limited (*22*).

Land-use modelers (see, e.g., refs *11, 15, 17*) exploring the Brazilian case generally pay little attention to the influence of legal aspects, i.e., how Brazilian regulations influence agriculture, including the size and spatial distribution of the expansion potential. As a consequence, they give little insights into how such regulations may come to shape the possible agricultural expansion. Yet, variations in land-use change have correlated with changes in government policy and legal regulations of agricultural activities (*23*). The influence of land-use policies on land-use dynamics also depends on the state of important underlying economic market forces driving land-use change (*14, 24*) as well as on local/regional factors such as topography, land tenure and vegetation dynamics, and road building (*25–28*). The role of nonstate actors in addressing aspects intended to be regulated through legal instruments has also been identified as important (*22, 29*).

Brazilian Legal Environmental Framework

Two main legal frameworks, the Forest Law and Preservation Areas (public national and state conservation parks and Indian reservations), in several ways influence Brazilian agriculture and its expansion pattern. The Forest Law divides rural private land into productive land and land dedicated to preservation, which is further subdivided into Legal Reserves, a specified proportion of all private farmland that is reserved for conservation, and Areas of Permanent Preservation (APP) including (i) riparian systems defined as vegetation strips along rivers and other water bodies with width varying depending on type and size of the water body, (ii) steep slopes (>45°), (iii) hill tops, and (iv) altitudes > 1800 m above sea level (masl). The primary rationale behind APP is freshwater protection and preventing degradation of areas with strategic value for freshwater recharge. APP are not allowed to be used for any type of production and should be maintained with the original native vegetation. Extremely steep slopes (>45°, or 100%) and altitudes above 1800 masl have limited suitability for agriculture, and reserving such areas for natural vegetation is consequently not controversial. However, "hill tops" is unclearly defined in the Forest Law, restricting possibilities for surveillance and enforcement of compliance. Riparian systems are natural places for agricultural expansion and thus under pressure in agricultural areas. Legal Reserves, today established to promote fauna

* Corresponding author phone: +55 19 3429 4503; fax: +55 19 3429 4555; e-mail: gerd@usp.br.
† University of São Paulo,
‡ Chalmers University of Technology.

10.1021/es1007824

and flora biodiversity conservation and sustainable use of natural resources, are primarily reserved for native vegetation but can contain some low-impact production systems, such as managed low-impact forest extraction, selected agroforestry systems, and bee keeping. These are suitable for small-scale family agriculture and possibly alternative production schemes aiming at niche markets. Conventional mechanized agriculture employing intensive inputs or forestry operations employing complete forest removal are not allowed.

The Forest Law covers all natural vegetation, not only the forests but also the physiognomies of the no-forest biomes such as the savannas (Cerrado), the typical sparse, thorny woods with drought-resistant trees in northeastern Brazil (Caatinga), the tropical wetland (Pantanal), the world biosphere reserve complex along the Atlantic coast (Atlantic Forest), and the grassland of South Brazil (Pampa).

Legislation Development, Application, and Imposed Restrictions

Restrictions on agriculture that are connected to issues of freshwater conservation (APP) are seen as more relevant by Brazilian actors than the general conservation purpose of Legal Reserves. Farmers and their representatives in the Brazilian parliament are not inclined to challenge the objective of freshwater protection and historically request minor revisions concerning APP in the Forest Law. Conversely, Legal Reserves are regularly subject to dispute, and their benefits are more often questioned. The proportion of private farmland that has to be set aside as Legal Reserves in the Forest Law has varied over time and is presently subject to debate. Currently, 35% of the private farmland should be protected as Legal Reserve in the savanna regions inside the Legal Amazon Region (LAR, area of 5 217 423 km^2, about 61% of Brazil's territory established by Federal Law). Outside the LAR, 20% of private farmland should be protected as Legal Reserves. Protection through APP claims additional land in these areas. In the majority of the forests in the LAR, 80% of the total area of private farmland should be protected as either Legal Reserve or APP. The main events of the historical development of the Forest Law and Preservation Areas are described in Table S1 in the Supporting Information. Preservation Areas are under public administration and do not allow conventional private agricultural use. Some exceptions apply to Indian Reservations, where self-sufficiency food production under low-impact traditional agricultural systems following management plans are allowed.

The described Brazilian legal environment framework is expected to become increasingly influential as a result of improved monitoring capacity, more strict local governance, effective legal enforcement, and also adaptations of the agriculture sector to new demands linked to certified markets where legality of operations is a primary requirement (*13, 30, 31*).

This article reports results from an assessment of Brazilian agriculture and its expansion potential, explicitly considering restrictions arising from the Brazilian environmental legislation. On the basis of the assessments, challenges for future expansion of Brazilian agriculture are discussed with an account of some possible approaches to address these challenges.

Methods

Data processing for the analysis was divided in two phases: phase 1 icludes data collection, preparation, auditing, and standardization, and phase 2 includes high-level data processing. Phase 2 was based on Boolean operators applied on binary raster files resulting from phase 1, each file representing a single variable. The pixels size in the raster files have a dimension of approximately 90 × 90 m and covered the entire continental Brazilian territory. The binary raster variables were obtained from basic information sources, most publicly available. The conversion of this information to binary variables was based on simplifications, data aggregation, and transformation of low to high complexity and varying according to the original format's compliance to the high-level data processing demands. The conversion steps are described in the Supporting Information.

Below, first, we describe the basic information sources and conversion procedures to the binary raster variables (phase 1) used in the high-level data processing (phase 2). We then describe the Boolean operators used in phase 2 and the adopted tools. Further information about the methodology is available for download at http://www.esalq.usp.br/AgLUE.

Basic Information Sources and Conversion Procedures (Phase 1)

Data Selection: Sources and Criteria. The data source selection criteria were developed to obtain the variables needed to model the Brazilian Forest Law in order to (i) identify Rural Private Land, (ii) split rural private land in Productive Areas and Private Land Dedicated to Conservation, (iii) split Private Land Dedicated to Conservation in Areas of Permanent Preservation (APP) and Legal Reserve, and (iv) identify Land under Public Conservation composed of parks and Indian reservations.

The data was subsequently processed to identify (i) the native vegetation deficit in Areas of Permanent Preservation, Legal Reserves, and Public Conservation Areas, (ii) the amount of anthropic land use in Rural Private Land and Protected Areas, and (iii) the amount of native vegetation excluded from Private and Public Conservation. The main considerations and sources used for data source selection are described in Table S3, Supporting Information.

The original vector (shape file format) and raster (geo tiff format) data files were first processed in a sequence of 1−5 steps to allow generation of the 13 variables considered in the high-level data processing. These resulting 13 variables were converted in single binary raster format (occurrence, value = 1; no occurrence, value = 0) that were further processed using a sequence of Boolean rules. Table S4, Supporting Information, describes the first 5 processing steps applied on the original vector and raster data. Data processing of these first 5 steps was done using TNT-Mips GIS v. 2009.

The land-use classes of the original shape files had distinct categories and were thus first regrouped into five classes: (i) native vegetation, (ii) anthropic, (iii) urban, (iv) rivers and water body, and (v) no data. These classes were further processed resulting in the final binary variables according to Table S4, Supporting Information. The binary high-level process raster files were created covering the entire continental Brazilian territory and having a pixel size of 90 × 90 m. Table S5, Supporting Information, describes a riparian buffer model applied to the shape file of hydrography. The original shape file was first split into smaller files to allow the buffer zone calculations according to the widths determined by the Forest Law. The vector buffers were further processed to raster format, resulting in a mosaic.

Modeling Land Use and Legal Environmental Aspects (Phase 2)

The variables considered in the high level of data processing are related to land use: native vegetation, NV; agriculture, Ag; pasture, Ps; silviculture, Sv; unspecified anthropic, AU; urban, Ur; rivers and water body, Wa; no data, ND. They reflect physical conditions or landscape positions: riparian systems as areas for permanent protection, APP, slope classes SLP 1−7, and land suitability for agriculture SU or political

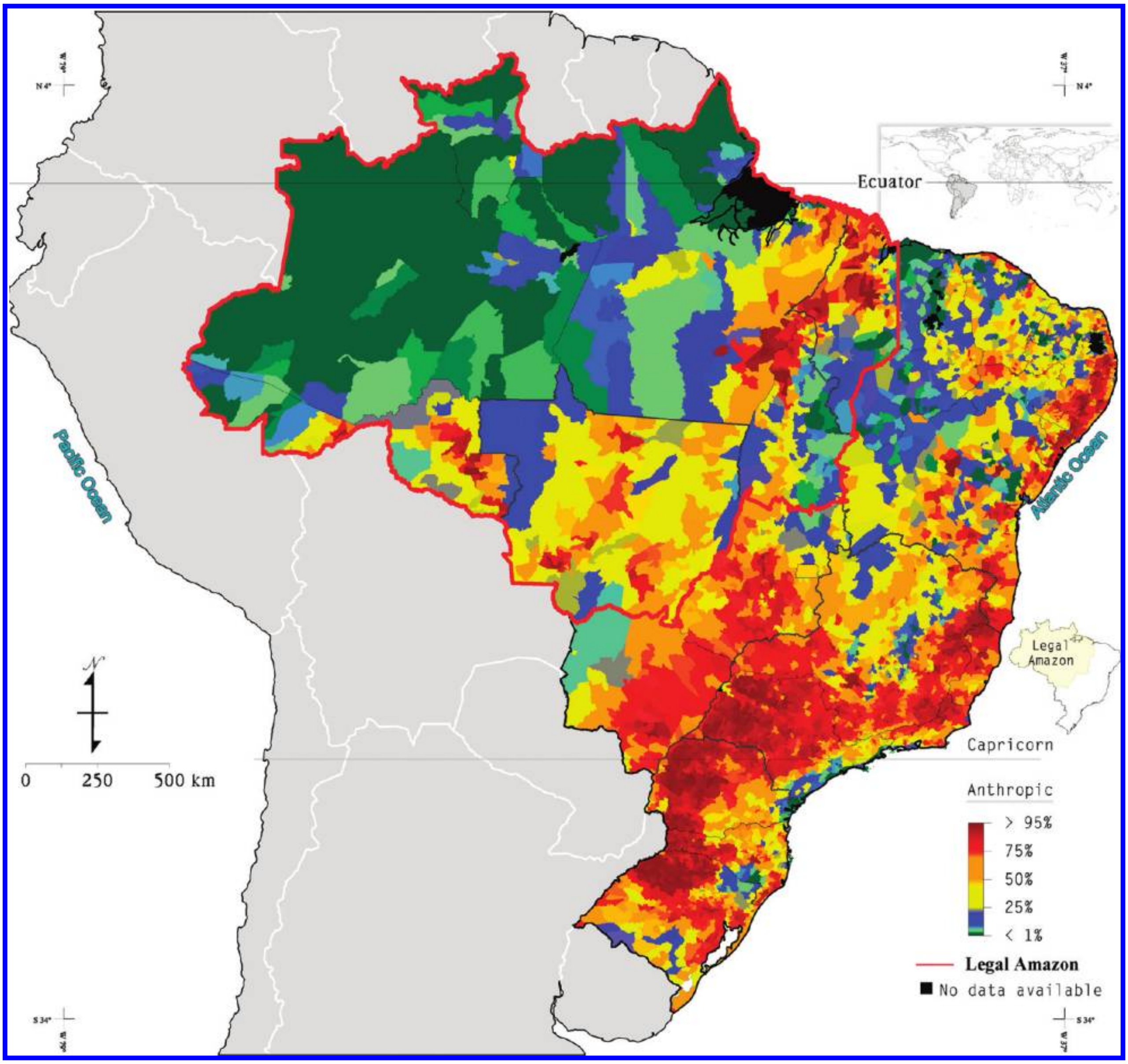

FIGURE 1. Percentage of total municipal area under anthropic land use (mainly agricultural).

conditions: conservation parks, CP; Indian reservation, IR; biome, Bio; Legal Amazon, LA; consolidated agriculture zones in the macro economic and environmental zoning inside the Legal Amazon (described in Table S6, Supporting Information, and the resulting land-use map in Figure S1 and slope map in Figure S2, Supporting Information).

Independent of its original resolution and format, the variables summarized in Table S6, Supporting Information, were converted into coregistered binary raster files with the same line and column dimensions, geographic extents (Brazilian continental territory), and cell size (line = 83.3 m × column = 86.7 m), matching the most detailed input data (SRTM-DEM). By these, direct Boolean, mathematic, or logic operations could be implemented covering the entire feature space among these variables. The operations over the spatial dimension of the variables were made by Database operators on subsets of data extracted from result variables covering the desired extensions (e.g., Biome Amazon, Pantanal, LAR).

The binary raster and a set of vector data were processed by geospatial software according to logic or mathematical expressions using GIS tools, resulting in output model variables as described in the following subsections.

First Raster Process. In the software Raster Process module, each raster variable defined in Table S6, Supporting Information, is processed according to mathematical or logical expression described in Table S7, Supporting Information, covering the needed feature space over the entire raster spatial dimension on a cell-by-cell basis. The resulting variables were further processed as described in the Vector-Raster subsection.

Vector-Raster Process. The Vector-Raster Process used the raster objects created in the First Raster Process module to compute attribute tables containing variables measurements for vector polygons, covering different extractions of the spatial dimension. The extraction areas were specified by a vector object related to political or administrative borders (municipality, regions, states) or geomorphology divisions (watersheds, basins, biomes). Table S8, Supporting Information, defines the vector and database operations applied to the First Raster Process module output variables and the resulting information.

Results

We find that the incidence of anthropic land, mainly land under crops, livestock, and planted forest, varies considerably

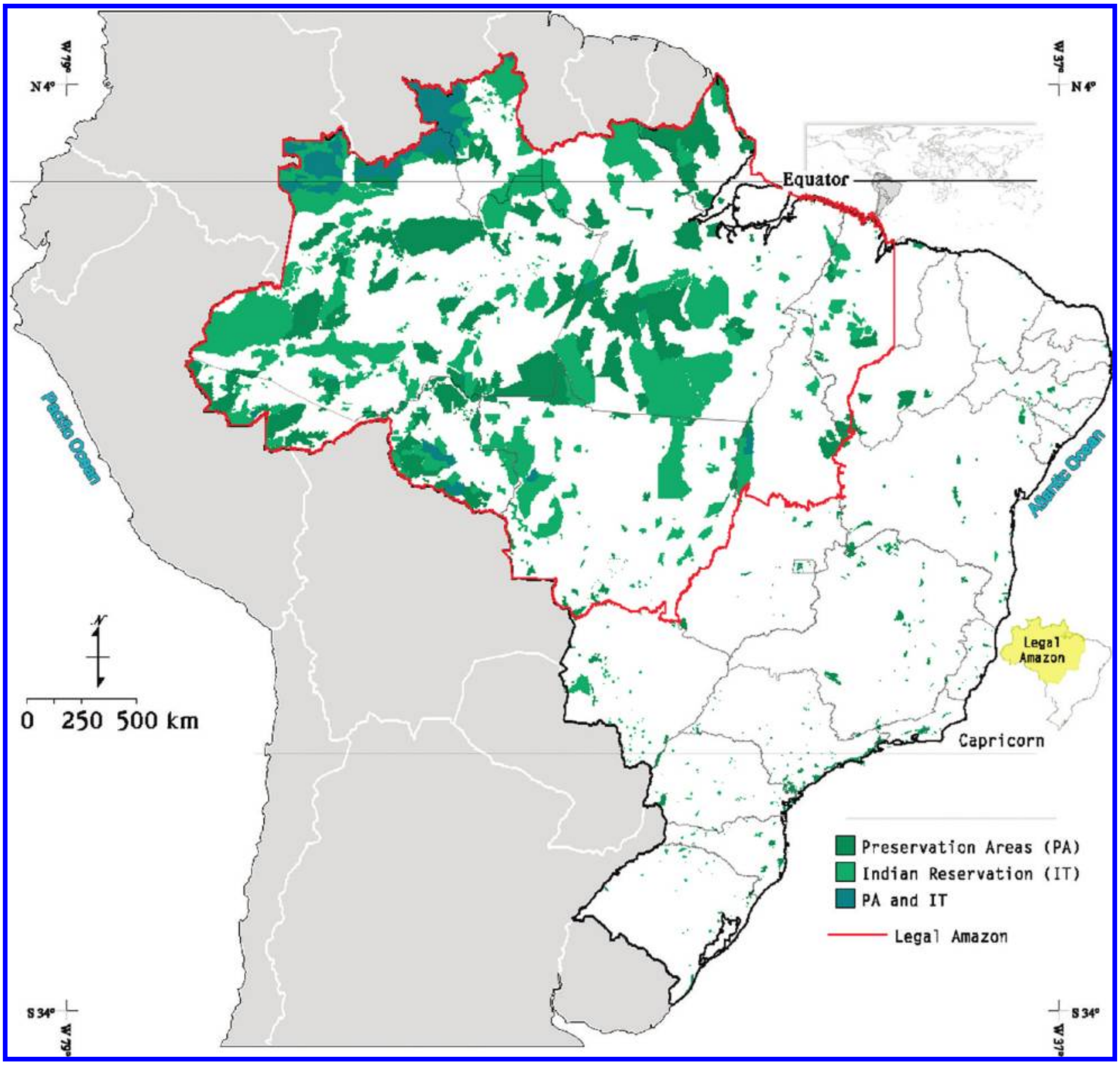

FIGURE 2. Preservation areas and the Legal Amazon Region.

among biomes, ranging from close to 70% of total area in the Atlantic forest biome to slightly less than 10% in Pantanal outside LAR. The regional variation is also large, ranging from about 63% in the South to about 12% in the North region (Figure 1, Table S2, Supporting Information).

Public preservation areas and Indian reservations cover about 20% of the Brazilian territory. Conservation areas on private land are composed of conservation areas in APP (12%) and the Legal Reserve area (30%) required for fulfillment of the Forest Law. Thus, twice as much privately owned land should be protected under the Forest Law than what is protected in parks and reservations (Figure 2, Table S2, Supporting Information).

The effectiveness of protection was found to vary greatly. Illegal anthropic land use was observed in 3% of the park and reservation areas (5 Mha), compared to 42% of APP (43 Mha), Table S2, Supporting Information. However, parks and reservation areas are unevenly distributed in Brazil (Figure 2). In the North region 39% of the territory, 54% in the state of Amapá, consists of parks and reservations. In contrast, the only state in the South and Southeast regions having more than 4% of the territory in parks and reservations is Rio de Janeiro (8%). The Central-West region (mostly Savannas or Cerrado), where most of the recent agricultural expansion has taken place, has 11% and the Northeast region has 4% in parks and reservations. The most developed and densely populated regions, which encompass important biomes for biodiversity (e.g., Atlantic Forest) have very limited areas in parks and reservations and greater presence of anthropic land use inside these areas.

Full compliance with the Forest Law requires that about 254 Mha of private farmland, an area more than twice the size of the EU27 cropland area, is protected as Legal Reserves. We estimate that Legal Reserves on private farmland cover about 218 Mha, i.e., there is a deficit of about 36 Mha. The Legal Reserve deficit varies among regions, ranging from about 8% in the Southeast to 24% in the North, and also among biomes (Figure 3). LAR has the largest deficit, about 27% for the region as a whole but ranging from only 1% in Pantanal to 34% (22 Mha) in the Amazon forest biome where 80% of the private farmland area has to be set aside for APP + Legal Reserves.

Part of the natural vegetation in areas experiencing agriculture expansion is presently not protected (Figure 4). The large savanna biome outside LAR (Cerrado) has at least 27 Mha of unprotected natural vegetation. In total, about 68

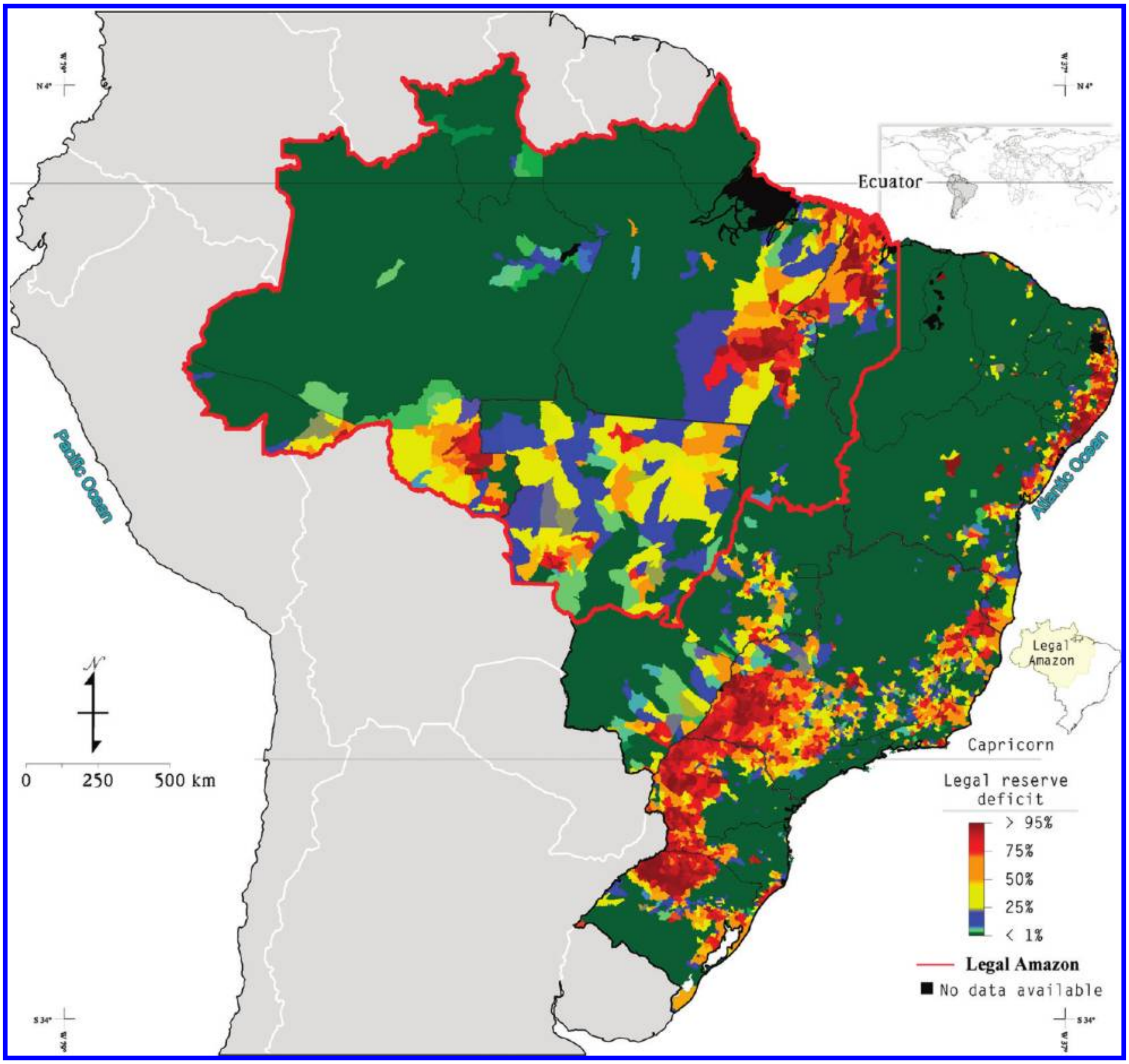

FIGURE 3. Spatial distribution of the Legal Reserve deficit (about 36 Mha in total). The map shows the Legal Reserve deficit aggregated at the municipality level, i.e., deficit, % = [(deficit, ha/needed legal reserve, ha)] × 100.

Mha of natural vegetation outside LAR is unprotected, and inside LAR, 24 Mha is unprotected, of which 14 Mha is savanna. The total area of unprotected natural vegetation (92 Mha) is roughly twice the area presently occupied by the four major Brazilian crops (soybean, corn, sugar cane, beans) or 1.4 times the total agriculture area excluding pastures (64 Mha).

Conclusion and Discussion

The legal frameworks in place do not effectively achieve the objectives of protecting water and native vegetation on private farmland in Brazil. State administration of protection in conservation parks and Indian reservations is more effective, but such protection is limited in extent in the more developed and agricultural regions. Illegal land use in Legal Reserves and APP is widespread, including the traditional agriculture areas of the South and Southeast regions, the recent expansion areas (Cerrado) in the Central West Region, the almost untouched Northern Amazon region, and the semiarid Northeast region where rainfed agriculture is climatically restricted. Full compliance with the environmental legislation would require radical changes in Brazilian agriculture. Agricultural production would have to be interrupted on large areas of private land that has long been under agricultural use. The land owners would in addition have to invest in the rehabilitation of the native vegetation, which is technically difficult and expensive. For instance, 24% of current agricultural land in the North region would have to be reconverted to native vegetation (mainly reforested). In Mato Grosso, where a large part of the recent agricultural expansion has taken place, the Legal Reserve deficit is about 9 Mha or 26% of the present agriculture. In the state of São Paulo, the major sugar cane producing state in Brazil, it is about 2.6 Mha or 13% of the established agriculture.

The challenges for Brazilian agriculture expansion in relation to the environmental legislation look different in distinct regions. Future expansion may lead to increasing conflict of interest between agricultural development and nature protection in regions where agricultural land is currently sparse and where parks and reservations cover a substantial part of the territory. In traditional agricultural regions, where croplands and pastures cover a large part of the area, diverging standpoints may instead concern rules and procedures for addressing the issue of widespread illegal

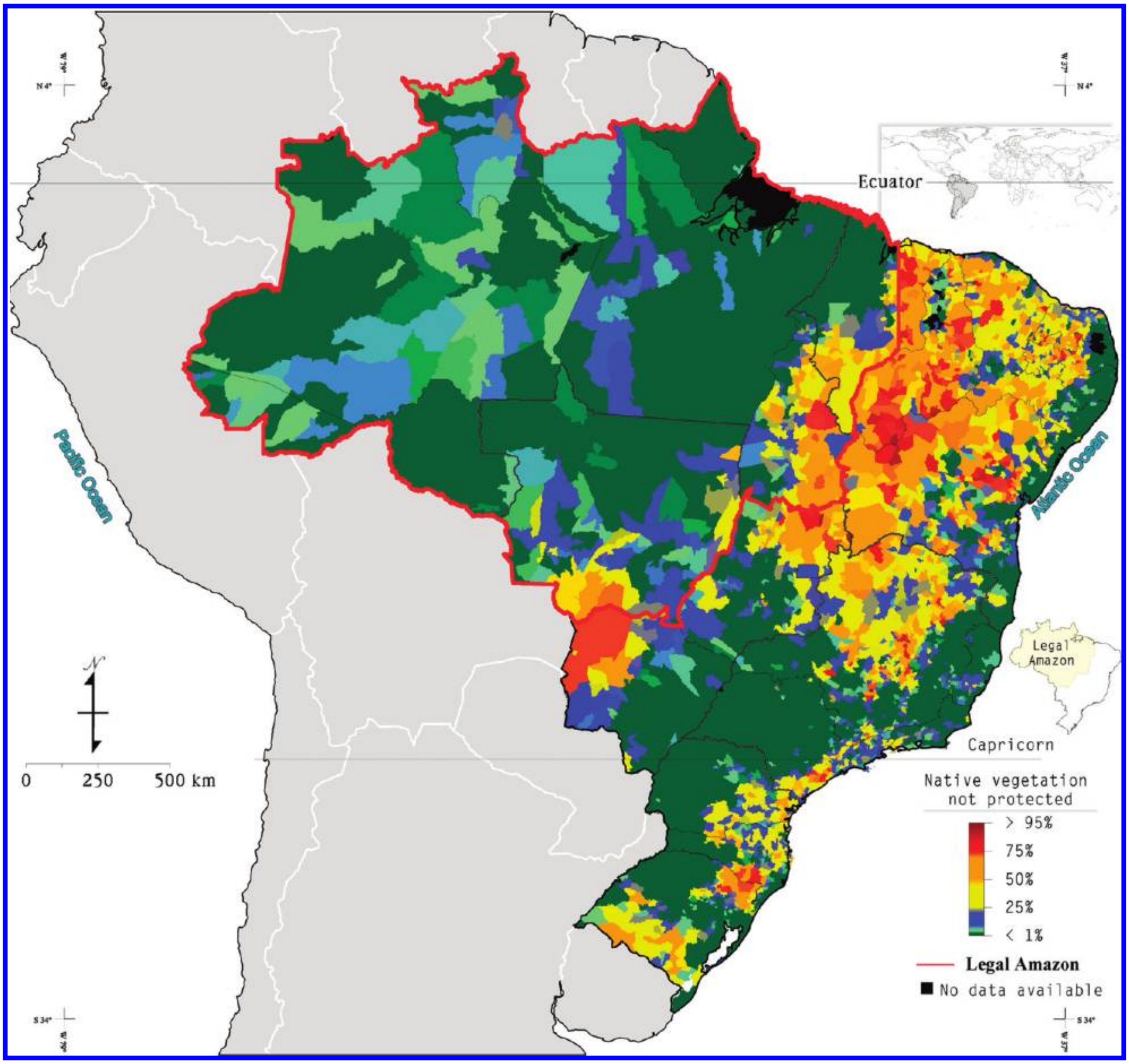

FIGURE 4. Percentage of total municipal area that is presently covered by unprotected native vegetation (i.e., native vegetation that can be converted to agricultural land use without violating any law).

anthropic use of protected areas and noncompliance with Legal Reserve requirements.

Enforcement of full compliance using strong and inflexible measures would likely meet strong resistance among farmers and negative socio-economic effects. Furthermore, the conversion of agricultural land into native vegetation could lead to other presently unprotected natural ecosystems becoming converted to farmland in order to compensate for the lost agriculture production. A development process involving both adaptation of agriculture to legal restrictions and revision of the laws regulating land use can therefore be expected. In this context, the lack of protection of natural vegetation in prospective expansion regions warrants attention and measures to enhance protection of such vegetation.

An incremental revision of the Forest Law that maintains the present structure and related mechanisms may not lead to more effective protection of natural vegetation. Several propositions have been forwarded in relation to a possible revision of the Forest Law, which is presently a topic for the Brazilian parliament. These include (i) reducing the protection requirement on farmland areas in LAR forest biomes from 80% to 50%, (ii) allowing APP to be counted as Legal Reserves, thus reducing the combined APP + Legal Reserve requirement, and (iii) introducing more flexible rules for meeting requirements by allowing farmers having a deficit in protected area to compensate by investing in protection outside the farm. Options (i) and (ii) would lead to lower protection requirements and likely negative outcomes for biodiversity and greenhouse gas emissions associated with land use change. For instance, if the protection requirement on farmland area in LAR forest biomes becomes reduced from 80% to 50%, additional large areas of Amazon forests can be legally converted to farmland. Option (iii) may lead to protection of presently unprotected land but fails to address problems related to water and natural vegetation in areas having the Legal Reserve deficit. Compensation schemes concern spatial limitations, in essence how far away from their own land can farmers invest in preservation areas? The answer will depend on prioritization of different objectives. The use of compensation schemes as an instrument for protecting presently unprotected native vegetation will require that farmers can invest in compensation far away from their own land. For instance, the unprotected native Cerrado vegetation outside LAR (27 Mha) is much larger than the Legal Reserve deficit in the same biome (2 Mha), implying that if only the farmers in this same area are allowed to compensate for their deficit by protecting native Cerrado vegetation less than 10% of the presently unprotected vegetation would become protected. Allowing farmers in other regions to invest in Cerrado protection could increase protection but might meet objections because protection investment far away would not address problems related to water and natural vegetation in areas having the Legal Reserve deficit.

A revision of the Brazilian approach to environmental protection could be required, including new legal and regulatory mechanisms as well as voluntary commitments to avoid agriculture expansion displacing natural ecosystems. Land users could be offered to register ownership of unprotected natural vegetation units on their land and rent out or sell these units to other land users in the surrounding area that need to compensate for noncompliance with the Forest Law. As discussed above, the spatial scope for such trade needs to be carefully defined based on assessing its contribution to the objectives of natural resources protection that forms the rationale behind the Forest Law. The possibility to link this market to the emerging REDD mechanism also warrants close consideration.

Certification systems that regulate production aimed for specific markets can also contribute positively. However, the risk of leakage effects following from strict implementation of rules needs to be considered; the above notion, that enforcement of compliance with the Forest Law may lead to other presently unprotected natural ecosystems becoming converted to farmland in order to compensate for the lost agriculture production, is a valid concern also in relation to certification systems. Finally, certified production may not be an option for producers lacking capacity to meet the requirements (on some aspects of the production but also related to monitoring, accounting, and reporting).

Acknowledgments

The authors thank Sylvia Preiler, IIASA, and three anonymous reviewers for constructive comments. Support from Esalq-USP, Chalmers University of Technology, and the Swedish Energy Agency is gratefully acknowledged.

Supporting Information Available

Detailed description of data sources, the model used in this study, and additional comments. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) OECD-FAO, *Agricultural outlook 2009−2018*; Organization for Economic Co-Operation and Development; Food and Agriculture Organization of the United Nations, Rome; OECD Publishing: 2009 (www.fao.org/es/esc/en/highlight_599.html).

(2) Morton, D. C.; DeFries, R. S.; Shimabukuro, Y. E.; Anderson, L. O.; Arai, E.; del Bon Espirito-Santo, F.; Freitas, R.; Morisette, J. Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proc. Natl. Acad. Sci.* **2006**, *103*, 14637–14641.

(3) Sawyer, S. Climate change, biofuels and eco-social impacts in the Brazilian Amazon and Cerrado. *Philos. Trans. R. Soc.* **2008**, *363*, 1747–1752.

(4) IAASTD. Agriculture at a crossroads. *International Assessment of Agricultural Knowledge, Science and Technology for Development*; IAASTD/Island Press: Washington, D.C., 2009; Vol. III, Latin America and the Caribbean, http://www.agassessment.org/.

(5) Cardoso da Silva, J. M.; Bates, J. M. Biogeographic patterns and conservation in the South American cerrado: a Tropical Savanna Hotspot. *BioScience* **2002**, *52*, 225–234.

(6) Sparovek, G.; Barretto, A.; Berndes, G.; Martins, S. P.; Maule, R. F. Environmental, land-use and economic implications of Brazilian sugarcane expansion 1996−2006. *Mitigation and Adaptation Strategies for Global Change* **2009**, *14*, 285–298.

(7) Barona, E.; Ramankutty, N.; Hyman, G.; Coomes, O. T. The role of pasture and soybean in deforestation of the Brazilian Amazon. *Environ. Res. Lett.* **2010**, *5*, 024002. (9pp).

(8) Fearnside, P. M. Soybean cultivation as a threat to the environment in Brazil. *Environ. Conserv.* **2001**, *28*, 23–38.

(9) Scharlemann, J. P. W.; Laurance, W. F. Environmental science—how green are biofuels. *Science* **2008**, *319*, 43–44.

(10) Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land clearing and the biofuel carbon debt. *Science* **2008**, *319*, 1235–1238.

(11) Fischer, G.; Teixeira, E.; Hiznyik, E. T.; Van Velthuizen, H. Land use dynamics and sugarcane production In *Sugarcane ethanol - Contributions to climate change mitigation and the environment*; Zuurbier, P., van de Vooren, J., Eds.; Wageningen Academic Publishers: Wageningen, The Netherlands, 2008; pp 29−62.

(12) Martinelli, L.; Filoso, S. Expansion of sugarcane ethanol production in Brazil: environmental and social challenges. *Ecol. Appl.s* **2008**, *18*, 885–898.

(13) Nepstad, D. C.; Stickler, C. M.; Soares-Filho, B.; Merry, F. Interactions among Amazon land use, forests and climate: prospects for a near-term forest tipping point. *Philos. Trans. R. Soc.* **2008**, *363*, 1737–1746.

(14) Rodrigues, A. S.; Ewers, R. M.; Parry, L.; Souza, Jr., C.; Verissimo, A.; Balmford, A. Boom-and-bust development patterns across the Amazon deforestation frontier. *Science* **2009**, *324*, 1435–1437.

(15) Lapola, D. M.; Schaldach, R.; Alcamo, J.; Bondeau, A.; Koch, J.; Koelking, C.; Priess, J. A. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proc. Natl. Acad. Sci.* **2010**, *107*, 3388–3393.

(16) BNDES/CGEE, FAO, ECLAC. *Sugarcane-based bioethanol: Energy for sustainable development*, 1st ed.; Brazilian Development Bank, BNDES, and Center for Strategic Studies and Management Science, Technology and Innovation, CGEE: Rio de Janeiro, 2008.

(17) Nassar, A. M.; Rudorff, B. F. T.; Antoniazzi, L. B., Aguiar, D. A.; Bacchi, M. R. P.; Adami, M. Prospects of the sugarcane expansion in Brazil: impacts on direct land and indirect land use changes. In *Sugarcane ethanol-Contributions to climate change mitigation and the environment*; Zuurbier, P., van de Vooren, J., Eds.; Wageningen Academic Publishers: Wageningen, The Netherlands, 2008; pp 63−93.

(18) Leite, R. C. C.; Leal, M. R. L. V.; Cortez, L. A. B.; Griffin, W. M.; Scandiffio, M. I. G. Can Brazil Replace 5% of the 2025 Gasoline World Demand with Ethanol. *Energy* **2009**, *34*, 655–661.

(19) Goldemberg, J.; Coelho, S. T.; Guardabassi, P. The sustainability of ethanol production from sugarcane. *Energy Policy* **2008**, *36*, 2086–2097.

(20) Lambin, E. F.; Turner, B. L., II; Geist, H. J.; Agbola, S. B.; Angelsen, A.; Bruce, J. W.; Coomes, O. T.; Dirzo, R.; Fischer, G.; Folke, C.; George, P. S.; Homewood, K.; Imbernon, J.; Leemans, R.; Li, X.; Moran, E. F.; Mortimore, M.; Ramakrishnan, P. S.; Richards, J. F.; Skanes, H.; Steffen, W.; Stone, G. D.; Svedin, U.; Veldkamp, T. A.; Vogel, C.; Xu, J. The causes of land-use and land-cover change: moving beyond the myths. *Global Environ. Change* **2001**, *11* (4), 261–269.

(21) Lepers, E.; Lambin, E. F.; Janetos, A. C.; De Fries, R.; Achard, F.; Ramankutty, N.; Scholes, R. J. A synthesis of information on rapid land-cover change for the period 1981−2000. *Bioscience* **2005**, (55), 115–125.

(22) Rudel, T. Changing agents of deforestation: from state-initiated to enterprise driven processes, 1970−2000. *Land Use Policy* **2007**, *24*, 35–41.

(23) Hirakuri, S. *Can law save the forest? Lessons from Finland and Brazil*; Forest Law Enforcement Governance and Trade, Center for International Forestry Research: Jakarta, Indonesia, 2003; ISBN 979-3361-02-6.

(24) Malhi, Y.; Roberts, J.; Betts, R.; Killeen, T.; Li, W.; Nobre, C. Climate change, deforestation, and the fate of the Amazon. *Science* **2007**, *319*, 169–172.

(25) Brannstrom, C.; Jepson, W.; Filippi, A. M.; Redo, D.; Xu, Z.; Ganesh, S. Land change in the Brazilian Savanna (Cerrado), 1986−2002: Comparative analysis and implications for land-use policy. *Land Use Policy* **2008**, *25*, 579–595.

(26) Nepstad, D.; Carvalho, G; Barros, A. C.; Alencar, A.; Capobianco, J. P.; Bishop, J.; Mountinho, P.; Lefebre, P.; Lopes Silva, U.; Prins, E. 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. *Forest Ecol. Manage.* **2001**, *154*, 395–407.

(27) Pfaff, A.; Robalino, J.; Walker, R.; Aldrich, S.; Caldas, M.; Reis, E.; Perz, S.; Bohrer, C.; Arima, E.; Laurance, W.; Kirby, K. Road investments, spatial spillovers, and deforestation in the Brazilian Amazon. *J. Reg. Sci.* **2007**, *47*, 109–123.
(28) Perz, S.; Brilhante, S.; Brown, F.; Caldas, M.; Ikeda, S.; Mendoze, E.; Overdevest, C.; Reis, V.; Reyes, J. F.; Rojas, D.; Schmink, M.; Souza, C.; Walker, R. Road building, land use and climate change: prospects for environmental governance in the Amazon. *Philos. Trans. R. Soc. B* **2008**, *363*, 1889–1895.
(29) Brannstrom, C. Environmental policy reform on north-eastern Brazil's agricultural frontier. *Geoforum* **2005**, *36*, 257–271.
(30) Tollefson, J. Brazil goes to war against logging. *Nature* **2008**, *452*, 134–135.
(31) Nepstad, D.; Soares, B. S.; Merry, F.; Lima, A.; Moutinho, P.; Carter, J.; Bowman, M.; Cattaneo, A.; Rodrigues, H.; Schwartzman, S.; McGrath, D. G.; Stickler, C. M.; Lubowski, R.; Piris-Cabezas, P.; Rivero, S.; Alencar, A.; Almeida, O.; Stella, O. The end of deforestation in the Brazilian Amazon. *Science* **2009**, *326*, 1350–1351.

ES1007824