Governance, agricultural intensification, and land sparing in tropical South America

Michele Graziano Ceddia[a,1], Nicholas Oliver Bardsley[b], Sergio Gomez-y-Paloma[c], and Sabine Sedlacek[a]

[a]Department of Public Governance and Sustainable Development, MODUL University Vienna, 1190 Vienna, Austria; [b]School of Agriculture, Policy, and Development, University of Reading, Reading RG6 6AR, United Kingdom; [c]Institute for Prospective Technological Studies, European Commission Joint Research Centre, 41092 Seville, Spain

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In this paper we address two topical questions: How do the quality of governance and agricultural intensification impact on spatial expansion of agriculture? Which aspects of governance are more likely to ensure that agricultural intensification allows sparing land for nature? Using data from the Food and Agriculture Organization, the World Bank, the World Database on Protected Areas, and the Yale Center for Environmental Law and Policy, we estimate a panel data model for six South American countries and quantify the effects of major determinants of agricultural land expansion, including various dimensions of governance, over the period 1970–2006. The results indicate that the effect of agricultural intensification on agricultural expansion is conditional on the quality and type of governance. When considering conventional aspects of governance, agricultural intensification leads to an expansion of agricultural area when governance scores are high. When looking specifically at environmental aspects of governance, intensification leads to a spatial contraction of agriculture when governance scores are high, signaling a sustainable intensification process.

deforestation | Jevons paradox

The ongoing process of deforestation calls for urgent attention. The latest Food and Agriculture Organization (FAO) report on the state of the world's forest resources estimates that over the period 2000–2010 more than 50 million hectares have been lost. At the global level, the annual rate of deforestation seems to have slowed, from an estimated 0.20% *per annum* (p.a.) for the period 1990–2000 to 0.13% for the period 2000–2010. This hides many regional differences. South America accounts for over 20% of the remaining global forest resources and has almost half of its total land covered by forests. The annual rate of deforestation has remained constant in South America at 0.45% p.a. This rate is significantly higher than the global average rate (1).

The Millennium Ecosystem Assessment pointed out the distinction between direct and indirect drivers of ecosystem changes (2). The main direct cause of tropical deforestation remains agricultural expansion, followed by wood extraction (3). Understanding the causes of agricultural expansion may then prove useful to understand deforestation processes. The main indirect, underlying, causes of deforestation include economic growth, population growth, institutional change, and technological development (4–6).

The role of technology seems to be particularly important with respect to agricultural production, where much of the increase in output over the past 40 y has been attributed to higher yields rather than expansion of the area under cultivation. Given the coupling of agricultural land expansion and deforestation it is not surprising that both the scientific and the policy community are placing a significant emphasis on sustainable agricultural intensification to reduce pressure on forests, thus sparing land for nature (7–9), while meeting the coming food security challenge (10, 11). Clearly the magnitude of the land-sparing effect will depend on a range of demographic, technological, and socioeconomic factors (12, 13). From an empirical point of view, however, the evidence supporting the land-sparing hypothesis is mixed. On the one hand a positive correlation between agricultural intensification and agricultural contraction has been reported (8). On the other hand, it has also been noted how agricultural intensification and yield increase may generate the Jevons paradox (14–16), referring to cases in which an improvement in resource use efficiency leads to increased rather than decreased use. Thus, the possibility exists that an increase in agricultural productivity may augment the profitability of land conversion and lead to further agricultural expansion (17–20).

Among the various socioeconomic factors, those that most correlate with agricultural expansion include crop prices and production costs (6), the need to generate foreign exchange earnings to service external debt (21), per capita gross domestic product (GDP) (22) and population (4, 5).

The role of political–institutional and governance factors has also been investigated. A significant amount of research has drawn on World Bank (WB) governance quality indicators, which include (23): voice and accountability (capturing the extent to which people can participate in a country's democratic process), political stability and absence of violence (capturing the likelihood that a government will be overthrown by violent means), government effectiveness (capturing the quality of public services), regulatory quality (capturing the ability of the government to formulate sound and independent policies and promote the private sector), rule of law (capturing the quality of contract enforcement and property rights), and corruption control (capturing the extent to which public power is exerted for private gains). Usually a negative relationship between governance scores and deforestation is

Significance

Tropical South America has forest resources of global significance but exhibits a relatively high rate of deforestation. As agricultural expansion remains the most important cause of forest loss and degradation there, it is important to understand its main drivers. In this paper we address two important questions: How do the quality of governance and agricultural intensification combine to impact the spatial expansion of agriculture? Which aspects of governance are more likely to ensure that agricultural intensification allows sparing land for nature? By distinguishing between conventional and environmental dimensions of governance (which includes also the establishment of protected areas), we investigate which of these two aspects, by interacting with the process of agricultural intensification, is likely to promote land sparing.

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[1]To whom correspondence should be addressed. E-mail: graziano.ceddia@modul.ac.at.

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reported, that is, higher levels of governance as measured by the WB are associated with lower levels of forest clearance (24, 25). However, different results have also been obtained (18, 26, 27). In fact it has been argued that better governance improves the bureaucratic efficiency and facilitates land credit and policies that may stimulate agricultural expansion.

Both agricultural intensification and institutional/governance factors are important (alongside other socioeconomic variables) to understand the process of agricultural expansion, although the reported results are contrasting. As governance quality includes multiple dimensions, further specifications are in order. WB indicators capture aspects of governance associated with conditions necessary for the establishment of market-oriented society. The strengthening of these governance aspects appears to be closely associated with increased economic activity, including agricultural expansion, rather than with environmental conservation per se. The key role of the national state in establishing and enforcing secure, tradable, property rights necessary for the functioning of a market economy has been abundantly documented (28, 29).

In addition there are specifically environmental aspects of governance, which aim to reconcile economic development and environmental protection. In this domain, there is a vast amount of literature on the effect of protected areas on deforestation (30–36). Whereas research quantifying the effect of other aspects of environmental governance (other than the establishment of protected areas) on agricultural expansion is sparser, but indicates their potential to significantly reduce deforestation (37).

In recent years extensive efforts have been devoted to the development of indicators capturing various aspects of environmental governance. Here it is noteworthy mentioning two: the 2005 Environmental Sustainability Index (ESI) project (www.yale.edu/esi) and the Environmental Performance Index (EPI) project (www.epi.yale.edu). The former aggregates 21 indicators covering five components: environmental systems, environmental stresses, human vulnerability, social and institutional capacity, and global stewardship (38). The latter focuses on two policy objectives, measuring environmental stresses to human health and ecosystems vitality, and evaluates 22 indicators spanning across a number of policy areas (39). The effect of these broader environmental governance aspects on agricultural expansion and deforestation has not yet been assessed.

In this context, two questions become of paramount importance: How do the quality of governance and agricultural intensification jointly impact on spatial expansion of agriculture? Which aspects of governance are more likely to ensure that agricultural intensification delivers its benefits in terms of reduced pressure to spatially expand agricultural areas? The purpose of this paper is to explore how different dimensions of governance affect agricultural expansion. We contribute as follows to the literature on land cover change. First, the interaction between the quality of governance and agricultural intensification is explicitly modeled, and the effects of such interaction on the occurrence of land sparing or Jevons paradox in tropical South America are estimated. Second, a broader set of governance indicators are considered, including WB indicators (which we refer to as "conventional" governance indicators) but also indicators of environmental governance quality.

Data from the FAO, the WB, the World Database on Protected Areas (WDPA), the Yale Center for Environmental Law and Policy (YCELP) and the International Institute for Applied Systems Analysis (IIASA) for six tropical South American countries (Bolivia, Brazil, Colombia, Paraguay, Peru, and Venezuela) are combined to construct a panel data and study the major determinants of agricultural land expansion over the period 1970–2006. The focus on the six countries mentioned above is justified by the fact that (*i*) they covered 94% of the tropical forest area in South America in 2010 (1), (*ii*) tropical forests are those most threatened by habitat change (2), and (*iii*) deforestation in South America has failed to decline over the past 20 y and remains above the world average (1). The exclusion of some South American countries (Ecuador, French Guiana, Guyana, and Suriname) is due to the incompleteness of the relative datasets. Such countries, however, do not differ significantly in terms of the quality of conventional governance (as measured through a number of WB indicators) from the six countries considered in this study. As such, sample selection bias can be excluded.

The role of various socioeconomic factors (per capita GDP, agricultural exports, agricultural value added, population, and service on external debt) and the role of agricultural intensification are accounted for in the statistical model. All these factors have been shown to have a significant effect on agricultural expansion (21, 22, 40). Agricultural intensification is quantified by considering the value of agricultural output (at constant prices) per hectare of agricultural land. The use of this indicator allows us to easily aggregate both crop and livestock production. This in turn is important to us, as the dependent variable in the empirical model is given by the total agricultural area, including both arable land and pastures. The quality of governance is also accounted for. We form two sets of models, one including conventional dimensions of governance, as measured by the WB (models 1–3), and another capturing various environmental aspects (models 4–6). Scores for the quality of the various governance aspects are reported in Table S1, whereas the descriptive statistics for the sample are presented in Table S2. Additional models accounting for all of the six dimensions of governance simultaneously and for the quality of available land resources (as reported by the Global Agro-Ecological Zones database, www.gaez.iiasa.ac.at) are also considered (*SI Text* and Tables S3–S9).

Results and Discussion

A number of models are estimated to tease out the effect of variation in governance quality and intensification on agricultural area. Here we only discuss the statistically preferred specifications, while additional results are reported elsewhere (*SI Text*). The models have the following structure

$$\begin{aligned}\log(ALit) = {} & \mu + \alpha_i + \lambda_t + \gamma_1(GOV_i \times AOHA_{it}) + \beta_1 \log\ (AOHA_{it}) \\ & + \beta_2 \log^2(AOHA_{it}) + \theta_1 \log(POP_{it}) + \theta_2 \log^2(POP_{it}) \\ & + \theta_3 \log(GDPC_{it}) + \theta_4 \log^2(GDPC_{it}) + \theta_5 \log^3(GDPC_{it}) \\ & + \theta_6 \log(EX_{it}) + \theta_7 \log^2(EX_{it}) + \theta_8 \log(PEDS_{it}) \\ & + \theta_9 \log^2(PEDS_{it}) + \theta_{10} \log(AVA_{it}) \\ & + \theta_{11}\left[\log(PEDS_{it}) \times \log(AVA_{it})\right] + v_{it},\end{aligned} \quad [1]$$

where AL_{it} indicates agricultural land in the ith country at time t, GOV_i is the country governance quality score, $AOHA_{it}$ is the measure of agricultural intensification, POP_{it} is the country total population, $GDPC_{it}$ is the per capita GDP, EX_{it} is the index of agricultural exports, $PEDS_{it}$ is the measure of service on external debt, AVA_{it} is the measure of agricultural value added, and v_{it} is the idiosyncratic error term. The terms μ, α_i, and λ_t represent the regression constant, the country-specific effect, and the time effect, respectively.

Estimation is performed through a panel data regression (with autocorrelation and heteroskedasticity robust covariance matrix) with both one- and two-way random and fixed effects.

The results are reported in Tables 1 and 2 (models 1–3 and models 4–6, respectively). The best estimator, on the basis of the Lagrange multiplier (LM) and Hausman statistic, is the two-way Fixed Effect (FE) model, which implies the existence of both structural differences among countries and a time trend. The latter in particular may reflect some of the unobserved variability in the quality of governance. To discuss the effect of governance

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Table 1. **Regression results for models 1–3**

Variables	Model 1 (*GOV* = *CORC*)	Model 2 (*GOV* = *ROL*)	Model 3 (*GOV* = *ACC*)
Log(*AOHA*)	$-0.711^{§}$ (0.171)	$-1.212^{§}$ (0.163)	$-0.971^{§}$ (0.108)
Log^2(*AOHA*)	$0.073^{§}$ (0.019)	$0.149^{§}$ (0.019)	$0.102^{§}$ (0.011)
Log(*POP*)	$1.406^{‡}$ (0.453)	$1.568^{§}$ (0.381)	$3.358^{§}$ (0.327)
Log^2(*POP*)	0.006 (0.016)	−0.0003 (0.014)	$-0.068^{§}$ (0.011)
Log(*GDPC*)	$49.804^{§}$ (7.316)	$30.104^{§}$ (6.904)	4.990 (5.754)
Log^2(*GDPC*)	$-6.596^{§}$ (0.965)	$-3.988^{§}$ (0.911)	−0.626 (0.761)
Log^3(*GDPC*)	$0.290^{§}$ (0.042)	$0.175^{§}$ (0.040)	0.026 (0.033)
Log(*EX*)	0.066 (0.044)	$0.099^{†}$ (0.038)	0.054* (0.028)
Log^2(*EX*)	−0.004 (0.006)	−0.009* (0.005)	−0.006 (0.004)
Log(*PEDS*)	−0.119* (0.065)	$-0.157^{‡}$ (0.055)	$-0.142^{§}$ (0.041)
Log^2(*PEDS*)	0.003 (0.016)	0.003 (0.014)	0.001 (0.010)
Log(*AVA*)	−0.029 (0.048)	−0.048 (0.042)	$-0.081^{†}$ (0.032)
Log(*PEDS*) × log(*AVA*)	$0.054^{‡}$ (0.019)	$0.067^{§}$ (0.016)	$0.059^{§}$ (0.012)
GOV × *AOHA*	$0.001^{§}$ (0.0004)	$0.003^{§}$ (0.0003)	$0.004^{§}$ (0.0003)
Constant	$-137.592^{§}$ (17.849)	$-88.260^{§}$ (16.863)	$-37.207^{‡}$ (13.690)
Adjusted R^2	0.997	0.998	0.999
Log-likelihood	379.779	410.358	468.938
F significance probability	0.000	0.000	0.000
Hausmann	$75.80^{§}$	$127.17^{§}$	$294.34^{§}$
LM	$199.82^{§}$	$126.76^{§}$	$19.22^{§}$
AIC	−3.003	−3.287	−3.832
Preferred model	Two-way FE	Two-way FE	Two-way FE

Dependent variable: log(*AL*); *10% s.l.; †5% s.l.; ‡1% s.l.; §0.1% s.l. s.l., significance level.

quality and intensification on the agricultural area, we compute elasticities. The role of other socioeconomic and demographic factors like per capita GDP, population, agricultural exports and service on external debt is discussed elsewhere (*SI Text*).

The Interaction of Conventional Governance and Intensification. Consider the models accounting for the conventional dimensions of governance first, as measured by the WB indicators. Given the model specification, the elasticity of agricultural area with respect to intensification (AOHA) is given by $\varepsilon_{AOHA} = \gamma_1(GOV_i \times AOHA_{it}) + \beta_1 + 2\beta_2 \log(AOHA_{it})$. In model 1, the WB corruption control indicator (CORC) is used as a measure of governance quality. Given the values of the estimated coefficients (Table 1), an increase in intensification is associated with contraction of agricultural area (as ε_{AOHA} remains negative) when corruption control is low or moderate (*CORC* set at the sample minimum or sample mean, respectively). However, when the corruption control score is high (*CORC* set at the sample maximum) agricultural intensification leads to agricultural expansion, as ε_{AOHA} becomes positive even for moderate intensification levels (Fig. 1*A*).

Analogous results are obtained when considering the other two WB governance indicators, rule of law (*ROL*) and voice and

Table 2. **Regression results for models 4–6**

Variables	Model 4 (*GOV* = *PA*)	Model 5 (*GOV* = *ESI*)	Model 6 (*GOV* = *EPI*)
Log(*AOHA*)	$-0.709^{§}$ (0.154)	$-1.780^{§}$ (0.309)	$-1.308^{§}$ (0.192)
Log^2(*AOHA*)	$0.070^{§}$ (0.016)	$0.246^{§}$ (0.047)	$0.168^{§}$ (0.025)
Log(*POP*)	0.339 (0.410)	0.276 (0.426)	0.198 (0.400)
Log^2(*POP*)	$0.036^{†}$ (0.016)	−0.009 (0.015)	0.026* (0.015)
Log(*GDPC*)	$42.825^{§}$ (7.139)	$47.461^{§}$ (7.172)	$38.492^{§}$ (7.062)
Log^2(*GDPC*)	$-5.680^{§}$ (0.941)	$-6.314^{§}$ (0.944)	$-5.115^{§}$ (0.931)
Log^3(*GDPC*)	$0.249^{§}$ (0.041)	$0.278^{§}$ (0.041)	$0.225^{§}$ (0.041)
Log(*EX*)	0.082* (0.042)	0.069 (0.043)	$0.083^{†}$ (0.040)
Log^2(*EX*)	−0.005 (0.006)	−0.004 (0.006)	−0.006 (0.006)
Log(*PEDS*)	$-0.123^{†}$ (0.060)	−0.050 (0.060)	−0.100* (0.058)
Log^2(*PEDS*)	0.006 (0.015)	−0.002 (0.015)	0.006 (0.014)
Log(*AVA*)	−0.020 (0.046)	−0.009 (0.047)	−0.029 (0.044)
Log(*PEDS*) × log(*AVA*)	$0.052^{‡}$ (0.017)	$0.034^{†}$ (0.017)	$0.044^{‡}$ (0.016)
GOV × *AOHA*	$-0.00003^{§}$ (0.000005)	$-0.00009^{§}$ (0.00002)	$0.00006^{§}$ (0.000008)
Constant	$-110.699^{§}$ (17.961)	$-111.576^{§}$ (18.824)	$-93.523^{§}$ (18.159)
Adjusted R^2	0.997	0.997	0.997
Log-likelihood	390.926	384.92	397.418
Pr > F	0.000	0.000	0.000
Hausmann	$86.55^{§}$	$75.11^{§}$	$97.26^{§}$
LM	$159.76^{§}$	$165.85^{§}$	$54.32^{§}$
AIC	−3.106	−3.050	−3.167
Preferred model	Two-way FE	Two-way FE	Two-way FE

Dependent variable: log(*AL*); *10% s.l.; †5% s.l.; ‡1% s.l.; §0.1% s.l. s.l., significance level.

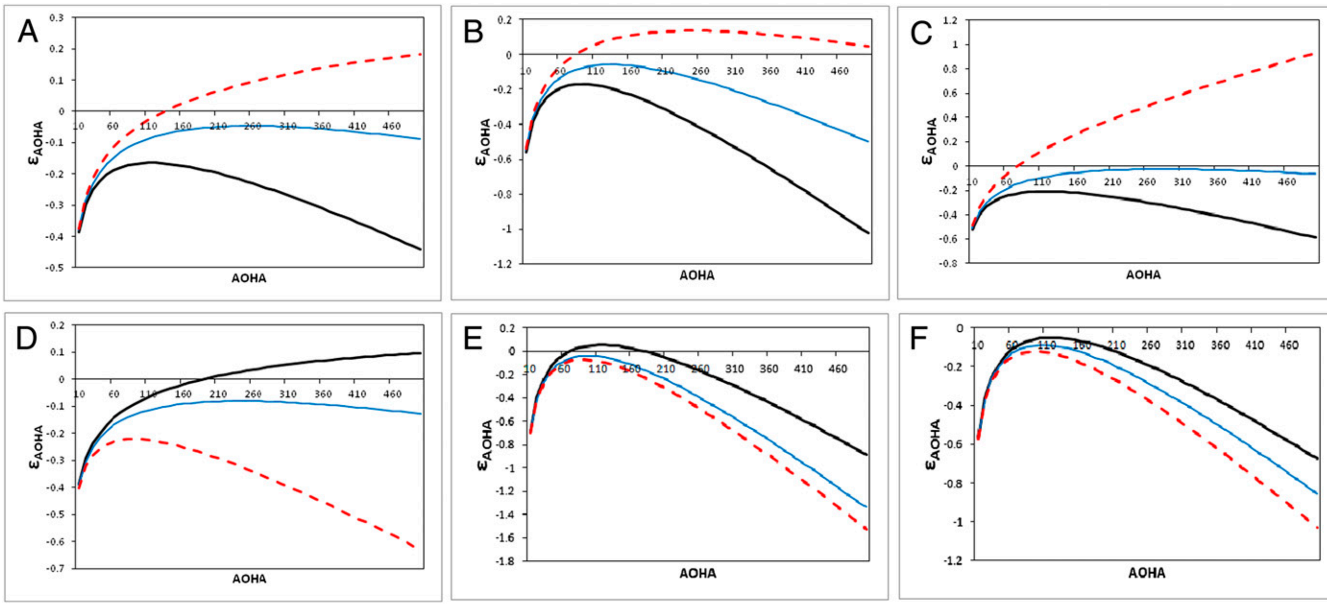

Fig. 1. The elasticity of agricultural land with respect to agricultural intensification ε_{AOHA} as estimated with model 1 (*GOV* = *CORC* in *A*), model 2 (*GOV* = *ROL* in *B*), model 3 (*GOV* = *ACC* in *C*), model 4 (*GOV* = *PA* in *D*), model 5 (*GOV* = *ESI* in *E*), and model 6 (*GOV* = *EPI* in *F*). In computing the elasticity, the governance scores are set at high (sample maximum, red dashed line), moderate (sample mean, blue solid line), and low (sample minimum, black solid line) values. When conventional governance scores are high, intensification leads to agricultural expansion (thus signaling a Jevons paradox), whereas when conventional governance scores are low or moderate, intensification leads to agricultural contraction (thus signaling land sparing). Conversely, when the environmental governance indicator takes high or moderate values, land sparing occurs. For low values of the environmental governance indicator, either a Jevons paradox occurs (*D* and *E*) or the intensity of the land-sparing effect is reduced (*F*).

accountability (*ACC*) (Fig. 1 *B* and *C*). A number of considerations follow from these results. Firstly, they support the idea that the governance dimensions captured by the WB indicators reflect conditions necessary for the establishment of operational markets, rather than environmental protection per se. Under such conditions economic activity, including agriculture, tends to expand and, in the absence of effective environmental protection measures, leads to environmental degradation (including deforestation or forest degradation). These interpretations are corroborated by other empirical investigations. Better corruption control, for example, by increasing bureaucratic efficiency, has been reported to facilitate agricultural expansion (27). The strengthening of property rights in Nicaragua has reportedly stimulated agricultural investments and led to an acceleration of the deforestation process (26). Secondly, the results are consistent with the social function doctrine of private property (41). The doctrine suggests that state protection of private property ensures the fulfillment of a social function, where the latter has been primarily associated with the productive use of land. The social function doctrine is embedded in many South American constitutions, and has played an important role in the conversion of forested areas to agriculture (42).

The Interaction Between Intensification and Environmental Governance. Results are markedly different when the environmental dimensions of governance are accounted for (models 4–6). The expression for the elasticity of agricultural area with respect to intensification (*AOHA*) is still $\varepsilon_{AOHA} = \gamma_1(GOV_i \times AOHA_{it}) + \beta_1 + 2\beta_2 \log(AOHA_{it})$.

In model 4 the quality of environmental governance is approximated as the proportion of terrestrial area under formal environmental protection (proportion of terrestrial area under formal environmental protection, *PA*). Given the values of the estimated parameters (Table 2), when the governance indicator assumes moderate/high values (i.e., is evaluated at the sample mean or sample maximum) ε_{AOHA} is negative, denoting the occurrence of land sparing. In contrast, when PA takes low values (i.e., is evaluated at the sample minimum) ε_{AOHA} becomes positive even for moderate levels of agricultural intensification (Fig. 1*D*), thus indicating the existence of Jevons paradox in land use.

Qualitatively similar results are obtained with the other proxies for environmental governance (ESI and EPI). Interestingly, when ESI is set to the sample minimum, ε_{AOHA} becomes positive for moderate values of agricultural intensification (indicating the Jevons paradox), whereas it becomes negative again only when intensification is significantly increased (Fig. 1*E*). This suggests that, when the quality of environmental governance is poor, intensification may initially lead to agricultural expansion, whereas land sparing may occur only for significant increases in agricultural productivity. With EPI ε_{AOHA} is always negative (indicating land sparing), although the higher the EPI score, the less negative ε_{AOHA} is (Fig. 1*F*). This suggests that the magnitude of the land-sparing effect increases with the quality of environmental governance.

These results are interesting as they suggest that different dimensions of governance impact differently on propensities for land sparing or Jevons paradox to occur. In particular they indicate that to achieve sustainable agricultural intensification, increasing agricultural productivity and strengthening conventional governance (*sensu* the WB indicators) is not sufficient. The interaction between these two variables may actually create the conditions for further agricultural expansion, by lowering the costs associated with agricultural conversion (e.g., transaction costs, facility to obtain credit, legal fees, etc.). This argument is particularly strong for countries like Brazil, where both agricultural productivity and the quality of public governance are high. The problem is exacerbated by the increasing competition for land between the food and energy sectors, for biofuel production (43, 44), which results in increasing land grabbing (45) as documented in the Land Matrix database (www.landmatrix.org). Although not explicitly considered here, it is worth noting that whereas land grabs lead to agricultural expansion (which is the focus of the present paper), then they are also captured by our dependent variable.

Conclusions

This paper analyzes the effect of agricultural intensification on agricultural land expansion in tropical South America and addresses two interrelated questions: How do the quality of governance and agricultural intensification jointly impact on spatial expansion of agriculture? Which aspects of governance are more likely to ensure that agricultural intensification delivers its benefits in terms of reduced pressure to spatially expand agricultural areas?

The results obtained shed further light on the role of governance and agricultural intensification on agricultural expansion in tropical South America. With respect to the effect of conventional governance factors on agricultural expansion and deforestation, the existing literature reports contrasting results (25–27). With regard to the environmental dimension of governance, great emphasis has been placed on the beneficial role of protected areas (30–36).

Our results indicate that the interaction between different aspects of governance and agricultural intensification plays a crucial role in the occurrence of land sparing or Jevons paradox. When considering conventional governance indicators—namely indices of corruption control, voice and accountability, and rule of law—high governance scores coupled with agricultural intensification lead to the spatial expansion of agriculture, suggesting the existence of Jevons paradox. This interpretation is also consistent with the prevailing social function doctrine, which sees the protection of private property for land as functional to its productive use. On the other hand, when accounting for the quality of environmental governance, agricultural intensification is associated with the spatial contraction of agriculture, thus leading to a land-sparing effect.

On the basis of these results a few reflections are necessary. The role of agricultural intensification, as means of addressing food security without further impacting existing tropical forests needs to be carefully assessed. Increasing agricultural productivity is unsurprisingly invoked as a means of feeding a prospective 9 billion people. However, by itself it will not ensure that land is spared for nature because it may interact with other policies and generate counterproductive results. To prevent this from happening, agricultural intensification needs to be accompanied by policies that specifically focus on the environmental aspects of governance. Such policies could take the form of spatial constraints on the possibility of expanding agricultural areas, through stricter land use regulation, or by introducing incentives to maintain the existing forest cover, or by strengthening indigenous commons management-use regimes, depending on context.

Materials and Methods

Panel Data Analysis. An important part of the literature looking at the determinants of agricultural expansion/deforestation is based on cross-section analysis or bivariate correlations. This may be problematic as the former ignores temporal dynamics, whereas the latter ignores the effect of uncontrolled factors (46). A number of studies have used panel data techniques to overcome these issues (47). The question of interest in the present paper is to test whether the different dimensions of governance, through their interaction with a measure of agricultural intensification, play a role in the occurrence of land sparing or Jevons paradox. Although a number of models have been estimated, some of which account for the quality of land resources, whereas others include multiple dimensions of governance (*SI Text*), the statistically preferred ones have the following structure:

$$y_{it} = \mu + \alpha_i + \lambda_t + \boldsymbol{\gamma}\mathbf{w}_{it} + \boldsymbol{\beta}\mathbf{x}_{it} + \boldsymbol{\theta}\mathbf{z}_{it} + v_{it} \quad \textbf{[2a]}$$

$$v_{it} \sim N\left(0, \sigma_v^2\right). \quad \textbf{[2b]}$$

The dependent variable in expression **2** is a measure of agricultural land (including all cropland and pastures) in the *i*th country at time *t* (AL_{it}), whereas the independent variables include vectors for technological/intensification indicators ($\boldsymbol{x}_{it}$), socioeconomic variables ($\boldsymbol{z}_{it}$), and the interaction of various governance indicators (including proxies for the quality of environmental governance) with intensification factors ($\boldsymbol{w}_{it}$). Given the limitation of public available data, various governance indices ($\boldsymbol{q}_i$), which change across countries but not over time, are considered. The interaction of governance with one of the intensification factors ($\boldsymbol{x}_{it}$) is formed as $\boldsymbol{w}_{it} = \boldsymbol{q}_i \times \boldsymbol{x}_{it}$.

In expression **2**, α_i represents the individual-specific effects (i.e., varying between individual but not across time); λ_{tt} represents the time-specific effects (i.e., varying over time but now across individuals); μ is the regression constant; and $\boldsymbol{\gamma}$, $\boldsymbol{\beta}$, and $\boldsymbol{\theta}$ are vectors of parameters associated with the quality of environmental governance, technological/intensification, and socioeconomic variables, respectively, whereas v_{it} is the independently distributed error term with zero mean and finite variance.

The Data. The dependent variable in expression **2** is the logarithm of agricultural land, as reported by the FAO, in the *i*th country at time *t* (AL_{it}). Even though better data for land use are available (e.g., from remotely sensed images), FAO (http://faostat3.fao.org/faostat-gateway/go/to/home/E) data are used to maintain consistency with the other explanatory variables. Agricultural intensification ($AOHA_{it}$) is quantified as the ratio between the value of agricultural output (at constant prices) and agricultural land, both reported by the FAO. The elements of the vector $\boldsymbol{x}_{it}$, which represent the technological/intensification indicator in **[2a]**, used for the empirical analysis include log ($AOHA_{it}$) and $\log^2(AOHA_{it})$. The vector of socioeconomic factors includes data from the WB (http://data.worldbank.org/indicator) concerning population (POP_{it}), per capita GDP at constant US$2,000 ($GDPC_{it}$), agricultural value added as a share of the total GDP (AVA_{it}), service on external debt as a share of the GDP at current prices ($PEDS_{it}$), and FAO data on export quantity index (EX_{it}). In the empirical analysis the following elements of vector $\boldsymbol{z}_{it}$ are used: $\log(POP_{it})$, $\log^2(POP_{it})$, $\log(GDPC_{it})$, $\log^2(GDPC_{it})$, $\log^3(GDPC_{it})$, $\log(EX_{it})$, $\log^2(EX_{it})$, $\log(AVA_{it})$, $\log(PEDS_{it})$, $\log^2(PEDS_{it})$, and $\log(PEDS_{it}) \times \log(AVA_{it})$.

With respect to the conventional dimensions of governance, we use three indicators developed by the WB (http://info.worldbank.org/governance/wgi/index.aspx#home), related to *CORC*, *ROL*, and *ACC*. *CORC* reflects the perceived extent to which public officials use their power for private gain; *ROL* reflects the ability to enforce contracts and the security of property rights; *ACC* reflects the degree to which citizens are able to participate in the selection of their government (23). These indicators, which vary between −2.5 (indicating low levels of corruption control, voice and accountability, and rule of law) and +2.5 (indicating high levels of corruption control, voice and accountability and rule of law), have been chosen as they play a more significant role in agricultural expansion and deforestation (24, 48). As the indicators are available only from 1996, we calculate the country-specific (and time-invariant) average over the period 1996–2006 (labeled $CORC_i$, ROL_i, and ACC_i) and use it to form the vector $\boldsymbol{q}_i$.

To capture the environmental dimensions of governance, we also rely on three different indicators. The first is based on the proportion of terrestrial area which is formally protected, as reported by the WDPA (www.wdpa.org/Statistics.aspx). The data are available only from 1990, so we form the country-specific (and time-invariant) average over the period 1990–2006 (labeled PA_i). The second indicator is the ESI (www.yale.edu/esi/), developed conjunctly by the YCELP of Yale University, the Center for International Earth Science Information Network of Columbia University, the World Economic Forum, and the European Commission Joint Research Centre (38). The indicator, which includes a set of measures related to environmental, socioeconomic, institutional factors that characterize sustainability at the national level, is available only for 2005 at the country level (labeled ESI_i). The third indicator goes under the name of the EPI (http://epi.yale.edu/downloads) and incorporates 22 different indicators over 10 policy categories related to the effect of environmental degradation on human health and ecosystems vitality (39). As data are available for the period 2000–2010 only, we form the country-specific average (labeled EPI_i). The environmental governance indicators chosen reflect different aspects of environmental governance and form the remaining components of vector $\boldsymbol{q}_i$.

Using country-specific and time-invariant measures for the quality of governance (including dimensions of environmental governance) implies that no changes in these indices have occurred over 1970–2006. As noted elsewhere (49), this is a strong assumption imposed by the lack of publicly available data. In this respect, the use of the panel data method, which accounts for country-specific and time-variant effects, allows one to capture the effects of unobserved heterogeneity and thus mitigate the lack of data. Some of this heterogeneity will be attributable to unobserved variance in the measures of governance.

Finally, additional models that also account for the quality of available land resources have been estimated, but are included in *SI Text* and Tables S3–S8. Land quality is determined on the basis of a number of productivity indicators available on the Global Agro-Ecological Zones database developed by the IIASA (www.gaez.iiasa.ac.at).

The Statistical Model. The statistically preferred models conform to the following general linear expression

$$\begin{aligned}\log(ALit) = {} & \mu + \alpha_i + \lambda_t + \gamma_1(GOV_i \times AOHA_{it}) + \beta_1\log(AOHA_{it}) + \beta_2\log^2(AOHA_{it}) \\ & + \theta_1\log(POP_{it}) + \theta_2\log^2(POP_{it}) + \theta_3\log(GDPC_{it}) + \theta_4\log^2(GDPC_{it}) \\ & + \theta_5\log^3(GDPC_{it}) + \theta_6\log(EX_{it}) + \theta_7\log^2(EX_{it}) + \theta_8\log(PEDS_{it}) \\ & + \theta_9\log^2(PEDS_{it}) + \theta_{10}\log(AVA_{it}) + \theta_{11}\left[\log(PEDS_{it}) \times \log(AVA_{it})\right] \\ & + v_{it}.\end{aligned} \quad [3]$$

Six models with different GOV indicators are estimated. The first set of models (labeled model 1, 2, and 3, respectively) uses the WB indicators $GOV_i = CORC_i$, $GOV_i = ROL_i$, and $GOV_i = ACC_i$. The second set of models (labeled model 4, 5, and 6, respectively) uses the proxies for environmental governance ($GOV_i = PA_i$, $GOV_i = ESI_i$, and $GOV_i = EPI_i$, respectively). As the estimated models use different measures of governance (and are therefore nonnested), their relative performance can be assessed on the basis of the Akaike Information Criterion (AIC) (also reported in Tables 1 and 2). A small difference in the AIC suggests that all models perform equally well (50).

The logarithmic specification is convenient as it facilitates estimation of elasticities. Given a function $y = f(x_1 \ldots x_k \ldots x_m)$, the elasticity of y with respect to the kth independent variable is $\varepsilon_k = \partial\log(y)/\partial\log(x_k)$ and indicates the % change in y for a 1% change in x_k (assuming that all other independent variables do not change). The use of elasticities is appropriate in quantifying the effect of changes in independent variables when these are expressed in different units (51). The presence of logarithm products (including squared and cubic logarithms) allows us to relax the assumption of linear elasticity.

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