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Opportunities and challenges to the sustainable development of cattle raising in Brazil, 1970–2005☆

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Abstract

The paper provides historical and analytical perspectives for the assessment of the challenges and opportunities of cattle raising activities in the transition toward a low-carbon agriculture in Brazil. It is organized as follows. The first section poses the problem. The second presents long run historical perspectives on the development of cattle raising in Brazil. The third section analyzes the patterns of growth of cattle raising in Brazil based upon municipal panel data of Agricultural Census from 1975 to 2006. The fourth section uses a framework analogous to Hayami and Ruttan (1985) to estimate growth convergence equations for major aspects of cattle raising activities, namely the stocking ratio, the specialization in cattle and farm expansion. The report concludes with a discussion of policy options for a transition toward sustainable cattle raising in Brazil.

JEL classification: Q150; Q23; C330

Keywords: Panel data; Arrellano–Bond; Agricultural economics; Land use; Cattle ranching; Deforestation

Resumo

O trabalho propõe perspectivas histórica e analítica para uma avaliação dos desafios e oportunidades da pecuária no processo de transição para uma agricultura de baixo carbono no Brasil. Após a introdução, a segunda seção apresenta perspectivas históricas sobre o desenvolvimento secular da pecuária brasileira. A terceira seção analisa os padrões de crescimento da pecuária no Brasil com base em dados municipais dos Censos Agropecuários de 1975 a 1996. A quarta seção utiliza um esquema analítico análogo ao modelo de Hayami e Ruttan (1985) para estimar equações de convegência de crescimento das principais dimensões das atividades pecuárias, quais sejam, a intensificação das pastagens, o grau de especialização na pecuária e a expansão da atividade agrícola. O trabalho conclui com uma discussão das opções políticas na transição para pecuária sustentável no Brasil.

Palavras-chave: Análise de dados de painel; Arellano–Bond; Economia agrícola; Uso da terra; Pecuária; Desflorestamento

This paper presents historical and analytical perspectives on the challenges and opportunities of cattle raising activities in the transition toward a low-carbon agriculture in Brazil. It is organized as follows. The first section poses the problem. The second presents historical perspectives on the development of cattle raising in Brazil. The third section

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uses an analytical framework analogous to Hayami and Ruttan (1985) to decompose cattle herd in three multiplicative components: the stocking ratio, the cattle specialization ratio, and the farm area. This decomposition is then used to describe the municipal patterns of growth of cattle raising activities in Brazil from 1975 to 2005. The fourth section estimates simple equations of municipal growth convergence for each of the components of the identity. Finally, to identify the main factors behind the patterns of municipal growth convergence, the fifth section specifies and estimates conditional convergence models for each of the identity components. The paper concludes with a discussion of policy options for a transition toward sustainable cattle raising in Brazil.

1. The problem

Historically, cattle raising in Brazil has been extremely land intensive when compared both to other agricultural activities and to other countries. As late as 2006 – last Agro Census available – average stocking ratio in Brazil was less than one head per hectare. Therefore, cattle ranching is, by far, the most extensive use of land in Brazilian agriculture. In 2006, it responded for 48% of the farm area in Brazil and 19% of the value of agricultural output. In that same year, agricultural crops represented 10.6% of farm area and 66% of the value of output (IBGE, 2013).

Land abundance – defined both in terms of relative factor availability and open access to land property – and high transport costs were major historical drivers of the extensive land use patterns of cattle raising. This is currently true in the Brazilian Amazon where land is still abundant and property rights remain largely undefined. As consequence, cattle raising in Brazilian Amazon became the main source of deforestation and carbon emission (Reis and Margullis, 1990; Chomitz and Thomas, 2000; Andersen et al., 2002; Chomitz and Thomas, 2003; Moreira and Reis, 2003).

According to Census figures, from 1970 to 2006, agro-pastoral uses of land in Brazilian Amazon—where it can be roughly equated to deforestation—increased 42 million ha or 8.4% of the geographic area of the region.[2] Pasture areas contributed with approximately 70% of the deforested area in the period, crop areas with 24% and fallow areas with the remaining 6%. The significance of cattle raising as a source of carbon emission can be assessed taking account that carbon per hectare in pasture areas is, approximately, 5 ton/ha compared to 150 ton/ha in pristine forest areas (Fearnside and Guimaraes, 1996; Reis, 1996; FUNCATE—Fundação de Ciência, 2010; Houghton et al., 2012).

Other environmental damages caused by cattle raising in the Brazilian Amazon include soil compacting which makes the recovery of secondary vegetation much slower in former pasture areas than in the other traditional agricultural uses of land (Uhl et al., 1988; Weinhold, 1996; Andersen et al., 2002). The consequences are increased water run off and soil degradation, reduced agricultural productivity and thus further stimulus to shifts in the agricultural frontier and to deforestation.

The arguments above clearly suggest a win-win situation where there is ample scope of increased efficiency in Brazilian cattle raising activities with substantial environmental benefits from reduced clearing of native vegetation. The policy solution is just to bring inefficient cattle raisers to the technological frontier (Schneider et al., 2000; Cohn et al., 2011; Assunção et al., 2013c; Strassbourg, s.d.; Strassbourg, s.d.).

The problem, however, is made more complex given the equity and incentive issues involved. Since primeval times, cattle raising has been one of the most traditional channels of economic and social mobility in agrarian economies. This is particular true for poor and small farmers to whom wealth or capital accumulation is practically synonym to increase in cattle herd. No wonder cattle and capital have the same semantic root (Rebello, 2004; Pacheco, 2009; Pacheco and Poccard-Chapuis, 2012).

More important, small farmers usually tend to adopt technologies of cattle raising which are land intensive and inefficient. The main reasons behind are restricted access to finance education, technology and the very high intertemporal discount rates which are intrinsically related to poverty. From the individual perspective, extensive ranching becomes a rational choice in the attempt to maximize the mining of (unpaid) natural resources (Kennedy, 1964; Saudoulet and Janvry, 1995).

Furthermore, cattle is a fungible asset performing a multiplicity of valuable functions and services in the generation and storage of wealth. Chiefly among them are its self reproduction and accumulation capacity, resilience to unfavorable

[2] Based upon Landsat images, estimates of deforestation from 1978 to 2006 are close 54 million ha. Estimates of deforestation based upon Census data differ from those based upon satellite images because the latter started only in 1978 and, by that time, they underestimated the extent of deforestation. Thus, deforestation in 1977 was, approximately, 47.5 million ha according to Census figures and 15 million ha according to Landsat.

climate and geographic conditions, productive uses in generating physical force in agricultural, industrial and transportation activities (in particular the capacity to transport itself to the market place), hedge functions against inflation and financial uncertainties, reassurance of property rights on land, and last but not least, the capacity to produce milk, meat, leather and all kinds of derived products for both subsistence or commercial purposes. The problem is that most of these functions and services are hardly reflected in market prices thus giving rise to the misallocation of resources, inefficiencies, depletion of natural resources and environment degradation associated with extensive cattle ranching.

From a policy perspective, therefore, the crucial issues are, firstly, to identify the structural factors conditioning the choice of output, technologies, and land intensity made by farmers, with special focus on the poor small farmers. Secondly, to identify the best strategies to foster the increase of land productivity within the cattle raising sector, as well as the shift of inefficient cattle raising to other agricultural activities with less intensive uses of land. Thirdly, how best to impose quantitative regulations and taxes as well as other price based incentives to make cattle ranchers account for the environmental costs caused by their productive activities (Assunção et al., 2013c; Assunção, 2014).

2. Historical perspectives

Extensive cattle raising was, since early colonial times, one of the main drivers of the territorial settlement in Brazil. The economic rationale was, first, the natural ability of cattle to circumvent the lack of transport infrastructure. Furthermore, within the legal framework of *sesmarias*, property rights were based upon the effective use of land, an thus extensive ranching acted as an entitlement to landowners (Abreu, 1960; Goulart, 1965).

In the Northeast Region, cattle raising started in the late 16th century as a complementary activity to sugar plantations stretching in the southern direction by the São Francisco River Valley and in the northwest direction toward the State of Piauí. At the beginning of the 18th century cattle herd in the region are estimated to have reached more than one million animals (Alencastre, 1857; Abreu, 1954, 1960; Simonsen, 1957; Furtado, 1968; Andrade, 1973).

In the extreme South, cattle was first introduced by the Jesuit Missions in the early 17th century. As Portuguese Indian slave raids besieged the Missions pushing them beyond the Uruguay River, cattle herds escaped to the highlands of Vacarias where, according to estimates, approximately 100,000 wild animals grazed by the mid-18th century (Santos, 1984; Weech, 1992; Bell, 1998).

The third wave of cattle ranching took place in the southern and western areas of the State of Minas Gerais which complemented the São Francisco Rivers ranches to feed the mining areas in the 18th century and later on the city of Rio de Janeiro as the Colonial and Imperial capital of Brazil (Restitutti, 2006; Carrara, 2007).

Finally, in the mid-20th century, a new wave of cattle ranching unfolded toward the Northwest regions of the country, reaching the Amazon frontier in the 1970’s (Hecht and Cockburn, 1990; Bergamasco, 1995; Faminow, 1998; Dias et al., 2016).

After the late sixties, Brazilian agriculture underwent a strong modernization process driven by the expansion of roads and transportation infrastructure, public investments in agricultural research and development, and a plethora of credit and fiscal incentives to agricultural activities. Agricultural modernization definitely changed the patterns of agricultural growth toward intensification of land use notwithstanding the substantial expansion of the agricultural frontier.

Agricultural modernization in Brazil was coupled to a decline in the rates of growth of cattle herd which dropped rom 2.3% p.a. in 1975–85 to 1.3% in 1995–2005. For the same periods, the growth of pasture areas growth inflected from positive (0.8% p.a.) to negative rates (−0.9%), respectively. Thus, rates of growth of the stocking ratio accelerated from 1.5% p.a. to 2.3% p.a. in the respective periods. Compared to farm area, however, the share of pastures in farm showed relatively small changes, growing from 45%, in 1940, to 52%, in 1970, and back to 49%, in 2006.

The trends are welcome from both efficiency and environmental perspectives. Higher stocking ratios require smaller area for pastures, decreasing the pressures on clearing both in the forest and the cerrado areas. Demographic factors, including the delayed effects of urbanization as well as the decline of fertility rates in rural areas, played important roles. Not captured by the Census data, in recent years government policies to control deforestation started to play an important role (Assunção et al., 2012, 2013a,b,c)

Fig. 1 summarizes the evolution of cattle herds according to Brazilian states during the whole 20th century. The picture shows that, up to 1940, the Brazilian herd was practically stagnated (annual growth in the range 0–1% p.a.). Strong growth took place after 1940 (3–4% p.a.), with oscillations around a declining trend which was briefly interrupted during the last decade.

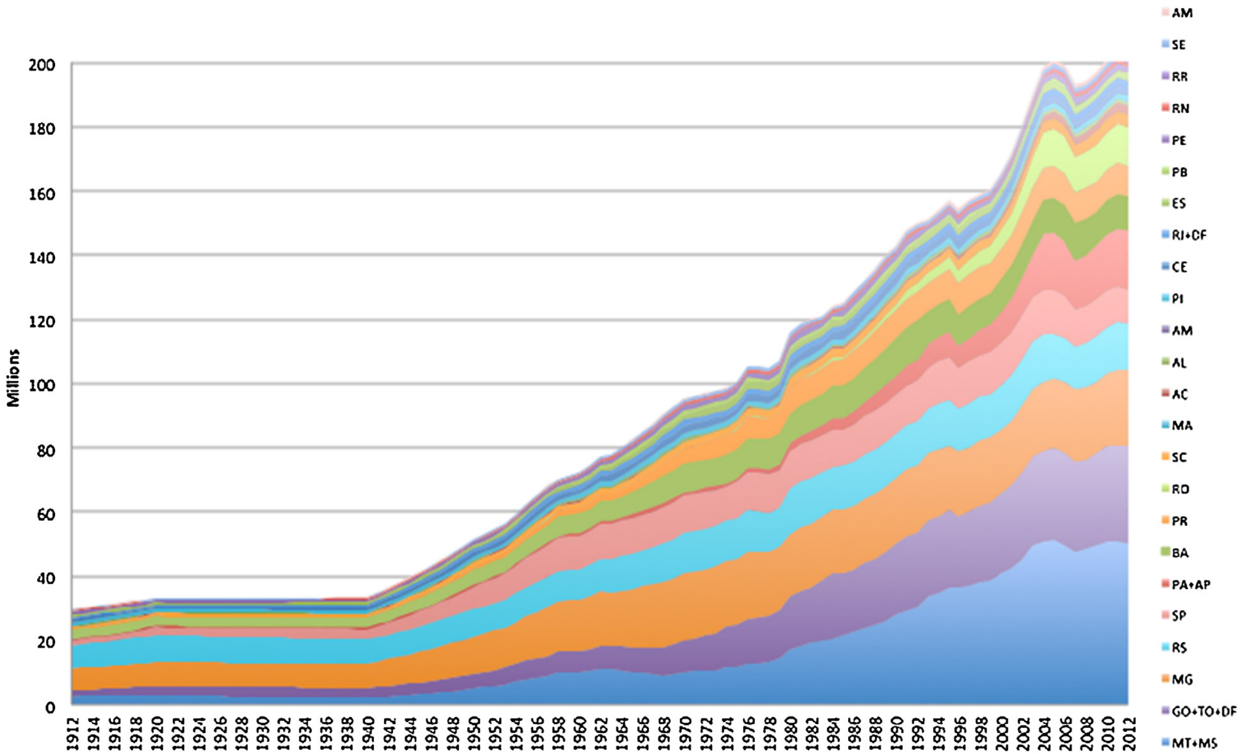

Fig. 1. Brazilian Cattle Herd Size by State from 1912–2012 (millions of heads).
Source and obs.: IBGE Census, AEB and PPM. Geometric interpolation for some years up to 1975.

Regionally, Minas Gerais (MG), Rio Grande do Sul (RS) were the leading cattle raising states up to 1970 when they were outpaced by the states of Mato Grosso + Mato Grosso do Sul (MT + MS) and Goiás + Tocantins (GO + TO). At present, cattle herds are mainly concentrated in the Cerrado areas of MG, GO + TO, and MT + MS.

3. Patterns of cattle raising growth, 1975–2005

This section analyzes the patterns of growth of cattle raising based upon municipal panel data of Brazilian Agricultural Census from 1975 to 2006. The choice of period is justified both by the timing of the modernization and the dislocation of agricultural frontier toward the northwest regions of the country (Reis and Blanco, 2000).

The analysis uses a decomposition analogous to the Hayami–Ruttan model (Hayami and Ruttan, 1985) derived from the identity:

$$C = \left(\frac{P}{F}\right) \times \left(\frac{C}{P}\right) \times F \tag{1}$$

where C is cattle herd size, P is pasture area, and F is farm area. Thus,

$$\mathrm{gc} = \mathrm{gpf} + \mathrm{gcp} + \mathrm{gf} \tag{2}$$

where the growth of cattle herd (gc) is additively decomposed in three major components, namely, the growth of the share of pasture in farm area (gpf) as a measure of the specialization in cattle raising activities; the growth of the socking ratio or of the number cattle heads per hectare of pasture (gcp) as a measure of the increases in the productivity of pastures; and the growth of farm area (gf) as a measure of the extensive growth of agricultural activities in general.[3]

[3] An alternative specification would be $C = (C/P) \times (P/A) \times (A/F) \times F$ where A is agricultural area, including crops, pasture, planted forest, and fallow areas. The advantage would be to single out the contribution of agricultural areas to the growth of cattle herds. Since in Brazilian Amazon agricultural area is almost identical to deforestation, this specification would allow to bring the deforestation process into the analysis.

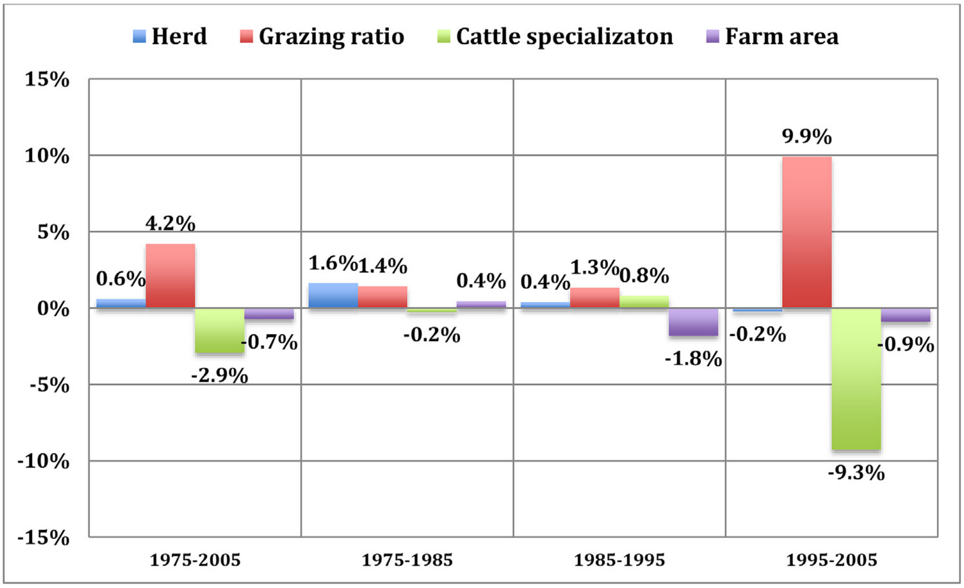

Fig. 2. Brazil: Average Growth Rates (% p.a.) of Municipal (MCA 1970–2005) of Herd, Grazing Ratio, Cattle Specialization, and Farm Area by Inter-Census Periods, 1975–2005.
Source and obs. IBGE Census. Geometric interpolations for the values of 2005.

Fig. 2 presents the breakdown of the municipal patterns of growth for the inter-census periods from 1975 to 2005. For the whole period, patterns of growth were characterized by a small expansion of cattle ranching with a significant intensification of pastures and a small reduction of cattle specialization. However, most of the action was concentrated in the nineties where both area under farm and herds contracted while pasture showed a significant increase in productivity and cattle specialization a significant reduction.

The immediate factors behind intensification of pastures were shifts from natural to planted pastures and the increased productivity of planted pastures with the application of biochemical inputs and improved forage cultivars created by the Brazilian Enterprise for Agricultural Research (EMBRAPA). Closely related, investments in transport infrastructure pushed the agricultural frontier toward the flatlands of the Cerrado ecosystem which allowed agricultural mechanization in a scale unseen before in Brazil.

In macroeconomic perspective, however, before 1995 extensive use of land in pastures as a hedge against hyperinflation and regional fiscal incentives were important factors in the expansion of low productivity cattle ranching. Thus the strong reduction of specialization in the 1995–2005 period is perhaps best explained by the combination of the end of hyperinflation which drastically reduced the incentives to cattle raising associated with land speculation, and the commodity price boom driven by the rise of China in the nineties.[4]

Fig. 3 shows the diverse regional patterns of growth of cattle raising activities from 1970 to 2005. The expansion of cattle herds took place mainly in the cerrado areas of the Center-West, North and Northeast Regions. The main factor behind was the low price of highly productive land which more than compensated the long distance and very high transport costs to domestic markets and international ports.

The North Region, practically coinciding with the Amazon rain forest, displays the typical dynamics of an agricultural frontier: substantial herd growth (7.5% p.a.) with a significant increase in grazing ratio (9.5 p.a.) and some reduction of specialization in cattle raising (−2.1% p.a.).

The performance of the Northeast Region is somewhat of a surprise given the soil and water constraints of the semi-arid areas. Rural credit together with investments in technical assistance and infrastructure, particularly in irrigation

[4] From 1985 to 1995, the reduction of farm area is partly explained by methodological changes introduced in the 1995 Census which moved the survey collection dates from peak season to off-season period thus loosing track of small temporary establishments like squatters and renters. But part of it reflected the abandonment and eviction due to the creation of reserves and protection areas in the Amazon region.

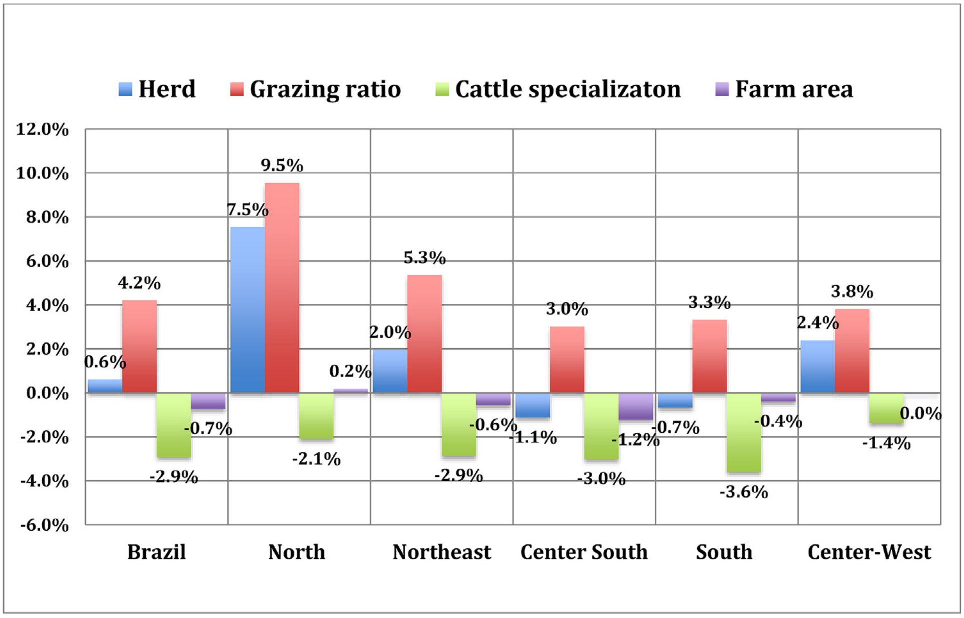

Fig. 3. Brazil: Average Growth Rates (% p.a.) of Municipal (MCA 1970–2005) of Herd, Grazing Ratio, Cattle Specialization, and Farm Area by Regions, 1975–2005.
Source and obs. IBGE Census. Geometric interpolations for the values of 2005.

and soil correction, were probably the main factors behind the significant intensification of cattle raising activities in the region.

Finally, traditional cattle areas in the Center-South and South Regions display small decreases in the size of herds and the farm areas coupled with significant reduction in specialization ratio. The expansion of area under farms is practically nihil in all regions except in the Center-South were the observed reduction is perhaps explained by urban encroachments.

4. Simple growth convergence, 1975–2005

This section presents econometric estimations of the municipal growth convergence of farm area, pasture intensification and specialization in cattle raising activities in Brazil from 1975 to 2005. Estimation is made for a panel of approximately 3650 minima comparable areas (AMC1970-2005) of Brazilian municipalities in the 4 Census years (3 inter-census periods) from 1975 to 2006.

Specifications are restricted to the simplest spatial dynamic model where the growth rates in inter-census periods for each dependent variable—geographic density of herds (gherd), stocking ratio (gstock), specialization ratio (gspecial), and geographic density of farm area (gfarma)—are solely determined by the logarithm of the ratio or geographic density of the respective dependent variable in the initial Census year.

In all cases, the estimated equation is thus:

$$\log\left(\frac{y_{i,t}}{y_{i,t-n}}\right)^{1/n} = \alpha + \beta \times \log\left(y_{i,t-n}\right) \quad (3)$$

where $y_{i,t}$ is, alternatively, herd density, grazing ratio, specialization ratio, or farm area density in municipality i ($i = 1, \ldots 3650$), Census year t ($t = 1975$, 1985, 1995, and 2006)

β is a estimated coefficient that measures the speed of convergence of the dependent variable in case: when the value of β is negative the municipal distribution of variable in case converges; conversely, when the value β is positive, the municipal distribution of the variable in case diverges.

Table 1 presents the results of Ordinary Least Square (OLS), Seemingly Unrelated (SURE) and Fixed Effects (FE) estimations of the municipal panel data for the four Census years from 1975 to 2005. In addition to the respective lagged values of he dependent, equations include dummies for Census years.

Table 1
OLS, SURE and FE panel estimates of simple growth convergence of herd density, stocking ratio, specialization ratio, and farm area density for Brazilian Municipalities (AMC7005) in inter-census periods from 1975 to 2005.

	Ordinary leas square (OLS)				Seemingly related estimation (SURE)			Fixed effects (FE)			
(1) Variable	(2) gherd	(3) gstock	(4) gspecial	(5) gfarma	(6) gstock	(7) gspecial	(8) gfarma	(9) gherd	(10) gstock	(11) gspecial	(12) gfarma
Constant	−0.013	0.006	0.003	−0.001	0.007	−0.007	−0.001	−0.10	−0.005	−0.07	−0.03
	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	−(0.003)***	−(0.001)***	−(0.002)***	−(0.001)***
L.ldherd	−0.019							−0.078			
	(0.000)***							−0.002***			
L.lstock		−0.040			−0.036				−0.088		
		(0.001)***			(0.001)***				−0.002***		
L.lspecial			0.006			−0.004				−0.075	
			(0.001)***			(0.001)***				−0.002***	
L.ldfarma				−0.015			−0.016				−0.10
				(0.001)***			(0.001)***				−(0.001)***
FE.1995	−0.009	0.005	0.011	−0.022	0.004	0.010	−0.021	7.50E − 05	0.012	0.009	−0.018
	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)**	(0.001)***	(0.001)***	−0.001	−0.001***	−0.001***	−(0.001)***
FE.2005	−0.014	0.096	−0.091	−0.015	0.095	−0.090	−0.015	−0.0029	0.11	−0.086	−0.027
	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	−(0.001)**	−(0.001)***	−(0.001)***	−(0.001)***
N. Obs.	10,852	10,846	10,864	10,899	10,837	10,837	10,852	10,846	10,864	10,899	10,899
R-Sq							0.26	0.50	0.62	0.52	0.52
N. of AMC							3637	3638	3642	3647	3647
Fixed effects	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes

Source: Author's estimates.

Std. error below estimates: $*p < 0.05$, $**p < 0.1$, $***p < 0.01$. For all explanatory variables values refer to the initial year of the respective intercensus period. L. refers to lagged values, l to the neperian logarithm, and shares in absolute values.

Table 2
Basic statistics of the seemingly unrelated regression and the correlation matrix of residuals.

Equations	Obs.	Parms	RMSE	*R*-sq	chi2	Prob	gstock	gspecial	gfarma	gherd
gstock	10,837	3	0.060	0.38	7121	0	1			0.31
gspecial	10,837	3	0.055	0.40	7614	0	−0.53	1		0.30
gfarma	10,837	3	0.036	0.11	1656	0	−0.17	−0.17	1	0.35
gherd										1

Figures in columns 2 show OLS estimated values of β close to -0.02 for herd density. Thus, each additional percentage point in the geographic density of municipal herd in the initial Census year implies, approximately, 0.02% less in the average annual growth rate of the municipal herd in the Census periods from 1975 to 2005.

Columns 3–5 of Table 1 show that convergence of stocking ratio are much faster, farm area growth shows a slower convergence while specialization ratio shows a divergent process, that is, it grows faster the higher the initial specialization ratio. Moreover, the estimated values for the constant and period dummies show that most of the action was concentrated in the 1995–2005 period when there was strong growth in the stocking ratios and a strong decline in specialization ratio.

The results show that farm area is declining and converging at slow rates. Pasture intensification showed strong growth in the last decade and converged at faster rates. Finally, cattle specialization showed a strong decline in the last decade coupled to a diverging process, thus leading to concentration of cattle raising in the municipal distribution.

OLS estimations assume that the growth of stocking ratio, specialization ratio, and farm area density is independent process and therefore the estimation errors are uncorrelated across equations. This an untenable assumption because, on the one hand, farm area density will tend to increase more in areas more prone to specialization in cattle and were the growth of pasture areas is smaller. On the other hand, spatial inertia and externalities suggest that the diffusion of technological changes and growth of productivity as well as organization innovations leading to less specialization are more likely to take place where farm density is already high and therefore grows less. By neglecting these possibilities of interactions in the growth processes, OLS estimations will tend to be biased and inefficient.

To circumvent the problems raised above, a SURE (Seemingly Unrelated Estimation) model assuming that estimation errors are correlated across equations is proposed. Table 2 presents basic statistics of the SURE estimation model while columns 6–8 of Table 1 present the values of the convergence parameters estimated. Notice that the equation for the growth of cattle herd itself is not included in this system specification because it is, by definition, identical to the sum of the three other components. Table 2 shows that correlation of residuals is significant only in the growth equations for stocking ratio and specialization ratio were the correlation coefficient is -0.53. That is, a significant negative association between abnormal growth in the intensification of pastures – that is, much higher or lower than predicted by the convergence model – and abnormal growth in the specialization in cattle raising activities. Deviant growth of cattle herds is more likely to be coupled to exceptional growth of the specialization cattle raising activities. In the same tandem, exceptional growth in pasture intensification is usually associated with cattle specialization exceptionally slow. When these interactions are taken in account, the main difference in estimation is a slow convergent instead of a divergent process of cattle specialization. The other estimates are practically the same.

Accordingly, results in Table 1 show that only in the equation for growth of the specialization ratio there is significant differences between the OLS and SURE estimates. Indeed, estimate of beta-convergence in the growth of the specialization equation is now one of significant slow convergence and not of significant slow divergence as in the OLS results.[5]

Closing the section, columns 9–12 of Table 1 present two-way fixed effects (FE) convergence estimates for the Brazilian municipalities from 1975 to 2005. Two-way fixed effects models are equivalent to specify "dummy" variables for each period as well as for each municipality to capture the effects of variables that are constant in time such as geographic and accessibility conditions including soil, hypsometry, climate, vegetation, and other characteristics of

[5] An alternative specification of the model would be to include the equation for herd growth in the system of equations to be estimated by SURE. Results not presented in the paper show that when this is done the beta-convergence estimated become very close to each other since all of the variables are highly correlated with the growth of herd. Indeed, statistics in Table 2 show that there are relatively strong correlation of residual of the growth of herd with all other variables.

the ecological system, distance to the sea and to main cities and capitals which are proxies for regional and national markets, and, finally, the "structural" socio-economic conditions which were relatively stable during the period under analysis (1975–2005).

The purpose is to 'filter' the estimates of the speed of convergence from spurious effects introduced by the association of cattle raising growth with the geographic variables and other structural characteristics of municipalities above mentioned. Naturally, fixed effect models will not be able to eliminate bias introduced by endogenous and omitted variable problems.

As we should expect, fixed effects estimation of the equations shows that the municipal characteristics that are invariant in time are very important for growth convergence of cattle raising activities. The speed of convergence among similar municipalities is twice or three time as fast than those observed for the OLS and SURE estimation models.

The absolute value increases in the speed of convergence were particularly strong for the growth of farm area and specialization ratio which before displayed a divergence process.

5. Conditional spatial convergence, 1970–2005

To explain the spatial patterns of growth of cattle raising in Brazil, this section enlarges the specifications of the simple growth convergence equations to incorporate the main factors conditioning the growth of herd size (gherd), stocking ratio (gstock), cattle specialization (gspecial), and the area under farms (gfarma) of Brazilian municipalities (AMC 1970–2005) in Census years from 1975 to 2005.

In addition to the lagged values of level of the respective dependent variables, the conditioning factors considered include the municipal conditions of accessibility and transport costs, credit availability and interest rates, the shares of wage and rent in total costs, the land/labor ratio, poverty and average years of schooling as a proxy of human capital, and finally, a synthetic description of the agrarian structure of the municipality given by the number of farms in three size classes: small, medium and big. The data sources and definition of the variables are given in Appendix A.

To minimize problems of endogeneity in the estimations, all the explanatory variables are specified as lagged values, that is, they describe the conditions prevailing in the municipalities at the initial Census year of the respective growth period, namely, 1975, 1985 and 1995.

Models were at first estimated by ordinary least square (OLS) method. In addition, to take account of the possible interactions between the growth process of different components or dimensions of cattle raising activities, an alternative specification assumes a seemingly unrelated model (SURE) where the growth of stocking ratio, specialization ratio, and farm area density are which are independent across time, but may have cross-equation contemporaneous correlations. Therefore they characterize dependent stochastic process where estimation errors are correlated across equations. Notice that the equation for the growth of cattle herd itself is not included in this system specification because it is, by definition, identical to the sum of the three other components.

Finally, to take account of the effects of municipal variables that are constant in time such as climate, vegetation, soil and hypsometric attributes, altitude, geographic distance to the sea, ports, as well as to other reference points, additional estimations are made with a two-way fixed effects fixed effects (FE). Otherwise, the exclusion of these fixed municipal characteristics could generate bias in the values of estimated coefficients.

Model specification is always a problem. Omitted variables in particular pervade OLS and SURE models leading to violation of the strict exogeneity assumption and, therefore, to biased estimates. Obvious candidates for omitted variables are, among other, access to technical assistance, use of fertilizers and herbicides. The only hope is that model specifications allowing fixed effects for municipalities will, at least, take care of the effects of omitted variables that are relatively constant in time (soil, climate, hypsometry, as well as other infrastructure characteristics of the municipalities, etc.) thus minimizing the specification problem. In fact, fixed effects model "use each municipality as her own control. By doing so, they actually control for all the stable, unobserved variables, just as if these variables had been measured and included in the regression model. In that sense, these statistical models perform neatly the same function as random assignment in a designed experiment" (Allison, 2009).

It should be noted, however that in the presence of lagged values of the dependent variables fixed effect models also violates the strict exogeneity assumption which states that x_{it} it is statistically independent of ε_{it}, for different time periods. This happens because one component of x_{it} is y itself at an earlier point in time (Allison, 2009). The proposed solution to this problem is to to use the Arellano-Bond (1991) estimation method (denote by AB) which are presented below. For the reasons above, in the analyses that follow attention will paid, preferentially, to the results of FE and AB estimation methods.

The generic specification of the model is:

$$\log\left(\frac{y_{i,t}}{y_{i,t-n}}\right)^{1/n} = \alpha + \beta \times \log\left(y_{i,t-n}\right) + \gamma \times X_{i,t-n} + \text{fe.time} + \text{fe.amc7005} + \varepsilon_{it} \quad (4)$$

where

$y_{i,t}$—is the dependent variable in case for município i in year t. The dependent variables considered are, alternatively, the rates of growth of herd size, grazing ratio, cattle specialization ratio, and of the farm area of Brazilian municipalities in the inter-Census periods from 1975 to 1985, 1985 to 1995, and 1995 to 2005.

$X_{i,t-n}$—is the set of explanatory variables referring to the demographic, economic, social, and transport conditions in Brazilian municipalities the initial Census year of the respective growth period, namely, 1975, 1985 and 1995.

fe.amc7005—are the dummy variables capturing the fixed effects for each of the minimum comparable area of municipalities in Census years from 1970 to 2005 (AMC7005)

fe.time—dummy variables capturing the fixed effects for the previous growth previous to the Census 1985 and 1995.

Tables B1–B4 in Appendix B report the results of estimations of the ordinary leas square (OLS), seemingly unrelated (SURE), fixed effects (FE) and Arrellano Bond (AB) models, respectively. Table 3 below gives a summary presentation of these results listing the dependent variables as well as the acronyms of the estimation method in the top two rows and the explanatory variables in the first left column. Results are qualitatively summarized by indicating the insignificant, positive or negative effect of the variable in the rows by a zero (o), plus (+) or minus (−) signal, respectively, and the significance level of the estimated coefficient by the number of plus or minus signals according to the following rule: a zero signal when the estimated coefficient is not significant at 0.05, that is $p > 0.05$; one minus or plus signal when $p < 0.05$; two minus or plus signals when $p < 0.01$; and three signals if $p < 0.001$.

5.1. Cattle herd

Estimates of the OLS, FE, and AB models of rates of growth of cattle herd appear, respectively, in columns 2–4 of Table 3. Results show that, except for transport costs (SHTRN) and the proxies of the agrarian structure SHSMAF and SHMEDF, all other variables are significant explaining factors in the AB model specification.

Herd tend to grow more the farther away the municipality is from São Paulo and from State capitals indicating that the expansion of cattle herds go hand in hand with the expansion of the frontier where land is the relative abundant factor. That argument is reinforced by the findings that higher population density (POPDEN) and higher land rent (SHRENT) also significantly reduces herd growth, and to some extent, by the non-significance of transport costs to local markets (SHTRNSP) as well. The suggested policy prescription is the introduction of measures creating disincentives to cattle raising, including land and pasture taxation in particular, credit constraints, as well as straightforward environmental zoning with prohibition of settlements or pastures in areas beyond certain geographical limits.

The previous results, however, are to some extent contradicted by the fact that rural labor scarcity as measured by higher wages (SHWAGE) and by a smaller share of rural population (SHPOPRUR) have significant negative effects the growth of herds (though there is some disagreement among models with regards the signal of the latter variable). Thus, the negative effect of population density takes place mainly through urban population.

The incidence of poverty (POVERTY) has a positive significant effect on the growth of herd. A possible interpretation is the classical role played by cattle as a channel of upward mobility to poor farms but it should be kept in mind that the measures of poverty used is not restricted to rural population. Other possibility would be through the labor market but the insignificance of the wage costs casts some doubt on the likelihood of this hypothesis.

The genuinely puzzling result, however, is the strongly significant and positive effect of average schooling (SCHOOL25) on the growth of cattle herd. The result becomes even more puzzling given the fact that the schooling measure refers to municipal population as a whole and not to rural population. A possible explanation is simply that, everything else constant, more human capital implies more capacity of accumulation and growth. But the puzzling aspect is that not necessarily accumulation would be directed toward cattle. On the contrary, it seems reasonable to

Table 3
Estimation results: qualitative effects of explatory variables for models of the rates of growth of herd, stocking ratio, specialization ratio, and farm area according to ordiry least square (OLS), seemingly unrelated (SURE), fixed effets (FE), and Arellano Bond panel data (AB) estimates.

Variable	gherd			gstock				gspecial				gfarm			
	OLS	FE	AB	OLS	SURE	FE	AB	OLS	SURE	FE	AB	OLS	SURE	FE	AB
Diesp	−−−	−−−	−−−	+++	+++	−−−	−−−	o	−−−	+++	o	−−−	−−−	o	+++
Diece	o	−−−	−−−	o	−	−−−	−−−	o	o	o	o	o	++	−−−	−−−
Shtrn	−−	o	o	+++	+++	o	++	−−−	−−−	−	−−−	o	o	+	+++
Loan	−−−	−−−	−−−	+++	+++	o	+++	−−−	−−−	−−−	−−−	+++	+++	+++	−−−
Interest	o	o	−−−	−−−	−−−	−−	−−−	o	o	−−	−−−	++	++		o
Shrent	−−−	−−−	−−−	+++	++	+++	o	o	−	−−−	−−−	++	+	o	o
Shwage	−−−	o	−−−	−−−	−−−	−−	o	o	o	o	−−−	o	o	o	−
Popden	−−−	o	−−−	+++	+	+++	+++	−−	−−−	−−−	−−−	o	o	−−−	−−−
Poprur	−−	o	+++	+++	++	o	−−−	o	+	o	+++	o	+	−−	+++
Schl25	++	−−−	++	+	++	−−−	+++	+	+	o	o	−−	−−−	o	−−−
Poverty	+++	+++	+++	−	o	+	+++	+++	+++	++	o	+++	+++	o	+++
Shsmaf	−−−	o	o	o	o	+	o	o	-	−−−	−−−	o	o	o	o
Shmedf	−−−	o	o	−	−−	++	o	o	o	−−	−−−	o	o	o	o
Ldherd	−−−	−−−	−−−												
Lstock				−−−	−−−	−−−									
Lspecial								+++	−−−	−−−	+				
Ldfarm												−−−	−−−	−−−	o
FE.1995	+	o		+++	+++	+++		+++	+++	+++		−−−	−−−	−−−	
FE.2005	−−−	−−−		+++	+++	+++		−−−	−−−	−−−		−−−	−−−	−−−	
FE.AM197005	No	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes	No	No	Yes	Yes
N. Obs.	10,234	10,234	6620	10,239	10,229	10,229	6617	10,238	10,229	10,238	6622	10,251	10,229	10,251	6630

Source: Author's estimates.
Obs.: Signals in the table mean: o = not significant at 5%; +++ = positive and significant at 0.1%; ++ = positive and significat at 1%; + = positive and significant at 5%; −−− = negative and significant at 0.01%; −− = negative and significant at 1%; − = negative and significant at 5%.

expect that more educated population would have broader and better economic opportunities thus shifting away from cattle raising to other agricultural or urban activities.

Availability of credit (LOAN) and cost of credit (INTEREST) show very significant negative effects on the growth of cattle herds. The direction of the effect of loan is counter-intuitive and probably related to the fact that availability of credit refers to total loans, not loans specifically purported to finance cattle raising activities. Agricultural credit lines in Brazil, however, are almost exclusively oriented toward agricultural crops with a very small portion of going to cattle raising activities. Most of the growth in cattle herd are therefore self-financed by farmers, particularly in the case of small ones. More credit is therefore expected to be associated with the growth of crops and thus it is reasonable to expect that it would appear as having a negative effect on the growth of cattle herd.

The lagged dependent variable (LDHERD) shows that there is significant convergence of the herd size, which given the constancy of the geographic areas of municipalities (AMC7005) is equivalent to the geographic density of municipalities. Figures in Table B1 show much higher coefficients that are five times bigger than the equivalent ones in columns 2–5 of Table B1. It should be kept in mind, however, that controlling for fixed effects of municipalities as is the case of FE and AB models is equivalent as specify are specified as "structurally" different municipalities and therefore they converge to different (steady state) equilibria levels of herd density.

Finally, the figures for the coefficients of time fixed effects (FE.1995 and FE.2005) show exogenous effect that brought significant reductions of the growth of herds in the periods 1985–95 and 1995–2005 for all municipalities. The magnitude of the effect was particularly strong in the latter period when municipal rates of growth of cattle herds reduced 1.3%. Macroeconomic developments and stabilization in particularly could have caused the decline in the relative profitability of cattle herd. Moreover, the growth of China shifted the patterns of Brazilian exports toward agricultural exports.

5.2. Stocking ratio

The growth and convergence of the stocking ratio are especially important process to reconcile the conflicting objectives of production and environmental preservation. To that extent their determinant are crucial for the elaboration of both agricultural and environmental policies.

Estimates of the models of the determinants of the rates of growth of the stocking ratio (or the productivity of pasture as measured by the ratio cattle heads/ha of pasture) are presented in columns 5–8 of Table 3. The AB estimates show that both the distance to São Paulo (DIESP) and the nearest State capital (DIECE) have significant negative effects on the growth of stocking ratio. Thus, the proximity to major markets or urban center comes out as a significant advantage suggesting that pasture intensification is mainly driven by accessibility to regional and international markets as well as to other kind of economic or institutional infrastructure like R&D, technological diffusion, technical support etc. captured by the distance to São Paulo and state capitals. However, in light of this argument, we get a counter-intuitive positive and significant effect of local transport cost (SHTRN).

As we would expect, the effect of credit availability (LOAN) is positive and significant, while the cost of credit (INTEREST) has a negative and significant effect on the growth of pasture intensification. Thus, bot availability and the cost of credit are important factors for the growth of pasture productivity. The obvious policy implication would be to create or to expand subsidized credit lines specifically oriented toward pasture intensification.

Though in disagreement with other models the AB model shows that both land rents (SHRENT) and the wage bill share (SHWAGE) have no significant effect the growth of pasture productivity. The velocity of the intensification of pasture is not driven by factor price signals but by other channels of transmission of technologies. Thus, the result does not support the Hayami and Ruttan (1985) hypothesis that relative factor prices induces technological change in pasture productivity. Note, however, that in the other models cheap land and high wages, typical of frontier areas, tend to slow down the speed of pasture intensification.

The above argument is complemented by the significant positive effect of population density (POPDEN) which echoes the (Boserup, 1965) hypothesis on the conditions of agricultural growth. It is important to note that rural population (SHPOPRUR) has negative significant effect (at least in the AB estimation). That would mean that technological improvements are induced by urban population. Qualifying the Boserup hypothesis, however, it is urban agglomeration, not population density per se, the determinant factor of technological improvement.

The significant positive effect of schooling (SCHOOL25) on the growth of pasture productivity confirms the intuitive association of technological improvement with higher levels of education of the population, no matter if we refer to rural, urban or total population. The obvious policy implication is that more education will bring a faster pasture intensification. Once again, the effect of poverty (POVERTY) in the AB model is positive and counter-intuitive.

In what concerns the agrarian structure, estimations show that the share of small (SHSMAF) and medium (SHMEDF) farms have no significant effect on productivity growth (though, for medium farm, the signal is not confirmed by the OLS and SURE models). The conclusion is that nothing significant in terms of pasture productivity is to be expected by any kind of agrarian reform or property fragmentation.

The time fixed effects (FE.1995 and FE.2005) show significant positive effects on the rates of growth of pasture productivity for both periods, 1985–95 and 1999–2005. The magnitude of the effect was particularly strong in the period 1995–2005 when it reaches amazing rates in the order of 10% p.a. As mentioned, the likely explanations lies in the across the board effects related to macroeconomic stabilization, the growth of China as well as the diffusion of new technologies.

Finally, the speed of convergence in the rates of growth of the productivity of pastures (LSTOCK) are much higher in the simple regression models of Table 3. Indeed, figures are now 0.09 in the FE model, compared to 0.045 in the OLS model and 0.033 in the SURE model. The reason behind is that estimation of convergence is now restricted to "clubs" of municipalities which display very similar conditions in what concerns factor availability and relative prices; human capital; accessibility and transport costs to both regional, national and regional markets; agrarian structure; and in other fixed attributes in the case of the FE model. Thus, convergence is very fast inside each "club" but the different clubs are converging to quite different values of cattle herd density, grazing ratio, cattle herd specialization, and farm area density. This is specially true in the case of FE estimations.

5.3. Cattle specialization

Table 3 shows that the processes of growth of cattle specialization (GSPECIAL, columns 9–12) and of productivity of pastures (GSTOCK, columns 4–8) are to some extent mirror images of each other in the sense that the same variables have opposite effects in each of these processes. This is no surprise given the high negative correlation between these processes shown in Section 4 above.

AB model estimations show that the growth of cattle specialization is not significantly affected by locational advantages such as the proximity of large national or regional markets or urban centers. Both the effects of the distance to São Paulo (DIESP) and the distance to the nearest State capital (DIECE) have no significant effect. Note, en passant, that in the equation of productivity growth both effects were significant and negative.

The effects of both availability and the cost of credit (LOAN and INTEREST) are both negative. This puzzling result is, once again, probably explained by the fact that agricultural credit lines are almost exclusively directed toward agricultural crops. Thus, differently from pasture productivity, here credit availability will induce the expansion of crop areas in detriment of pasture growth. However, cheap credit induces higher growth of both cattle specialization and productivity of pasture.

Cheap land (SHRENT) and labor (SHWAGE) costs increase the growth of specialization in cattle raising indicating that market incentives play a significant role in this case. Recall that for the growth of pasture productivity both effects were not significant.

Population density (POPDEN) induces lower growth of cattle specialization. But again this is mainly an effect of urban population, since the share of rural population (SHRUR) has positive significant effect on the growth of specialization. Again, effects are distinct from the ones obtained in the models of the growth of pasture productivity.

Schooling (SCHOOL25) and poverty (POVERTY) have no significant effect on the growth of specialization in cattle, thus reinforcing the notion that human capital and knowledge are not essential factors for the growth of cattle specialization.

The agrarian structure effects are such that the share of both small (SHSMAF) and median (SHMEDF) farms have no significant effects on cattle specialization. A tentative explanation would be that the expansion of specialized farms comes through green field investment in big farms and not through the process of consolidation of small and medium farms. Conversely, fragmentation will not affect significantly the growth of specialization.

The time fixed effects (FE.1995 and FE.2005) are not estimated by AB models because they tend to be "washed" out by the double differentiation. The other models show that, independent of the conditions prevailing in the municipalities, there was a significant acceleration of cattle specialization from 1970 to 1985, and a significant deceleration from 1995 to 2005. The magnitude of the effect was much bigger in the latter period, that is, −5.7% p.a. compared to +1.6% in

1985–95, in the FE model. Apart from the effects associated with the growth of international trade, in particular with China, which acted in favor of soybean, other possible explanations are credit and environmental policies concerning the Amazon frontier which became more increasingly restrictive during this period, particularly for cattle raising.

Finally, the lagged value of the specialization ratio (LSPECIAL) shows a mildly significant and positive effect indicating a divergence process of the growth of specialization, that is, municipalities would tend to specialize completely or not at all in cattle raising activities. The other models show mixed results some times with negative and other times with positive estimates. The strange aspect of the results is that divergence is not necessarily coupled with a spacial specialization, at least as far as the distances to city of São Paulo and to other State capitals are concerned.

5.4. Farm area expansion

Closing the section, estimations of the model of growth of the farm area show a spatial pattern of growth with significant positive effect for the distance to the city of São Paulo (DIESP) and a significant negative effect for the distance to the nearest State capital (DIECE), thus indicating the regional specialization in toward the northwest regions which is the remotest region to São Paulo. Reinforcing the patterns of spatial and regional specialization, the population density (POPDEN) is negative and significant while the share of rural population (SHRURN) and the share of transport costs (SHTRN) are positive and significant. The credit availability (LOAN) is negative and significant, suggesting that credit goes to already settled areas and that new farms together with frontier expansions are self-financed. The cost of credit (INTEREST), as well as of the price of land (SHRENT) has no significant effect on the growth of farm area. Curiously, the cost of labor (SHWAGE) has a mildly negative and significant effect. Market prices have negligible effects, anyway. Schooling (SCHOOL25) has a significant negative effect, and poverty (POVERTY) has a positive significant effect on the growth of farming. Farms grow faster in municipalities with less education and more poverty. Finally, the variables describing the agrarian structure (SHSMAF and SHMEDF) are not significant for the growth of farm. This result sounds a bit surprising because farm expansion and fragmentation of property could be thought as somewhat antithetical processes.

6. Policy options for sustainable development

This section discusses policy options for a sustainable development of cattle ranching in Brazil. The first lesson to be drawn is that the extensive land use pattern as well as other inefficiencies of cattle raising in Brazil have deep and persistent economic and institutional roots. Land abundance – defined both in terms of relative factor availability and open access to land property – and high transport costs were major historical drivers of the extensive land use patterns of cattle raising in Brazil. These conditions are still pervasive in the Brazilian Amazon and to that extent the expansion of cattle ranching remains, by far, the most important source of deforestation in the region (Reis and Margullis, 1990; Chomitz and Thomas, 2000; Andersen et al., 2002; Chomitz and Thomas, 2003).

The structure of incentives provided by the Brazilian institutional context impairs simple policy proposals to bring inefficient cattle raisers to the technological frontier (Schneider et al., 2000; Cohn et al., 2011; Assunção et al., 2013c; Strassbourg, s.d.; Strassbourg, s.d.). The problem becomes even more complex once we recognize the social and equity issues derived from the fact that cattle raising has always been and still is as one of the most traditional channels of economic and social mobility in agrarian economies, particularly for poor and small farmers. For those social segments, wealth or capital accumulation is practically synonym to increase in cattle herd. Furthermore, from and individual perspective, extensive cattle ranching is amply justified by the price incentives provided by cheap land and by the mining of unpaid natural resources (Rebello, 2004; Pacheco, 2009; Pacheco and Poccard-Chapuis, 2012). Fortunately, however, empirical results show that pasture intensification is not driven by factor price signals.

From a policy perspective the crucial issues are:, first, to identify the structural factors conditioning the choice of output, technologies, and land intensity made by farmers, with special focus on poor small farmers. Second, to identify the best strategies to foster the increase of land productivity within the cattle raising sector, as well as the shift of inefficient cattle raising to other agricultural activities with less intensive uses of land. Third, how to best impose quantitative regulations and taxes as well as other price based incentives to make cattle ranchers account for the environmental costs caused by their productive activities (Assunção et al., 2013c; Assunção, 2014).

The empirical analysis of the paper provided a few preliminary steps in this direction. Thus, estimation results show first that projected changes in transport costs – to both regional, national and international markets – will bring forth challenges and opportunities for cattle raising and agriculture, in general. Reductions of transport cost to all market levels will tend to increase the rates of growth of Brazilian cattle herd. Decomposing this effect, it is possible to see that it will be associated with a less extensive pattern of cattle ranching, with higher growth of pasture productivity, and reduced growth in cattle specialization. The effect on farm area depends on the strategy of transport investments to be implemented. Transport cost reduction to domestic and national markets will tend to increase the growth of farm areas while the increased density of the local and regional network will tend to decrease the growth of farm area. A more thorough assessment of the regional implications of transport costs would require the regional disaggregation of result that is outside the scope to this paper.

The second important result is fundamental role played by education and human capital. More education will create alternatives inside and outside agriculture thus reducing the rates of growth of farm area, cattle specialization and increasing the growth of pasture intensification, all such factors leading to a decreased rate of growth of herd. Thus education is perhaps the best policy option to halt the expansion of extensive cattle ranching. The big question mark is how fast educational policies, particularly in rural environments, can be implemented.

The estimation of the effects of credit policies is also of interest to policy implementation. Credit availability hardly affects the growth of herd size. Though it tends to increase the growth of farm area, this is associated with a significant reduction of the growth of cattle specialization as well as a significant increase of the growth of pasture productivity. Thus, the net result of credit constraints will probably be an increased growth of pasture areas.

Differently, interest rates have a negative impact on the growth of herd size with hardly any effect on pasture productivity. Thus, higher interest rates will tend to decrease of pasture.

When we put both results together, credit crunch situations, combining both quantitative constraints and interest rates, rise will probably tend to have no effects on herd size and pasture areas close to null.

Poverty alleviation, be it by means of government social policies or market mechanism, is undoubtedly a top policy priority in Brazil. From an environmental perspective, however, it will bring some policy trade-offs which are related to the arguments mentioned before that extensive and inefficient cattle ranching is a traditional channel for the upward mobility of poor people in rural areas. Thus, tough poverty reduction has no significant implication for the growth of farm area and it tends to reduce the growth of cattle specialization, it will significantly increase the growth of herd with negative effects on the productivity of pasture. Thus, pasture area will tend to show a faster increase as poverty goes down.

Urbanization and the growth of population density show contradictory effects. On the one hand, population density has hardly any effect on the growth of cattle herd. It affects negatively the growth of farms and cattle specialization and positively the intensification of pastures. As a consequence it tends to reduce pasture areas. Urbanization, on the other hand, has some effect on the growth of cattle herd but no effects on pasture productivity and, therefore, it will tend to increase pasture areas. Perhaps it should be qualified that urbanization is practically coming to a halt in the Brazilian case and therefore not much can be expected form their effects when compared to those of the growth of population density per se.

A policy issue which deserve a more thorough scrutiny is the size distribution of farms. The estimation result shows that they have practically no effects on all the relevant variables. Once gain, further assessment would require a better treatment of regional disaggregation as well as of cross-effects with other relevant explanatory variables.

Finally, extensions of the research will attempt to isolate the effects of cattle raising on three major dimensions of development: efficiency measured by the average productivity of labor in agricultural activities; welfare measured by the average household income per capita of the municipality; and equity measured by the Theil index of income per capita the municipality. For each of those dimensions the basic idea is to estimate an auto-regressive model with the lagged value of the dependent variable and changes in cattle raising activity as explanatory variables.

Thus, cheaper land leads to slower intensification of pastures and faster specialization in cattle with no significant effect on the expansion of farming.

Intuitively one would expect that more human capital diverts entrepreneurial abilities as well as employment capabilities to secondary and urban activities. Furthermore, human capital tends to shift agricultural activities toward crops as well as to increase the productivity of pastures. For all theses reasons, more human capital tends to reduce the growth of herd size. However, results are confusing. Estimates show that the effects of this variable are significantly affected by the introduction of fixed effects. OS and SURE show positive effects on the growth of herds, productivity of pasture and specialization in cattle and a slowing effect on the expansion of farms. FE, on the hard show a reduction of the growth of farms and productivity.

Appendix A.

Database: sources and variables

The Brazilian Statistical Office (IBGE) undertook Agricultural Census in 1970, 1975, 1980, 1985, 1995/96, and 2006/07. From the Agricultural Census is possible to obtain municipal data on land use in agriculture (annual crops, permanent crops, pastures, fallow lands, plantations and natural forests), rural employment, value of land, value and size of cattle herds, and other main assets, quantity and value of major agricultural outputs, destination of shipments, among other variables. For the 1985, 1995/96 and 2006/07 Censuses information is disaggregated according to 14 classes of size of agricultural establishments and the legal arrangements concerning property of land or work relations (proprietor, sharecropper, squatter and other conditions). In addition, annual municipal surveys from 1973 to 2010 provide data on the quantity, value, and crop area of agricultural products, as well as on the quantity and value of output of cattle raising activities (meat, dairy products, eggs, etc.), cattle herds size and value.

IBGE Demographic Census provide decennial data on municipal population from 1970 to 2010. For Census years 1970, 1980, 1991 and 1996 (Contagem da Populacao) 2000, 2007 and 2010, it is possible to get detailed data for urban and rural population; average years of schooling, mortality, life expectation, and income. Based upon the Demographic Census data IPEA/FJP (Fundacao Joao Pinheiro) provide estimates of household income per capita and size distribution of income (Gini and Theil indices) and HDI (Human Development Index) as well as poverty rations for both rural and urban households at municipal level for the Census years 1970, 1980, 1991, 2000 and 2010. Variables like income per capita, inequality indices, poverty incidence ratio, and average years of schooling for the Agricultural Census years were obtained by interpolation of the values estimated for Minimum Comparable Area by population weighted average of the municipal values observed in Demographic Census years.

The changes in number and area of municipalities require that municípios are lumped together in Minimum Comparable Geographic Area (MCA) to allow consistent geographic comparisons in time from 1970 to 2006.

The definition of the explanatory variables specified in the conditional convergence models are given below:

- Diesp—the economic distance or the effective road distance from the municipality to the city of São Paulo normalized by the quality of road modalities (paved, unpaved, etc.) in the years of 1970, 1985, and 1995 (geometric interpolation). It is as proxy of accessibility to national and international markets (ports of Santos and Paranaguá) as well as to major urban center.
- Diece—analogously defined, the economic or effective distance to the nearest State capital as proxy of regional market and urban center
- Shtrnsp—the share of transport costs in total costs of production of agricultural establishment. It is a measure the relative importance of transportation costs for the acquisition of production inputs or output sales in local markets. Here, as in the other cost variables, the variable is normalized by the value of total costs to avoid the distortions across time and space introduced by the hyperinflation context of the Brazilian economy during the period analyzed.
- Loan—the value of total loans to agricultural establishments is introduced as a proxy of credit availability. The Census dictionary is not clear if it is a measure of the value of outstanding loans at end of the Census year or of the value of loans granted during the Census year. The vast majority of credit lines go to agricultural crops.
- Interest—the cost of credit as measured by the ratio between interest payment of agricultural establishments during the Census period and the value of loans (LOAN) as defined above. Needless to say, the variable is not immune to inflationary as well as other kind of distortions.
- Shrent—is the ratio between payments of rent to total cost expenditure in each municipality. It is included as a proxy of the cost of land and thus of land availability. It should be kept in mind, however, that rented parcels are usually land of higher quality. In addition, the share of farm area rented differs across municipalities. It is expected, that both problems do not severely bias the results.
- Shwage—is simply the ratio of monetary wage bill in relation to total cost expenditure. It is an imperfect measure of the true relative importance of labor costs, to the extent that it does not take account of family labor as well as

of other forms of labor paid in kind (sharecropper, for instance). Nonetheless, it can be used as proxy of the labor skills or abundance.

- Popden—the density of population as measured by the geographic are of the municipality. Together with rural population it is a proxy of the abundance of labor in relation to land or geographic area of the municipality.
- Poprur—the share of rural population. It as measures the importance of agriculture in the municipality as well as the relative abundance of rural labor.
- School25—the average years of schooling of the population older than 25 year in the municipality. It is a proxy of level of education or human capital in the municipality. Unfortunately, it was not possible to get the equivalent measure for the rural population of the municipality which would be a more relevant variable for the analysis.
- Poverty—measures the share of poverty or the percentage of total municipal population living under the poverty line defined by a per capita household income smaller than the prevailing minimum wage in the Census reference period. Is as proxy of cheap labor as well as of the lack of human capital, income and employment opportunities. Again, the distinction between rural and urban contexts would be relevant for the purposes of the analysis.
- Shsmaf and Shmedf—the two variables describe the size distribution of farms by the number of farms in the size categories small (less that 100 ha) and medium (between 100 and 500), respectively. Naturally, the big farms are a residual category.
- Lagged dependent—for each growth equation we introduce the logarithm of lagged value of the dependent variable, that is, the value of the dependent variable in initial Census year of the growth period in case. Namely, LDHERD for the herd, LDSTOCK for the stocking ratio, LDSPECIAL for the cattle specialization, and finally, LDFARMA for the area under far equation.
- Time fixed effects—finally, we introduce dummies for time periods 1995–2005 (FE.1995) and 1995–2005 (FE.2005) as well municipalities (AMC7005) to capture the fixed effects of time periods and municipalities, respectively.

Appendix B. Estimation results for ordinary least square (OLS), seemingly unrelated (SURE), fixed effects (FE), Atellano–Bond (AB) models

Table B1
Ordinary least square—OLS—Estimates of conditional growth convergence of grazing ratio cattle specialization farm area density for Brazilian Minicipalities, 1975–2005 (std. error in parethesis below estimates).

Explanatory variables	Dependent variable: rate of growth (% p.a.) in inter-censi periods			
	gherd	gstock	gspecial	gfarma
L.diesp	−2.89E − 06	6.92E − 06	7.12E − 07	−4.63E − 06
	(6.32E − 07)***	(6.41E − 07)***	−6.60E − 07	(4.04E − 07)***
L.diece	−2.30E − 06	−1.07E − 06	5.98E − 07	1.18E − 06
	−1.66E − 06	−1.88E − 06	−1.77E − 06	−1.12E − 06
L.shtrnsp	−0.0755	0.1493	−0.119	−0.0034
	(0.0161)***	(0.0178)***	(0.0172)***	−0.0106
L.lnloan	−5.12E − 04	1.67E − 03	−2.81E − 03	2.64E − 03
	−3.04E − 04	(3.38E − 04)***	(3.21E − 04)***	(2.10E − 04)***
L.lninterest	−4.04E − 03	−4.33E − 03	3.90E − 04	7.70E − 04
	(4.34E − 04)***	(4.87E − 04)***	−4.64E − 04	(2.91E − 04)**
L.shrent	−0.0022	0.0367	−0.0151	0.0145
	−0.0078	(0.0088)***	−0.0083	(0.0052)**
L.shwage	−0.0319	−0.0457	−0.0048	−0.0029
	(0.0045)***	(0.0051)***	−0.0048	−0.003
L.lnpopden	−0.007	0.0038	−0.0019	−0.0003
	(0.0007)***	(0.0008)***	(0.0007)**	−0.0005
L.shpoprur	−0.0098	0.0135	0	0.0045
	(0.0036)**	(0.0041)***	−0.0039	−0.0024
L.schl25	0.0027	0.0022	0.0023	−0.0017
	(0.0010)**	(0.0011)*	(0.0010)*	−0.0007
L.poverty	0.0009	−0.0001	0.0003	0.0003
	0.0001	(0.0001)*	(0.0001)***	(0.0000)***

Table B1 (*Continued*)

Explanatory variables	Dependent variable: rate of growth (% p.a.) in inter-censi periods			
	gherd	gstock	gspecial	gfarma
L.shfarsma	−0.0467	−0.0013	−0.0155	−0.0095
	(0.0100)***	−0.0112	−0.0106	−0.0066
L.shfarmmed	−0.0436	−0.0304	−0.0189	−0.0073
	(0.0117)***	(0.0131)*	−0.0125	−0.0078
1995. time	0.0009	0.0099	0.0109	−0.016
	−0.0013	(0.0015)***	(0.0014)***	(0.0009)***
2005. time	−0.0076	0.0861	−0.075	−0.0198
	(0.0020)***	(0.0023)***	(0.0022)***	(0.0014)***
L.ldherd	−0.0161	–	–	–
	(0.0006)***	–	–	–
L.lstock	–	−0.045	–	–
	–	(0.0011)***	–	–
L.lspecial	–	–	0.0075	–
	–	–	(0.0008)***	–
L.ldfarma	–	–	–	−0.0196
	–	–	–	(0.0008)***
_cons	−0.0232	−0.0162	0.0204	−0.0225
	(0.0118)*	−0.0132	−0.0126	(0.0078)**
R^2	0.25	0.42	0.44	0.15
N	10,234	10,229	10,238	10,251

Source: Author's estimates.
Obs.: $*p<0.05$; $**p<0.1$; $***p<0.01$. For all explanatory variables values refer to the initial year of respective intercensus period. L. refers to lagged value; g to growth; l to the neperian log; and sh to shares in absolute values.

Table B2
Seemingly unrelated—SURE—Estimates of conditional growth convergence of grazing ratio cattle specialization farm area density for Brazilian Minicipalities, 1975–2005 (std. error in parenthesis below estimates).

Explanatory variables	Dependent variable: rate of growth (% p.a.) in inter-censi periods		
	gstock	gspecial	gfarma
L.diesp	0.000007	−0.000003	−0.000004
	(0.000001)***	(0.000001)***	(0.000000)***
L.diece	−0.000004	0.000001	0.000003
	(0.000002)*	−0.000002	(0.000001)**
L.shtrnsp	0.145	−0.166	−0.011
	(0.018)***	(0.017)***	−0.01
L.lnloan	0.001	−0.003	0.002
	(0.000)***	(0.000)***	(0.000)***
L.lninterest	−0.005	0	0.001
	(0.000)***	0	(0.000)**
L.shrent	0.024	−0.016	0.012
	(0.009)**	(0.008)*	(0.005)*
L.shwage	−0.037	−0.005	−0.003
	(0.005)***	−0.005	−0.003
L.schl25	0.002	0.002	−0.002
	(0.001)*	−0.001	(0.001)***
L.poverty	0	0	0
	0	(0.000)***	(0.000)***
L.lnpopden	0.001	−0.003	0
	−0.001	(0.001)***	0
L.shpoprur	0.009	−0.008	0.004
	(0.004)*	(0.004)*	−0.002
L.shfarsma	−0.007	−0.022	−0.009

Table B2 (*Continued*)

Explanatory variables	Dependent variable: rate of growth (% p.a.) in inter-censi periods		
	gstock	gspecial	gfarma
	−0.011	(0.011)*	−0.006
L.shfarmmed	−0.029	−0.014	−0.008
	(0.013)*	−0.012	−0.008
1995. time	0.009	0.011	−0.016
	(0.001)***	(0.001)***	(0.001)***
2005. time	0.084	−0.073	−0.019
	(0.002)***	(0.002)***	(0.001)***
L.lstock	−0.033	–	–
	(0.001)***	–	–
L.lspecial	–	−0.004	–
	–	(0.001)***	–
L.ldfarma	–	–	−0.021
	–	–	(0.001)***
_cons	−0.015	0.016	−0.016
	−0.013	−0.013	(0.008)*

Source: Author's estimates.

Obs.: $*p<0.05$; $**p<0.1$; $***p<0.01$. For all explanatory variables values refer to the initial year of respective intercensus period. L. referes to lagged value; g to growth; l to the neperian log; and sh to shares in absolute values.

Table B3

Fixed effects—FE—Estimates of conditional growth convergence of grazing ratio cattle specialization farm area density for Brazilian Minicipalities, 1975–2005 (std. error in parethesis below estimates).

Explanatory variables	Dependent variable: rate of growth (% p.a.) in inter-censi periods			
	gherd	gstock	gspecial	gfarma
L.diesp	−5.51E − 05	−6.38E − 05	1.29E − 05	−2.47E − 07
	(2.79E − 06)***	(3.12E − 06)***	(2.88E − 06)***	−1.54E − 06
L.diece	−8.06E − 05	−3.24E − 05	−6.22E − 06	−4.72E − 06
	(8.28E − 06)***	(9.34E − 06)***	−8.58E − 06	(4.71E − 06)**
L.shtrnsp	−0.027	0.0181	−0.0566	0.0299
	−0.022	−0.025	(0.0230)*	(0.0124)*
L.lnloan	−2.00E − 03	1.18E − 03	−3.70E − 03	1.82E − 03
	(5.68E − 04)***	−6.42E − 04	(5.90E − 04)***	(3.24E − 04)**
L.lninterest	−3.09E − 03	−1.62E − 03	−1.59E − 03	4.87E − 04
	(5.06E − 04)***	(5.75E − 04)**	(5.28E − 04)**	−2.86E − 04
L.shrent	−0.0113	0.0541	−0.0475	−0.0032
	−0.0119	(0.0135)***	(0.0125)***	−0.0067
L.shwage	−0.0276	−0.0248	−0.0037	0.0028
	(0.0067)***	(0.0076)**	−0.007	−0.0038
L.lnpopden	0.005	0.0517	−0.03	−0.0168
	−0.0031	(0.0036)***	(0.0033)***	(0.0018)***
L.shpoprur	−0.0184	0.0135	−0.0166	−0.0156
	−0.0101	−0.0115	−0.0105	(0.0057)**
L.schl25	−0.0208	−0.0208	0.0002	−0.0024
	(0.0026)***	(0.0029)***	−0.0027	−0.0015
L.poverty	0.0007	0.0003	0.0003	−0.0001
	(0.0001)***	(0.0001)*	(0.0001)**	−0.0001
L.shfarsma	−0.0201	0.0746	−0.0925	−0.0163
	−0.026	(0.0294)*	(0.0270)***	−0.0147
L.shfarmmed	−0.0085	0.0975	−0.0992	−0.0139
	−0.0301	(0.0341)**	(0.0313)**	−0.017
1995. time	0.0005	0.0055	0.0164	−0.0178
	−0.0028	−0.0032	(0.0030)***	(0.0016)***
2005. time	0.013	0.1018	−0.0574	−0.036
	(0.0054)*	(0.0062)***	(0.0057)***	(0.0031)***

Table B3 (*Continued*)

Explanatory variables	Dependent variable: rate of growth (% p.a.) in inter-censi periods			
	gherd	gstock	gspecial	gfarma
L.ldherd	−0.0941	–	–	–
	(0.0017)***	–	–	–
L.lstock	–	−0.0923	–	–
	–	(0.0020)***	–	–
L.lspecial	–	–	−0.0728	–
	–	–	(0.0018)***	–
L.ldfarma	–	–	–	−0.1107
	–	–	–	(0.0014)***
_cons	0.0672	0.1304	−0.0306	−0.011
	(0.0299)*	(0.0340)***	−0.0312	−0.0169
R^2	0.38	0.58	0.64	0.55
N	10,234	10,229	10,238	10,251
fe.amc7005	Yes	Yes	Yes	Yes

Source: Author's estimates.

Obs.: *$p < 0.05$; **$p < 0.1$; ***$p < 0.01$. For all explanatory variables values refer to the initial year of respective intercensus period; L. referes to lagged value; g to growth; l to the neperian log; and sh to shares in absolute values.

Table B4

Arellano–Bond dynamic panel data—AB—Estimates of conditional growth convergence of grazing ratio cattle specialization farm area density for Brazilian Minicipalities, 1975–2005 (std. error in parethesis below estimates).

Explanatory variables	Dependent variable: rate of growth (% p.a.) in inter-censi periods			
	gherd	gstock	gspecial	gfarma
L.diesp	−0.00057	−0.00054	0.00001	0.00006
	(0.00002)***	(0.00003)***	(0.00002)	(0.00001)***
L.diece	−0.00084	−0.00048	−0.00016	−0.00044
	(0.00008)***	(0.0001)***	(0.00009)	(0.00005)***
L.shtrnsp	−0.03385	0.44131	−0.65901	0.46901
	(−0.23211)	(0.26852)	(0.24438)**	(0.13177)***
L.lnloan	−0.02692	0.13762	−0.16579	−0.00511
	(0.00297)***	(0.00344)***	(0.00313)***	(0.00171)**
L.lninterest	−0.04489	−0.01754	−0.0276	−0.00464
	(0.00516)***	(0.00597)**	(0.00544)***	(0.00294)*
L.shrent	−0.00998	0.24642	−0.37106	−0.07055
	(0.12426)	(0.1437)	(0.13146)*	(0.07074)
L.shwage	−0.422	−0.07012	−0.24283	−0.07858
	(0.06937)***	(0.08023)	(0.07315)**	(0.0395)*
L.schl25	0.04677	0.1194	0.03259	−0.05712
	(0.01892)*	(0.02185)***	−0.01991	(0.01076)***
L.poverty	0.01354	0.00813	0.00023	0.0054
	(0.00094)***	(0.00109)***	(0.001)	(0.00054)***
L.lpopden	−0.08643	0.47275	−0.38532	−0.25437
	(0.03054)*	(0.03591)***	(0.0324)***	(0.01737)***
L.shpoprur	0.36164	−0.38447	0.51669	0.33806
	(0.09859)***	(0.11391)***	(0.10381)***	(0.05622)***
L.shfarsma	−0.33289	0.1762	−100,466	−0.21813
	(0.27982)	90.32248)	(0.29406)***	(0.15938)
L.shfarmmed	−0.14868	0.19069	−0.9956	−0.09168
	(0.32406)	(0.3739)	(0.34103)***	(0.18432)
L.ldherd	−0.10914			
	(0.01744)***			

Table B4 (*Continued*)

Explanatory variables	Dependent variable: rate of growth (% p.a.) in inter-censi periods			
	gherd	gstock	gspecial	gfarma
L.lstock		−0.02199 (0.0199)***		
L.lspecial			0.04454 (0.01848)**	
				−0.25413 (0.0173)***
N. of obs	6620	6617	6622	6630
N. of amc7005	3503	3503	3504	3508
N. of instruments	31	31	31	31
Wald chi2 (14)	1635.30	10,745.35	8924.67	23,597.92
Instruments for differenced equation GMM-type	L(2/.).ldherd	L(2/.).lstock	L(2/.).lspecial	L(2/.).ldfarma
Standard:	D.Lldherd	D.Llstock	D.Llspecial	D.Lldfarma
	D.Ldiesp D.Ldiece D.Lshtrnsp D.Llnloan D.Llninterest D.Lshrent D.Lshwage D.Lschl25 D.Lpoverty D.Llnpopden D.Lshpoprur D.Lshfarsma D.Lshfarmmed Lldherd Ldiesp Ldiece Lshtrnsp Llnloan Llninterest Lshrent Lshwage Lschl25 Lpoverty Llnpopden Lshpoprur Lshfarsma Lshfarmmed			
Instrument for level equation	cons	cons	cons	cons

Source: Author's estimates.

Obs.: $*p<0.05$; $**p<0.1$; $***p<0.01$. For all explanatory variables values refer to the initial year of respective intercensus period. L. referes to lagged value; g to growth; l to the neperian log; and sh to shares in absolute values.

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