Technical Appendix to

The Global Impacts of Biofuel Mandates

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by

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In this appendix, we supply supplementary materials on the model and additional results. We begin by outlining the partial equilibrium model used in the paper and then provide global maps of land cover changes, by AEZ. Finally, additional information on the Systematic Sensitivity Analysis is provided.

A Partial Equilibrium Model of the Ethanol Market

Consider an ethanol industry selling into two domestic market segments: in the first market, ethanol is used as a gasoline additive (QI), in strict proportion to total gasoline production. As discussed in the paper, legal developments in the additive market were an important component of the US ethanol boom between 2001 and 2006. The second market is the market for ethanol as an energy substitute (QE). In contrast to the additive market, the demand in this market is price sensitive, with ethanol's market share depending on its price, relative to refined petroleum. For ease of exposition, and to be consistent with the general equilibrium model, we will think of the additive demand as a derived demand by the petroleum refinery sector, and the energy substitution as being undertaken by consumers.

Market clearing, in the absence of exports, may then be written as:

$$QO = QI + QE \tag{1}$$

or, in percentage change form, where lower case denotes the percentage change in the upper case variable:

$$qo = (1-\alpha)qi + \alpha qe \tag{2}$$

where $\alpha = \mathrm{QE} / \mathrm{QO}$, is the share of total ethanol output (QO) going to the price sensitive side of the market.

Now we formally characterize the behavior of each source of demand for ethanol as follows (again, lower case variables denote percentage changes in their upper case counterparts):

$$qi = ai + qp \tag{3}$$

where $\mathrm{AI} = \mathrm{QI} / \mathrm{QP}$ is the ethanol input – output coefficient in the Leontief production function for petroleum products, so that when MTBE's are banned, for example, AI increases, thereby boosting intermediate input demand. For final demand we have:

$$qe = q - \sigma(pe - p) \tag{4}$$

Where Q is the aggregate demand for household liquid fuel consumption and σ is the constant elasticity of substitution (CES) amongst energy products consumed by the household. The price ratio PE / P refers to the price of ethanol relative to a composite price index of all energy products consumed by the household. The percentage change in this ratio is given by the difference in the two percentage changes: ($pe - p$). When pre-multiplied by σ, this determines the price-sensitive component of households' change in demand for ethanol. Substituting (3) and (4) into (2), we obtain a new expression for ethanol market clearing:

$$qo = (1 - \alpha)(ai + qp) + \alpha[q - \sigma(pe - p)] \tag{5}$$

On the supply side, we assume constant returns to scale in ethanol production, which, along with entry/exit, gives zero pure profits in the medium run:

$$po = \sum_j \theta_j pf_j \tag{6}$$

Where po is the percentage change in the producer price for ethanol, pf_j is the percentage change in price of input j, used in biofuel production, and θ_j is the cost share of that input. Assuming that corn is the only input in less than perfectly elastic supply, and that it is used in

fixed proportion to ethanol output (fixed QF_c / QO), we can complete the supply–side specifications with the following equations:

$$qf_c = qo \tag{7}$$

$$qf_c = \nu_c pf_c \tag{8}$$

where ν_c is the supply elasticity of corn to the ethanol sector. With $pf_j = 0 \ \forall j \neq c$, we can solve (6) for $pf_c = \theta_c^{-1} po$. Plugging this and (7) into (8) gives the *market supply of ethanol*:

$$qo = \nu_c \theta_c^{-1} po \tag{9}$$

We complete the model by allowing for ethanol subsidies. These are typically provided in the form of blenders' subsidies (U.S.) or tax abatements (EU). We write them here as the power of an *ad valorem* equivalent subsidy: $\mathrm{S} = \mathrm{PO} / \mathrm{PE}$, i.e. the ratio of producer to user prices for ethanol. Totally differentiating and converting to percentage change form, we have the final equation in the partial equilibrium model:

$$po = pe + s \tag{10}$$

Now, in solving this model, we will make the additional assumptions that: (a) the aggregate price of of liquid fuels is fixed ($p = 0$), and (b) aggregate household demand for liquid fuels is fixed ($q = 0$). All of these assumptions are relaxed in the empirical section of the model. Using (10) to eliminate *pe* from (6) and equating supply (9) and demand (6), we can solve for the equilibrium producer price of ethanol:

$$po^* = [(1-\alpha)ai + \alpha\sigma(p+s)] / [\nu_c \theta_c^{-1} \alpha\sigma] \tag{11}$$

Where $-\alpha\sigma = \varepsilon_d$ is the aggregate price elasticity of demand for ethanol, and $\nu_c \theta_c^{-1} = \varepsilon_s$ is the price elasticity of supply for ethanol. To determine the equilibrium output, multiply both sides

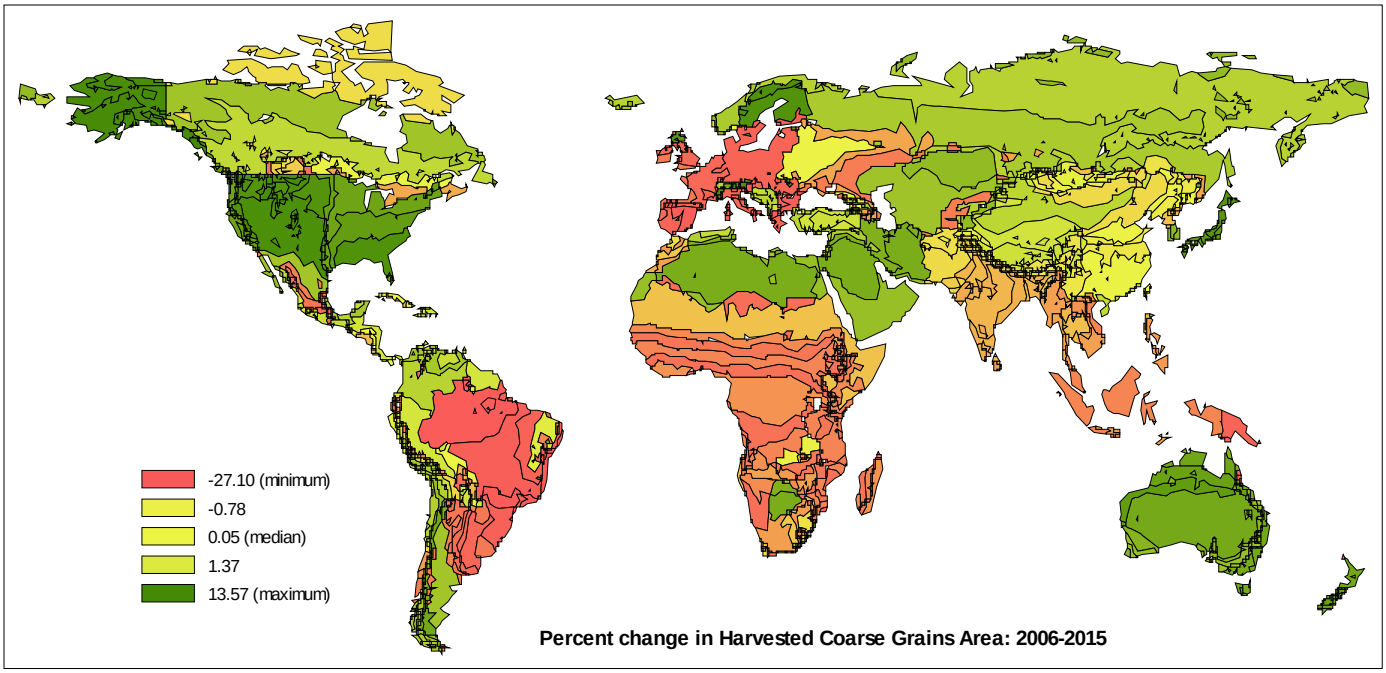
by ε_s to get the following (where we have used the definitions of supply and demand elasticities given above):

$$qo^* = \varepsilon_s[(1-\alpha)ai - \varepsilon_D(p+s)]/[\varepsilon_s - \varepsilon_D] \quad (12)$$

From (12), we can see a number of important things. First of all, the contribution of changes in the additive requirements of gasoline to total ethanol output depend on the change in the input-output ratio (*ai*) as well as the initial share of total sales going to this market segment. The price sensitive portion of the market depends on what happens to the price of liquid fuels in general (*p*) and the power of the *ad valorem* subsidy (*s*), which are additive in the solution of the model. Their significance depends on the share of the total market for ethanol that is price sensitive (α) and the ease of substitution between ethanol and other fuels (σ).

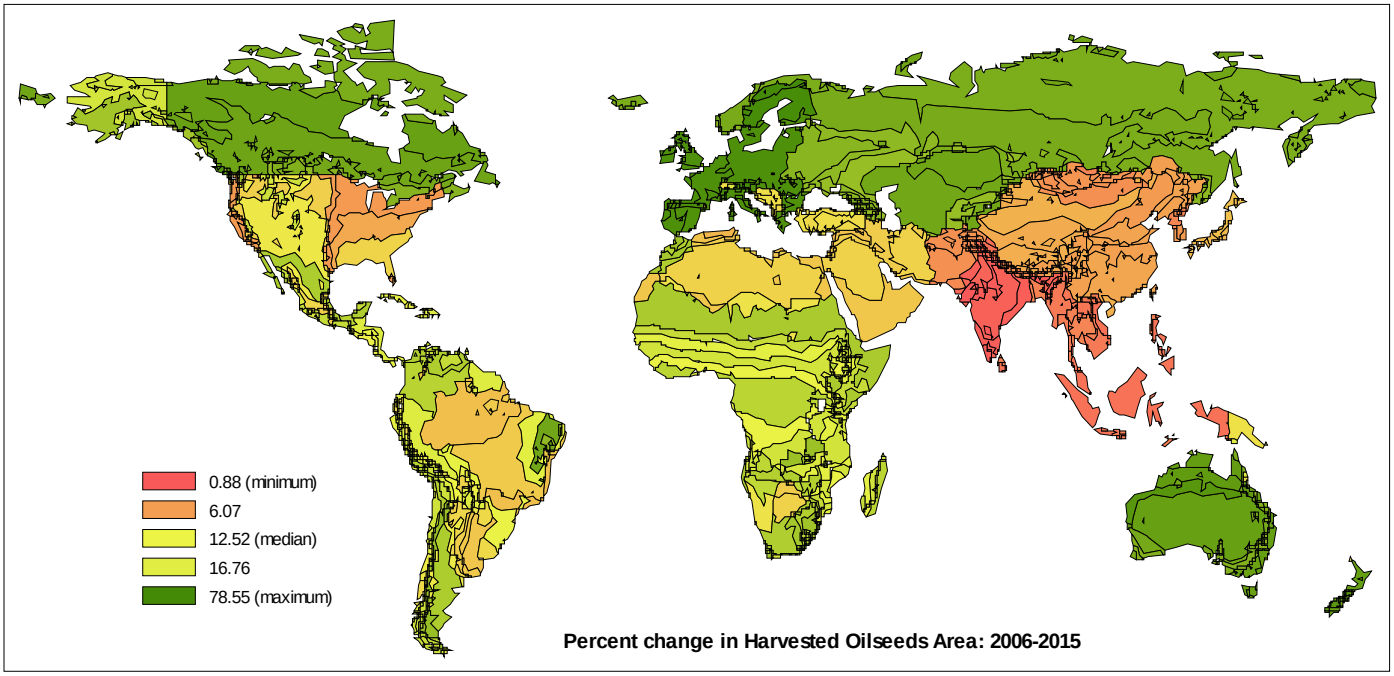
We also see from (12) that supply response is important. If the total availability of feedstock (corn) is fixed ($\nu_c = 0$), then $qo^* = 0$. Furthermore, as the supply response of corn rises ($\nu_c >> 0$)and the share of corn in overall ethanol costs falls ($\theta_c \to 0$), $\nu_c\theta_c^{-1} = \varepsilon_s$ rises, thereby boosting supply and dampening the equilibrium price change.

Equation (12) is critical when it comes to decomposing the contribution of the three main drivers of ethanol production over the 2001-2006 period.



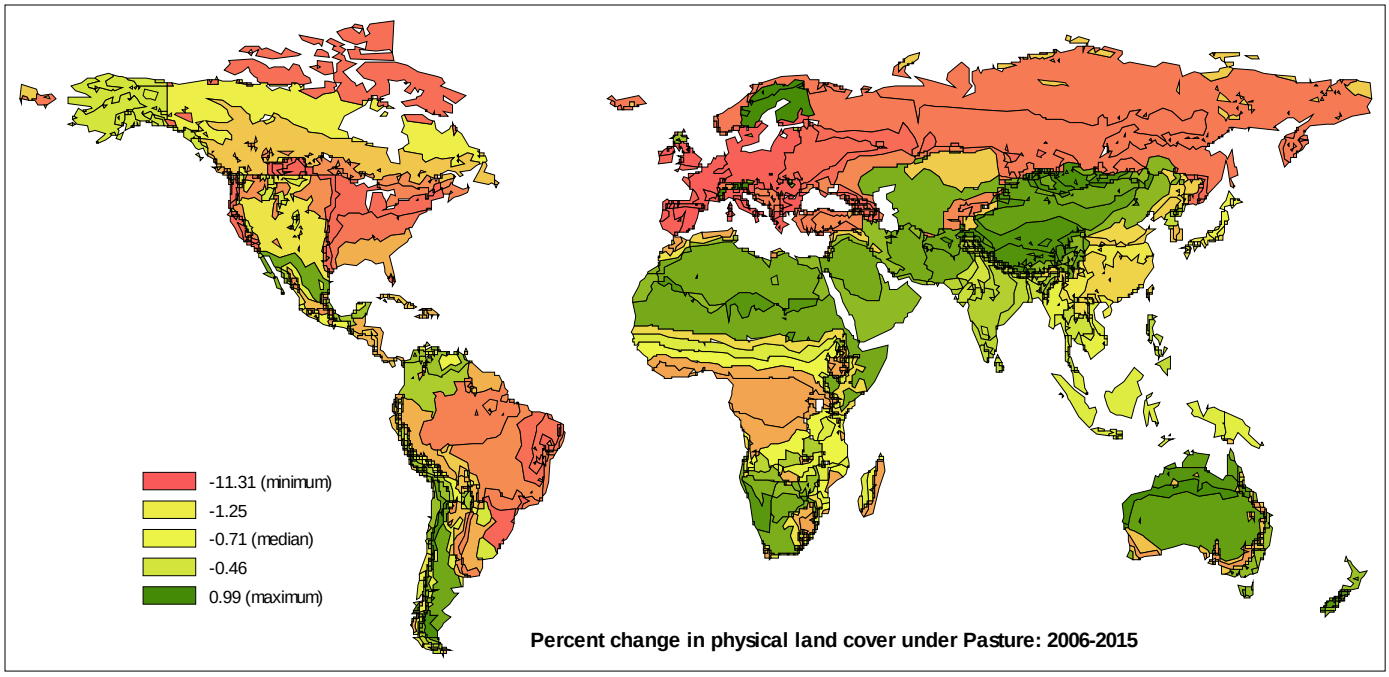
Coarse Grains: (2006-15)	USA	Canada	EU	Brazil
Percent change	5.4	-0.3	-5.1	-7.2
Change in million acres	5.0	-0.1	-4.3	-2.2

Figure 1. Change in Land Area under Coarse Grains across AEZs (2006-2015)



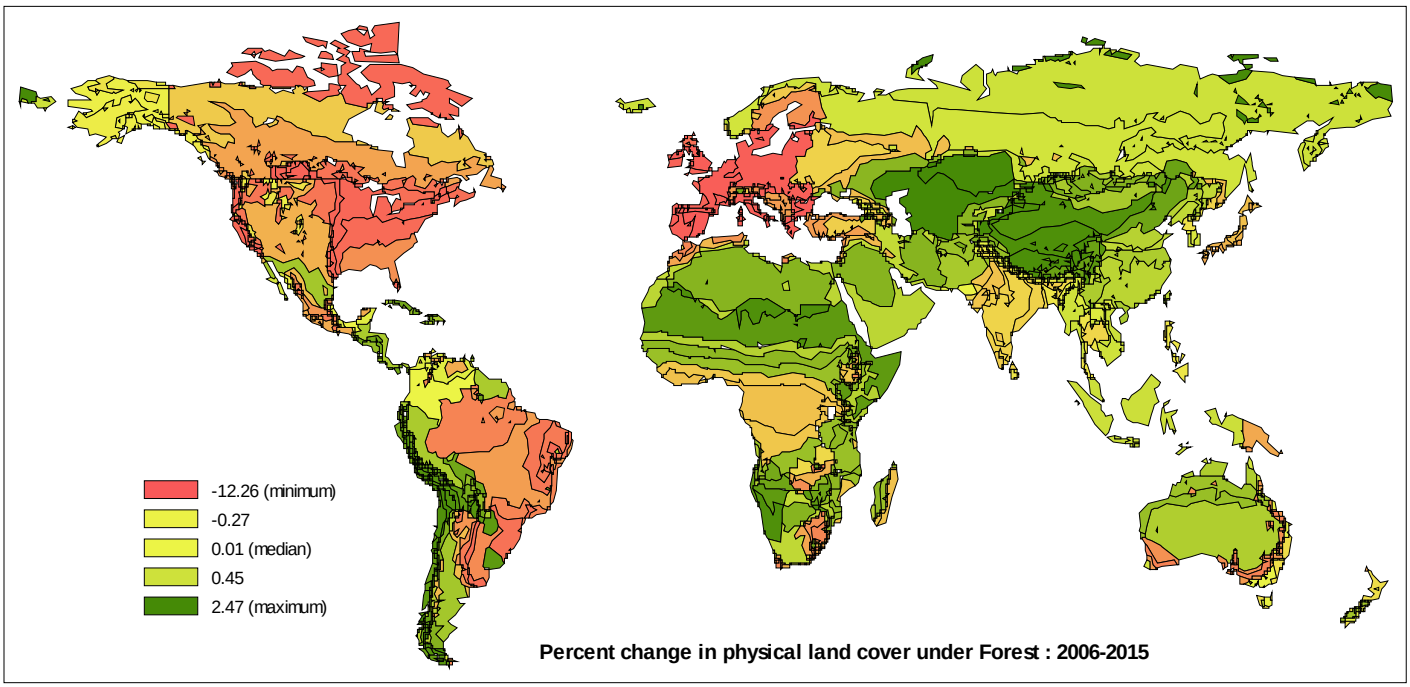
Oilseeds: (2006-15)	USA	Canada	EU	Brazil
Percent change	6.5	19.7	53.4	10.6
Change in million acres	5.3	3.4	19.3	3.7

Figure 2. Change in Land Area under Oilseeds across AEZs (2006-2015)



Pasture cover: (2006-15)	USA	Canada	EU	Brazil
Percent change	-1.2	-2.6	-4.9	-2.3
Change in million acres	-7.2	-1.3	-7.7	-10.3

Figure 3. Change in Land Area under Pasture land across AEZs (2006-2015).



Forest cover: (2006-15)	USA	Canada	EU	Brazil
Percent change	-0.9	-0.4	-4.3	-0.8
Change in million acres	-8.0	-3.2	-15.5	-2.9

Figure 4. Change in Land Area under Forest across AEZs (2006-2015).

Table A1. Systematic Sensitivity Analysis (SSA) of US and EU Biofuel Mandates – Amount of Variation of Key Parameters

	Parameters	Lower bound	Mean	Upper bound	Standard Deviation	Amount of Variation: SD*(6^0.5)
1	Yield elasticity[1] (YDE_Target)	0.00	0.40	0.80	0.163	0.400
2	Elasticity of transformation of land supply (ETRAE-2)[2]	-0.10	-0.50	-0.90	0.163	0.400
3	Elasticity. of transformation for crop land (ETRAE-1)[3]	-0.04	-0.20	-0.36	0.065	0.16
4	Armington CES elasticity of substitution for domestic and imported (ESUBD)[4]:					
	a. Coarse Grains	0.75	1.30	1.85	0.225	0.550
	b. Other Grains	2.43	4.52	6.61	0.853	2.089
	c. Oilseeds	2.05	2.45	2.85	0.163	0.400
	d. Sugarcane	1.70	2.70	3.70	0.408	1.000
	e. Other Agri	2.18	2.49	2.81	0.129	0.315

Sources: [1]Keeney and Hertel (2008); [2]Ahmed, Hertel and Lubowski (2009); [3]FAPRI (2004); [4]Hertel *et al.* (2007)

Table A2. Sensitivity Analysis of US and EU Biofuel Mandates for Variation in Key Parameters

Land Cover Change (%)	No change in parameters	Varying Armington Elasticity		Varying Yield elasticity		Cropland Cover elasticity		Harvested area elasticity	
		Lower	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
Parameter values →	Base parameters[1]	Vary by crop[2]		*0.10*	*0.80*	*-0.04*	*-0.36*	*-0.10*	*-0.90*
USA									
Crops	**0.69**	0.74	0.65	0.95	0.49	0.24	0.87	0.72	0.66
Forest	**-2.46**	-2.68	-2.32	-3.60	-1.67	-0.98	-2.95	-2.82	-2.35
Pasture	**-3.79**	-4.14	-3.59	-5.55	-2.59	-1.44	-4.62	-3.87	-3.64
EU									
Crops	**2.13**	2.28	2.00	2.41	1.84	0.61	2.97	2.34	2.04
Forest	**-8.21**	-9.07	-7.47	-9.74	-6.76	-2.73	-10.80	-9.55	-7.71
Pasture	**-9.45**	-10.42	-8.66	-11.47	-7.66	-3.48	-11.62	-10.81	-8.91
Brazil									
Crops	**2.85**	2.89	2.74	3.42	2.25	0.85	3.82	3.78	2.54
Forest	**-9.22**	-9.38	-8.81	-12.04	-6.72	-3.60	-11.02	-13.76	-7.88
Pasture	**-9.69**	-9.95	-9.12	-12.68	-7.09	-3.51	-12.01	-14.06	-8.46

Note: [1] Refers to the mean values of all the four parameters presented in Table A1.
[2] The lower and upper bound values respectively, for all the crops were included together. The lower and upper bound values of ESUBD for five crops considered were also analyzed when considered individually and the results are presented in Table A3.

Table A3. Sensitivity Analysis of Biofuel Mandates to Variation in Armington Elast. of Substitution for Crops (% Change)

Harvested area & land cover type	All Crops	**Coarse Grains**		**Oilseeds**		**Sugar-crops**		**Other Grains**		**Other Agri**	
		Lower	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
Parameter Values →	Base values[1]	*0.75*	*1.85*	*2.05*	*2.85*	*1.70*	*3.70*	*2.43*	*6.61*	*2.18*	*2.81*
USA											
CrGrains area	**6.20**	6.68	5.77	6.19	6.18	6.20	6.17	6.06	6.25	6.19	6.15
Oilseeds area	**7.69**	7.35	7.85	7.82	7.44	7.68	7.59	7.57	7.64	7.65	7.53
Sugarcane area	**-4.22**	-4.38	-4.08	-4.28	-4.16	-4.22	-4.21	-4.36	-4.13	-4.22	-4.19
OthGrains area	**-7.38**	-7.73	-7.01	-7.37	-7.28	-7.35	-7.31	-6.55	-7.77	-7.33	-7.29
OthAgri area	**-1.82**	-1.92	-1.71	-1.82	-1.79	-1.83	-1.79	-1.89	-1.75	-1.81	-1.76
Crops cover	**0.69**	0.71	0.67	0.70	0.68	0.69	0.69	0.71	0.68	0.69	0.69
Forest cover	**-2.46**	-2.54	-2.40	-2.50	-2.43	-2.46	-2.47	-2.54	-2.42	-2.46	-2.47
Pasture cover	**-3.79**	-3.91	-3.71	-3.88	-3.74	-3.79	-3.81	-3.92	-3.74	-3.80	-3.82
EU											
CrGrains area	**-8.97**	-8.49	-9.33	-9.88	-8.19	-8.98	-8.90	-9.35	-8.66	-8.95	-8.85
Oilseeds area	**47.82**	47.62	48.11	50.12	45.97	47.80	47.95	46.91	48.52	47.85	48.05
Sugarcane area	**-6.56**	-6.63	-6.72	-7.08	-6.35	-6.52	-6.83	-6.81	-6.61	-6.64	-6.91
OthGrains area	**-14.96**	-15.05	-14.63	-16.05	-13.83	-14.91	-14.74	-12.55	-16.36	-14.86	-14.64
OthAgri area	**-5.41**	-5.48	-5.70	-5.91	-5.33	-5.42	-5.75	-5.66	-5.58	-5.53	-5.96
Crops cover	**2.13**	2.15	2.11	2.23	2.04	2.13	2.12	2.18	2.09	2.13	2.12
Forest cover	**-8.21**	-8.28	-8.08	-8.74	-7.71	-8.21	-8.14	-8.47	-7.98	-8.19	-8.10
Pasture cover	**-9.45**	-9.53	-9.34	-10.05	-8.91	-9.45	-9.40	-9.74	-9.22	-9.44	-9.37
Brazil											
CrGrains area	**-10.47**	-9.37	-11.00	-10.61	-10.03	-10.48	-10.15	-10.57	-10.09	-10.37	-9.95
Oilseeds area	**6.39**	6.34	7.08	7.08	6.45	6.38	7.06	6.41	7.03	6.60	7.47
Sugarcane area	**22.88**	22.81	22.90	22.69	23.00	22.88	22.84	22.75	22.92	22.86	22.82
OthGrains area	**-17.95**	-17.89	-17.07	-18.02	-16.95	-17.70	-17.21	-14.91	-18.99	-17.54	-16.92
OthAgri area	**-10.58**	-10.66	-11.25	-10.70	-11.21	-10.59	-11.30	-10.70	-11.24	-10.82	-11.75
Crops cover	**2.85**	2.86	2.80	2.88	2.78	2.85	2.81	2.86	2.80	2.84	2.78
Forest cover	**-9.22**	-9.25	-9.04	-9.34	-8.97	-9.23	-9.06	-9.29	-9.02	-9.17	-8.96
Pasture cover	**-9.69**	-9.75	-9.43	-9.85	-9.34	-9.69	-9.48	-9.79	-9.42	-9.63	-9.35

Note: [1] Base values refer to the mean values of all the four parameters presented in Table A1.