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Adapting Natural Resource Enterprises under Global Warming in South America: A Mixed Logit Analysis

The planet Earth has been warming during the past century and will continue to warm in the coming centuries.[1] A warmer temperature in this century is highly likely to hurt low-latitude developing countries, even though it could impose only moderate damage to temperate developed nations.[2] Low-latitude developing countries are so vulnerable because they are already located in a hot climate and rely heavily on sectors that are highly climate sensitive, such as cropping and livestock management.[3] For example, these sectors account for more than a third of the economy and employ more than two-thirds of the population in agriculture-based countries.[4] Consequently, these countries will be seriously harmed by climate change unless prudent actions are taken to adapt to climate shifts by selecting heat-tolerant species and agricultural systems.[5] Without adaptations to climate change in these sectors, existing and future economic development programs in the region will turn out less effective.[6]

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I thank the members of the *Economía* panel for constructive comments. The household surveys were collected as part of the World Bank Project on Rural Income and Climate Change in Latin America.

1. Solomon and others (2007).
2. Nordhaus and Boyer (2000); Parry and others (2007).
3. Adams and others (1990); Rosenzweig and Parry (1994); Reilly and others (1996); Gitay and others (2001); Seo, Mendelsohn, and Munasinghe (2005); Butt and others (2005); Kurukulasuriya and others (2006); Sanghi and Mendelsohn (2008); Seo and Mendelsohn (2008a); Seo and others (2009).
4. Mata and Campos (2001); Magrin and others (2007); World Bank (2008).
5. Smit and Pilifosova (2001); Seo and Mendelsohn (2008b); Seo (2010a, 2010b).
6. World Bank (2008).

Researchers find that individuals are likely to adjust current practices in an effort to adapt to climate change. Farmers in Sri Lanka will make dramatic shifts toward commercial tree plantations such as coconut, rubber, and tea as global warming reduces paddy rice production sharply.[7] African farmers will adopt an integrated system of farming and livestock species such as sheep and goats more frequently when climate becomes hot and dry.[8] As climate change progresses, the ranges of most tree species such as white oak and paper birch are projected to move north, while the range of sugar maple will shift out of the United States entirely.[9] However, these studies provide only a partial analysis focused on a single sector, while an integrated assessment of natural resource sectors is rare, if not nonexistent. Although most researchers focus on crop vulnerabilities, livestock management accounts for as much of total agricultural income as crops, while forestry income accounts for 22 percent of the total income of rural households in developing countries.[10]

From this background, this paper develops an integrated adaptation model of natural-resource-intensive enterprises including crops, livestock, and forests and encompassing both specialized and diversified enterprises. Specialized enterprises, focusing on crops only, livestock only, or forests only, and diversified enterprises, combining crops and forests, crops and livestock, or crops, livestock, and forests, are modeled to explain the current sensitivities and future shifts in the choices of these enterprises when climate is changed. In contrast to Africa, South America is an ideal place for such a model since it relies heavily on livestock and forests in addition to crops.[11] Argentina and Brazil are the world's largest exporters and consumers of beef cattle.[12] The region is heavily forested in the north, has extensive grasslands in the southern plains, and features high mountains along the Andes range.[13] It has the world's largest rain forests in the Amazon, and its pasturelands are four to eight times larger than the cropland in major countries.[14]

This paper analyzes a rural household's adoption of one of these enterprises located across South America's varied climate zones. The surveys are collected from about 2,300 South American rural households in seven

7. Seo, Mendelsohn, and Munasinghe (2005).
8. Seo and Mendelsohn (2008b); Seo, (2010b).
9. Joyce and others (1995, 2000); Sohngen and Mendelsohn (1998).
10. Nin, Ehui, and Benin (2007); Vedeld and others (2007).
11. Mata and Campos (2001).
12. Steiger (2006).
13. Matthews (1983); FAO (2003b); World Resources Institute (2005).
14. Baethgen (1997).

countries across the continent. Using a mixed logit model, this paper estimates random coefficients with normal distributions and calculates the probabilities of different enterprises to be adopted by simulation methods.[15] Actual household choices are explained by climate factors, after controlling for other factors such as soils, market access, household characteristics, and country-specific effects. Based on the estimated parameters, this paper predicts dynamically expected changes in enterprise adoptions under multiple climate scenarios for 2020 and 2060, based on atmospheric-oceanic general circulation models (AOGCM).

The paper proceeds as follows. In the next section, I describe a mixed logit model that is applied to the analysis of the choice of natural resource enterprises under climate constraints. The subsequent section describes the data used in this study and their sources. The ensuing sections report estimation results, followed by simulation results for the next half century using multiple climate scenarios. The paper closes with a summary and policy discussions.

Theory

Given climate and geography, rural households invest in enterprises that will give the highest income. If climate is disturbed due to greenhouse effects, enterprise choices will be altered. Natural-resource-intensive enterprises such as crops, livestock, and forests are likely to be affected most by climate change. These enterprises are particularly at risk in South America, where vegetation is vastly forests and grasslands. This study examines the following six enterprises: crops only, livestock only, forests only, crops and livestock, crops and forests, and crops, livestock, and forests. The first three are specialized activities, whereas the latter three are diversified portfolios.

More formally, a rural household chooses one of these enterprises to maximize net revenue:

$$\text{(1)} \qquad \arg\ \max_j \left\{\pi_1^*, \pi_2^*, \ldots, \pi_j^*\right\}.$$

Let the net revenue from enterprise j be written as follows:

$$\text{(2)} \qquad \pi_j^* = \mathbf{Z}\boldsymbol{\gamma}_j + \eta_j,\ j = 1, \ldots, J,$$

15. McFadden (1974); McFadden and Train (2000); Train (2003).

where the subscript j is a categorical variable indicating enterprise j. The vector $\mathbf{Z}$ represents the set of explanatory variables for alternative j that is observable, η_j is the error term for the alternative j that is unobservable, and γ_j is the vector of random coefficients to be estimated.

The household will choose enterprise 1 if it is the most profitable alternative—that is, if

$$\pi_1^* > \pi_k^* \text{ for } \forall \text{ k} \neq 1 \; \left(\text{or if } \eta_k - \eta_1 < \boldsymbol{Z\gamma}_1 - \boldsymbol{Z\gamma}_k \text{ for k} \neq 1\right). \tag{3}$$

The probability P_1 of the first alternative being chosen is then

$$P_1 = \Pr\left(\eta_k - \eta_1 < \boldsymbol{Z\gamma}_1 - \boldsymbol{Z\gamma}_k\right) \forall \text{ k} \neq 1. \tag{4}$$

Assuming that η_j is independent and identically distributed (i.i.d.) and type I extreme-value distributed, the choice probability is the integral of the standard logit over all possible values of random coefficients, γ_j:[16]

$$P_1 = \int \left[\frac{\exp\left(\boldsymbol{Z\gamma}_1\right)}{\sum_{k=1}^{K} \exp\left(\boldsymbol{Z\gamma}_k\right)} \right] f\left(\boldsymbol{\gamma} | \theta\right) d\boldsymbol{\gamma}. \tag{5}$$

The mixing function, $f(\gamma | \theta)$, is assumed to be normally distributed, that is, $\gamma \sim N(\hat{\gamma}, W)$. With T random sampling, the simulated probability is calculated as the following average of the logit probabilities:[17]

$$\hat{P}_1 = \frac{1}{R} \sum_{t=1}^{T} L_1\left(\boldsymbol{\gamma}^t\right). \tag{6}$$

The simulated probabilities are inserted into the log-likelihood function to give simulated log likelihood (SLL). The maximum simulated likelihood estimator (MSLE) is the value of θ that maximizes the SLL. The mixed logit model is the most flexible of the various choice models, and it can approximate any random utility model.[18] Multinomial logit is a special case of the mixed logit when the mixing function is an indicator function.

16. On i.i.d. type I extreme-value distributions, see McFadden (1974).
17. Train (2003).
18. McFadden and Train (2000).

The independent variables in **Z** include climate, soils, household characteristics, socioeconomic variables, and country dummy variables. As climate changes, the probability of each enterprise being selected will change. The effects of climate change can be measured as the difference in the probability of each enterprise before and after climate change. That is, if the climate condition changes from S_1 to S_2 half a century from now, the change in the choice probability of enterprise k is measured as

$$\Delta P_k = P_k(S_2) - P_k(S_1). \tag{7}$$

Data

The key data used in this study are from the World Bank project on rural poverty and climate change in South America, which collected household surveys from more than 2,300 households across seven countries during the period from July 2003 to June 2004. Surveys were drawn from Argentina, Brazil, Chile, and Uruguay in the Southern Cone region and from Colombia, Ecuador, and Venezuela in the Andean region. In each country, 15–30 clusters were selected to cover a broad range of climatic zones in the country and 20–30 households were interviewed in each cluster.

Respondents were asked about the products they manage in the farming seasons during that year. The most important crops are cereals (namely, wheat, maize, barley, rice, and oats), oil seeds (soybean, peanuts, and sunflower), vegetables and tubers (potatoes and cassava), a variety of perennial grasses, and specialty crops (such as cotton, tobacco, tea, coffee, sugarcane, and sugar beet). Major animals raised are beef cattle, dairy cattle, sheep, pigs, chickens, and goats. Major trees are mango, pineapple, cashew, citrus, cacao, banana, palm, shea, apple, kola, peach, almond, prune, apricot, avocado, cherry, hickory, eucalyptus, lemon, and brazil nut.

Table 1 shows the distributions of the six most common enterprises by country. Three are specialized (that is, crops only, livestock only, and forests only), and three are diversified (crops and livestock, crops and forests, and crops, livestock, and forests). Crops-only enterprises account for 31 percent of the sampled households, crops and livestock for 36 percent, crops and forests for 7 percent, crops, livestock, and forests for 5 percent, and livestock only for 20 percent.

Across the continent, specialized crops enterprises are chosen most often in Argentina, Ecuador, and Venezuela, while specialization in livestock

TABLE 1. Percentage of Enterprise by Country

Country	*Crops only*	*Livestock only*	*Forests only*	*Crops + livestock*	*Crops + forests*	*Crops + livestock + forests*
Argentina	32.5	27.7	0.0	26.3	10.2	3.3
Brazil	23.2	14.2	0.6	40.4	11.9	9.8
Chile	27.7	11.6	0.0	59.1	1.7	0.0
Colombia	26.3	25.0	0.8	29.6	13.3	5.0
Ecuador	63.7	7.0	1.0	16.9	6.5	5.0
Uruguay	19.2	61.6	0.0	17.2	1.0	1.0
Venezuela	37.7	24.1	0.5	31.8	5.0	0.9
Sample total	30.5	20.1	0.7	36.5	7.2	4.9

enterprise is most common in Argentina and Uruguay. Specialization in forestry is rare in the region, but it is present in Brazil, Colombia, Ecuador, and Venezuela. Crops-livestock enterprises are most common in Brazil and Chile. Enterprises including forestry are less common, but crops-forests enterprises are relatively frequent in in Argentina, Brazil, and Colombia and crops-livestock-forests enterprises in Brazil, Colombia, and Ecuador.

Climate data are taken from two separate sources based on both satellites and ground weather stations. I use satellite temperature data recorded by the U.S. Department of Defense and precipitation data recorded at ground weather stations by the Climatic Research Unit.[19] The satellite temperature measurements proved superior to those from the weather stations for rural areas of the world because satellites can observe the entire surface of the earth, whereas many rural areas do not have a weather station nearby. Unfortunately, the satellites cannot directly measure precipitation on the ground, so the ground weather station precipitation data are currently the best proxy for rainfall available for agriculture.[20]

Soil data were obtained from the Food and Agriculture Organization (FAO), which maintains a digital soil map of the world.[21] The data were interpolated to the district level using a geographical information system. The data set reports percentages of the 116 dominant soil types, as well as other geographical information such as altitude, slope, and soil texture. The 116 dominant soils are grouped into twenty-six major categories, which I use for this analysis.

19. Basist and others (1998); New and others (2002).
20. Mendelsohn and others (2007).
21. FAO (2003a).

TABLE 2. Descriptive Statistics by Enterprise

Parameter	*Crops only*	*Livestock only*	*Forests only*	*Crops + livestock*	*Crops + forests*	*Crops + livestock + forests*
Summer temperature	19.97	23.11	22.63	20.78	20.80	22.09
Summer precipitation	117.98	137.32	144.73	115.00	152.41	158.78
Winter temperature	15.12	16.12	17.95	14.62	15.59	18.84
Winter precipitation	64.73	71.40	82.16	92.15	79.54	63.37
Acrisols (%)	2.27	4.28	0.00	6.39	5.96	2.50
Cambisols (%)	3.95	2.42	4.00	2.26	1.58	0.90
Luvisols (%)	6.75	3.55	13.33	8.91	4.32	3.85
Gleysols (%)	2.46	2.46	13.33	1.70	2.57	0.25
Regosols (%)	1.98	2.56	13.33	2.10	1.95	4.30
Planosols (%)	3.32	9.03	6.67	4.29	4.11	3.00
Electricity (dummy)	0.90	0.79	0.93	0.90	0.90	0.88
Flat (dummy)	0.65	0.70	0.60	0.57	0.61	0.67
Altitude (*m*)	328.08	327.65	113.20	361.03	341.29	498.67
Clay (dummy)	0.27	0.17	0.20	0.25	0.23	0.21
Distance (km)	184.24	223.30	177.61	209.16	194.38	179.14
Household size (*n*)	4.65	4.47	4.21	4.88	4.52	5.79
Age (*n*)	51.07	53.65	54.00	52.72	53.06	52.25
Gender female (dummy)	0.08	0.08	0.07	0.09	0.12	0.03
Education (*n*)	8.62	10.33	8.21	7.79	10.45	7.66
Andes (dummy)	0.44	0.26	0.13	0.25	0.29	0.23

Table 2 reports the descriptive statistics of the variables used in this study. Sample statistics of climate variables reveal variations of natural-resource-intensive enterprises across climate zones. Summer temperature is highest in a livestock-only enterprise and lowest in a crops-only enterprise. It is also high in a crops-livestock-forests enterprise. Summer precipitation is highest in crops-livestock-forests and crops-forests enterprises and lowest in a crops-livestock enterprise.

Other geographic variables show the variance across the enterprises. In terms of soil type, acrisols are found most often in crops-livestock and crops-forests enterprises, gleysols and luvisols are most common with forests-only options, and planosols are generally in livestock-only enterprises. Flat terrains are most likely to be used for livestock only, but least likely for forests only. Forests only are least likely under clay soils. The preferred arrangement at high altitudes is an all-inclusive portfolio of crops, livestock, and forests.

Socioeconomic variables include electricity provision, household size, age, education, distance to the nearest coast, and country dummies. Household heads who raise livestock only are the most educated, with ten years of schooling on average, and also the oldest, at fifty-two years of age. Younger household heads tend to specialize in crops, with an average age of forty. Crops only are also chosen by the least educated. A larger family tends to be diversified. Finally, livestock-only and crops-livestock enterprises are located farther from the coast, probably because they are favored in savannah conditions rather than coastal climates.

Empirical Results

South America comprises diverse ecological zones, as identified in the Global Vegetation and Land Use Dataset.[22] Northern Brazil and the Andean countries are predominantly tropical rainforests, tropical/subtropical drought-deciduous forests, and grasslands with less than 10 percent woody cover. The coastal areas of Brazil are predominantly xeromorphic forests and tropical/subtropical drought-deciduous forests, whereas the central areas are xeromorphic forests and grasslands with woody cover.[23] Uruguay is predominantly grasslands with shrub cover. Vast areas of grassland cover much of Argentina, with tall grasslands without woody cover in the northern areas of the country, followed by xeromorphic shrublands in the center and short grasslands and cold forests in the south. The major vegetation regions in Chile are cold-deciduous forests and temperate rainforests in the south, and xeromorphic forests, cold forests, and short grasslands in the center; the north is dominated by the Atacama desert. In Paraguay, the predominant vegetation type is xeromorphic forest.

Agriculture is practiced widely across the entire range of vegetation conditions in South America. It accounts for about 10 percent of the total GDP of the continent, but this percentage varies significantly by country.[24] The agricultural sector employs 30–40 percent of the economically active population and uses a third of the total land area.[25] Farmers grow various cereals, oil seeds, vegetables/tubers, perennial grasses, and specialty crops.

In addition to crops, livestock management is a key rural enterprise given that the continent is vastly occupied by grasslands, especially in Argentina, southern Brazil, and Uruguay. Indeed, animal husbandry is more important in South America than in any other continent in the world.[26] For example,

22. Matthews (1983).

23. A xeromorphic plant can survive in an environment that is deficient of water, such as a desert, by adapting its form or internal mechanisms.

24. World Bank (2004).

25. Mata and Campos (2001); World Resources Institute (2005).

26. Nin, Ehui, and Benin (2007).

pastures used for livestock are four to eight times larger than the croplands in major countries.[27] In addition, Argentina and Brazil are the world's largest beef cattle exporters, and Argentina is the world's largest consumer of beef per head annually.[28] Besides beef cattle, the most frequently raised animals are dairy cattle, chickens, pigs, goats, and sheep.[29]

Forests also cover a substantial area of the continent. Tropical rainforests are dominant in the Amazon Basin, while subtropical and temperate forests are found further south. South America accounts for around 70 percent of total world carbon dioxide emissions due to land use changes, mainly deforestation.[30] Forest income is an important component of the regional economy, probably more so than in the other continents.[31] People manage tree plantations for the sale of either timber products or nontimber products (or both). The most common tree varieties reported by the households who responded to the surveys are mango, pineapple, cashew, citrus, cacao, banana, palm, shea, apple, kola, peach, almond, prune, apricot, avocado, cherry, hickory, eucalyptus, lemon, and brazil nut.

As shown above in table 1, a majority of the respondents manage some combination of crops, animals, and trees, but substantial numbers of households specialize in either crops or livestock. The households that specialize in trees are rare in the sample. The descriptive statistics in tables 1 and 2 show that the choices of these major enterprises vary across climate and natural factors, let alone market and policy factors. Given the household surveys across the continent, I ask the following: Are the observed variations in enterprise adoptions by rural families a result of climate variations? If so, what are the implications of the climate changes predicted for the future in terms of the distribution of these natural-resource-intensive enterprises?

I take a microeconometric approach to model the statistical relationship between climatic variables and the choice of enterprises based on the actual household decisions made by South American rural families. A mixed logit model is run assuming that the decision to choose an enterprise is economically driven, that is, a farmer chooses one enterprise over the others to earn a

27. Baethgen (1997).
28. Steiger (2006).
29. Seo, McCarl, and Mendelsohn (2010).
30. Houghton (2008).
31. Peters, Gentry, and Mendelsohn (1989); Vedeld and others (2007). According to Vedeld and others (2007), who analyze fifty-one case studies from developing countries, forest income accounts for 22 percent of the total household income of the rural poor. Forest incomes are earned from wild foods, fuel wood, fodder, timber, grass/thatch, wild medicine, gold panning, and so on.

higher profit. Using a mixing function with a normal distribution, I estimate both fixed and random coefficients of the climatic and covariate variables.

Parameter estimates are shown in tables 3 and 4. Setting the crops-only enterprise as the base case, the tables show five sets of parameters for the specialized livestock-only and forests-only enterprises (table 3) and the diversified crops-livestock, crops-forests, crops-livestock-forests enterprises (table 4). The estimation of both fixed and random coefficients in the table took 118 minutes using simulation by a Halton sequence. The overall model

TABLE 3. A Mixed Logit Model of Enterprise Choice: Specialized Enterprises[a]

	Livestock only		*Forests only*	
Parameter	*Fixed*	*Random*	*Fixed*	*Random*
Intercept	−0.177	0.11	−0.114	0.51
Summer temperature	−0.484	0.0026	−0.716	0.02
Summer temperature squared	0.0198	0.0001	0.022	0.0007
Summer precipitation	0.0415	0.0008	0.027	0.0020
Summer precipitation squared	−8.7E−05	9.92E−07	−7.1E−05	1.85E−05
Winter temperature	−0.513	0.0005	−0.274	0.0053
Winter temperature squared	0.0116	0.0002	0.00774	0.0001
Winter precipitation	0.0185	0.001	0.014	0.0073
Winter precipitation squared	−5.5E−05	1.29E−06	−5.3E−05	2.38E−06
Acrisols	−0.00208	0.007	−0.23	0.03
Cambisols	0.0152	0.012	0.017	0.003
Gleysols	−0.00646	0.002	0.034	0.008
Regosols	−0.0013	0.0016	−0.188	0.005
Planosols	0.00408	0.004	0.0051	0.009
Electricity	−1.506	0.024	0.022	0.31
Flat	−0.428	0.11	−0.155	0.0017
Altitude	0.000408	0.00012	−0.0029	0.0012
Clay	−0.42	0.11	−0.0413	0.06
Distance	−0.00025	0.0002	0.0012	0.0006
Argentina	−0.0656	0.079	−0.38	0.018
Chile	0.37	0.15	−0.098	0.09
Colombia	1.37	0.47	−0.0704	0.22
Ecuador	−1.12	0.1	−0.23	0.01
Venezuela	0.506	0.21	−0.25	0.08
Household size	−0.036	0.025	−0.46	0.15
Age	0.033	0.00011	0.040	0.012
Gender	−0.066	0.26	−0.054	0.08
Education	0.093	0.0004	−0.061	0.07
Summary statistic				
No. observations	2,053			
McFadden's Index	0.27			
Likelihood ratio	1,994.7 ($p < 0.0001$)			

a. The baseline for the table is a crops-only enterprise.

TABLE 4. A Mixed Logit Model of Enterprise Choice: Diversified Enterprises[a]

	Crops + livestock		*Crops + forests*		*Crops + livestock + forests*	
Parameters	*Fixed*	*Random*	*Fixed*	*Random*	*Fixed*	*Random*
Intercept	−0.038	0.02	−0.108	0.19	−0.189	0.25
Summer temperature	0.43	0.06	−0.62	0.02	−1.25	0.008
Summer temperature squared	−0.0022	0.002	0.0175	0.0005	0.034	0.0008
Summer precipitation	0.024	0.009	0.0176	0.0015	0.025	0.0022
Summer precipitation squared	−0.00018	0.0001	−3.1E−05	1.4E−05	−0.00004	2.49E−06
Winter temperature	−0.82	0.08	−0.211	0.001	0.477	0.017
Winter temperature squared	0.022	0.001	0.00399	0.003	−0.0119	0.0007
Winter precipitation	−0.061	0.011	0.0199	0.0012	0.0308	0.01
Winter precipitation squared	0.00035	4.4E−05	−0.00005	3.36E−06	−0.00017	5.8E−05
Acrisols	0.122	0.042	0.0148	0.01	−0.022	0.002
Cambisols	−0.0421	0.028	−0.324	0.23	−0.107	0.09
Gleysols	−0.508	1.01	0.00717	0.01	−0.065	0.005
Regosols	−0.124	0.507	0.0043	0.0036	0.018	0.0074
Planosols	−0.0388	0.004	−0.00013	0.01	−0.305	0.17
Electricity	−0.146	0.0018	0.30	0.62	0.18	0.31
Flat	−0.653	0.03	−0.194	0.06	−0.009	0.14
Altitude	−0.00807	0.04	0.00067	0.0001	0.00104	0.0007
Clay	0.117	0.04	0.202	0.28	−0.46	0.10
Distance	0.00795	0.001	−0.0009	0.0002	−0.0016	0.0007
Argentina	−0.529	0.22	0.048	0.22	−0.132	0.23
Chile	0.382	0.10	−1.081	0.03	−0.22	0.143
Colombia	−0.0186	0.05	−0.044	0.35	−0.46	0.07
Ecuador	−0.0665	0.064	−0.367	0.11	−0.25	0.18
Venezuela	−0.125	0.0013	−0.756	0.038	−0.72	0.01
Household size	0.451	0.045	−0.057	0.048	0.13	0.07
Age	−0.0317	0.001	0.024	0.006	0.00054	0.0088
Gender	0.301	0.05	0.22	0.12	−0.46	0.05
Education	−0.37	0.34	0.12	0.04	−0.017	0.002
Summary statistic						
No. observations	2,053					
McFadden's Index	0.27					
Likelihood ratio	1,994.7 ($p < 0.0001$)					

a. The baseline for the table is a crops-only enterprise.

is highly significant, with goodness of fit measures including a McFadden's likelihood ratio index of 0.27, an Aldrich-Neslon of 0.51, and an adjusted Estrella of 0.61. Explanatory variables are climate, dominant soils, soil texture, land elevation, and socioeconomic variables such as household characteristics, distance to the coast, and country fixed effects.

The estimation results show that the choice of a livestock-only enterprise is highly significant against the choice of a crops-only enterprise, the base case. Climatic variables are highly significant across all the enterprises. The response function to summer temperature is U shaped for all enterprises except mixed crops-livestock enterprises.[32] The U-shaped response indicates that the choice of the corresponding enterprise increases in high-temperature zones, while an inverted U shape implies the opposite. Therefore, my estimates show that crops-only enterprises decline against the other enterprises in high-temperature zones. The response function to summer precipitation is hill shaped for all the enterprises against a crops-only enterprise. The response to winter precipitation follows an inverted U shape, except for the case of crops-livestock enterprises. Given the high correlations between climate means and climate variabilities, I dropped climate variability variables from the final regression.[33]

Geographic variables control spatial fixed effects. The presence of planosols, which are poor soils for crops and are dominant along the border of Argentina and Brazil, increases livestock-only enterprises, but not others.[34] Acrisols, which are dominant in southern Brazil and the Bolivian highlands, increase the log-odds of a crops-livestock enterprise, but not other enterprises. Cambisols, weak brownish soils, increase a livestock-only choice, but decrease a crops-livestock combination. Gleysols, which are dominant in the Amazon basin, decrease a crop-livestock-forests combination, but increase a forests-only enterprise. Regosols increase a crops-livestock-forests decision, but decrease others. High altitude households are more likely to combine crops, livestock, and forests or to choose to raise livestock only. The farther a family is from the coast, the more likely it will choose crops and livestock rather than livestock only; this may reflect the fact that livestock-only enterprises often export their products through seaports.

Socioeconomic factors are carefully controlled. Access to electricity decreases the choice of a livestock-only or crops-livestock enterprise over a crops-only enterprise. A larger family tends to choose a mixed enterprise such as crops and livestock or crops, livestock, and forests over a specialized enterprise, which probably reflects the availability of household labor. An older head of household tends to raise livestock only more frequently than a combination of crops and livestock. A more educated household head is more likely to choose a livestock-only enterprise, but less likely to diversify. This may reflect higher risk taking by people with more education. In contrast, female household heads tend to diversify more often due to risk aversion.

32. Summer and winter seasons are defined by correcting for the difference of seasons in the northern and southern hemispheres.

33. Including these variables does not change the qualitative results presented here, but it affects the magnitude of the changes.

34. FAO (2003a).

Country dummy variables aim to control country-specific fixed effects such as policy, trade, culture, and language.[35] Ecuadorian farms tend to specialize in crops only because of the large altitude variation across the country. Venezuelan farms are more often livestock only, as are Colombian farms. Chilean farms are more frequently livestock only or a mix of crops and livestock. Argentine farms are less likely than Brazilian farms to combine crops and livestock or to specialize in forests only.

A sensitivity analysis is presented in table 5.[36] I test the importance of two major factors: climate variabilities and seasonal climate variables. For the former, I test whether expected deviations from normal climate in the beginning of the farming year have a significant impact on the choice of enterprise. I include two variables for this: the standard deviation of seasonal temperature variables measured by satellites and the coefficient of variation of seasonal precipitation variables for the thirty-year period. These two variables capture the expected climate deviation at the time farming decisions are made. To measure the impact of seasonal climate variables, I test whether the definition of summer and winter seasons has a different impact in the Southern Cone versus the Andean region. I create climate and Andes interaction variables to test this difference.

After testing numerous specifications, I defined the final specification using the multinomial logit model (see table 5). The exercise shows that both expected temperature variability and precipitation variability are significant factors, and their impacts vary across the two major regions. The climate-Andes interaction variables are significant for summer and winter precipitations. Notably, when temperature variability is expected to be large, farmers tend to diversify into combined crops-livestock-forests enterprises. When precipitation variability is expected to be large, they tend to move out of livestock-only enterprises and increase forests-only ventures. The reduction of the livestock-only alternative in response to precipitation variation is greatest in the Andean region.

To compare the estimation results from the main model in tables 3 and 4 and those from the alternative model in table 5, I draw box plots of the

35. Since sample size and land size in Uruguay are small, they are included in the dummy variable for Argentina.

36. Table A1 in the appendix presents the estimation results from a parsimonious model that includes only climate variables as explanatory variables. The estimated parameters are highly significant, while the climate responses of the five enterprises are similar to those reported in tables 3, 4, and 5.

TABLE 5. Alternative Specification with Climate Variabilities and Regional Climate Interactions

Parameter	*Livestock only*	*Forests only*	*Crops + livestock*	*Crops + forests*	*Crops + livestock + forests*
Intercept	−3.3876*	−76.7174	−1.9464	−2.2217	−7.1058*
Summer temperature	0.1692	4.4226	0.2623*	−0.1923	−0.545
Summer temperature squared	0.00117	−0.1072	−0.00511	0.00337	0.0131
Summer precipitation	0.0168*	0.0458	0.00583	0.00622	0.00947
Summer precipitation squared	−0.00006*	−0.00013	−0.00002	−0.00002	−0.00001
Winter temperature	−0.3169*	1.5583	−0.1599*	0.0168	0.6839*
Winter temperature squared	0.0103*	−0.0349	0.00565*	0.00237	−0.0165*
Winter precipitation	0.0113*	0.058*	−0.00207	0.0193*	0.0236*
Winter precipitation squared	−0.00004*	−0.00014	0.000027	−0.00007*	−0.00006
Temperature variability	−0.0299	0.0332	−0.0252	0.0448*	0.0852*
Precipitation variability	−0.0326*	0.082*	−0.01*	−0.0137*	0.00742
Summer precipitation * Andes	0.0153*	−0.00239	−0.00112	0.00895*	0.00357
Winter precipitation * Andes	−0.0141*	−0.0522	−0.00462	−0.0142*	−0.0172*
Temperature variability * Andes	0.099*	−9.8014	0.0364	0.0507	−0.0142
Precipitation variability * Andes	−0.0441*	0.0936	−0.00743	−0.0444*	−0.0183
Luvisols	−0.00031	0.0296	0.0114*	0.00887	−0.00497
Gleysols	−0.0103	0.0465	−0.00692	−0.00458	−0.0677*
Planosols	0.00219	0.024	−0.00163	0.000163	−0.00867
Flat	−0.3178	−1.96*	−0.4219*	−0.3119	−0.2958
Altitude	0.0008*	−0.0052*	0.000465*	0.00081*	0.00124*
Clay	−0.2254	−1.1017	−0.3317*	−0.014	−0.1924
Household size	−0.0149	−0.1182	0.0566*	0.00934	0.1414*
Age	0.0305*	0.043	0.0106*	0.025*	0.0159
Education	0.1008*	0.0658	−0.0114	0.114*	0.0209
Summary statistic					
No. observations	2,053				
Likelihood ratio	2,047.5 ($p < 0.0001$)				

estimated choice probabilities of the six enterprises across the whole range of climate[37] (see figures 1 and 2). As shown in figure 1, as temperature becomes warmer across the horizontal axis, the crops-only choice falls rapidly after peaking at around 10° Celsius. The crops-livestock choice also falls initially, but it then stabilizes in temperate zones and increases in hotter zones. In contrast, livestock-only enterprises gradually increase as temperature rises. A similar pattern holds for the most diversified crops-livestock-forests enterprises. Forests-only enterprises increase, albeit minutely. The choice of a crops-forests enterprise fluctuates across the range. These plots are consistent

37. Plots from the alternative model are removed from the published version to save space, but are similar to those in figures 1 and 2. Differences are described below.

FIGURE 1. Estimated Probabilities of Choosing Enterprises over Temperature

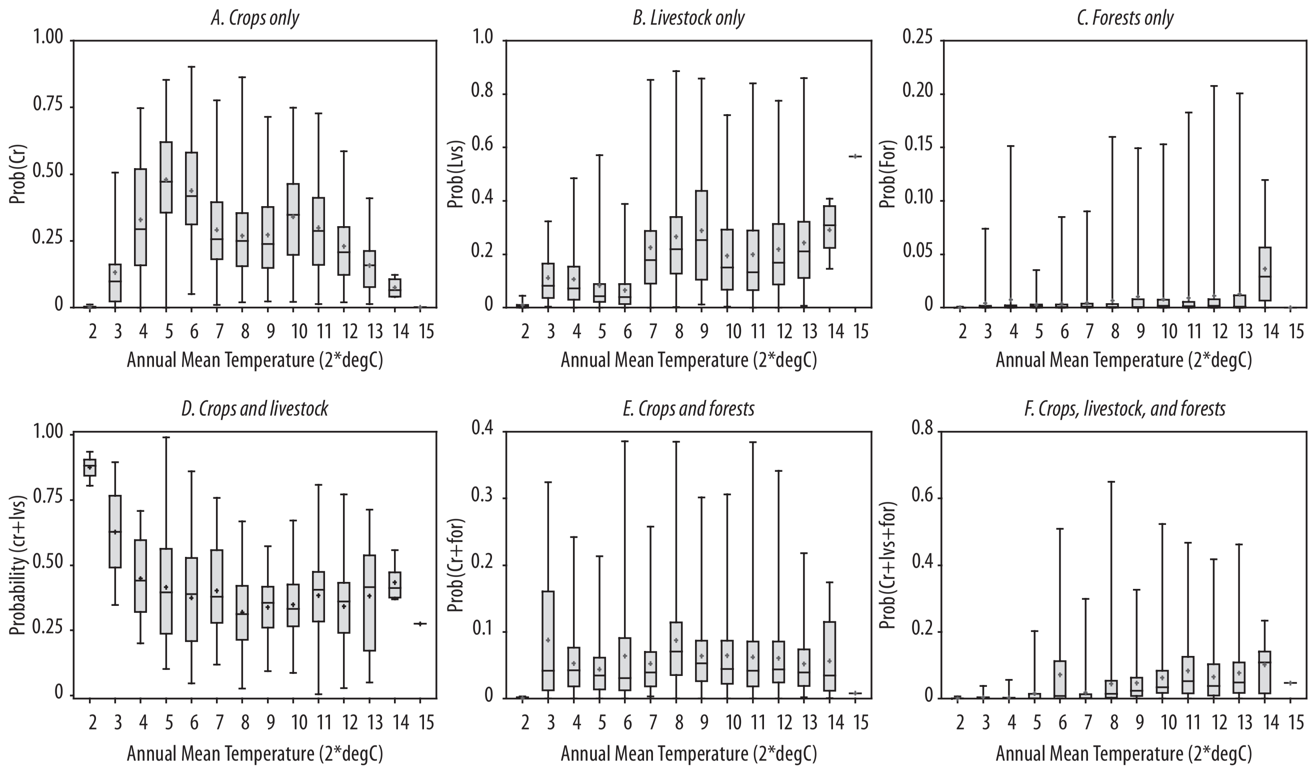

FIGURE 2. Estimated Probabilities of Choosing Enterprises over Precipitation

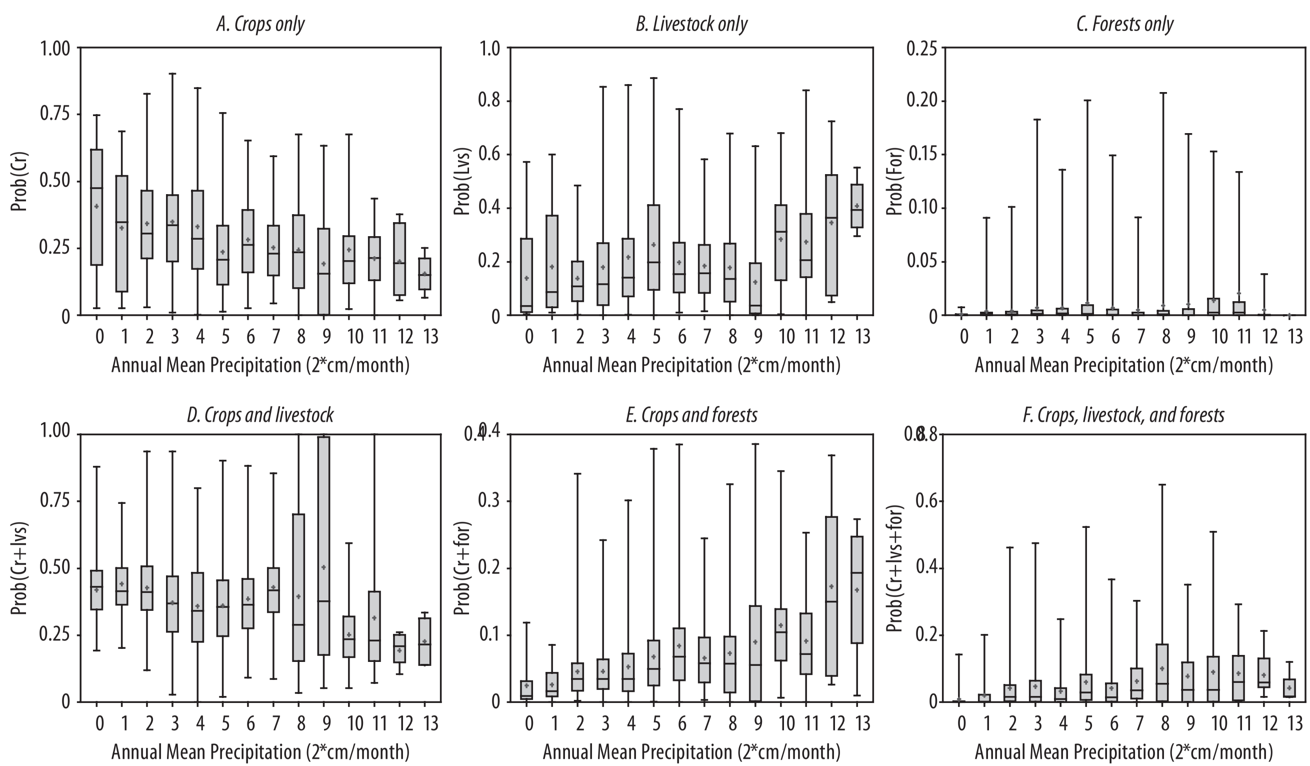

TABLE 6. Marginal Effects of Climate Change on Enterprise Choice
Percent

Scenario	*Crops only*	*Livestock only*	*Forests only*	*Crops + livestock*	*Crops + forests*	*Crops + livestock + forests*
Baseline	41.83	29.17	0.31	20.21	4.21	4.27
ΔTemperature	–3.57	3.17	0.04	0.19	–0.32	0.51
ΔPrecipitation	–1.16	0.88	–0.01	0.05	0.07	0.17

with agronomic studies that find high crop vulnerabilities, but they reveal a resilience of livestock enterprises and integrated enterprises.[38] These patterns are largely upheld when the alternative model is used to create the plots. However, under the alternative model, the crops-only enterprises hold up relatively well in the hottest zones, while crops-livestock-forests enterprises show a slight drop there.

Figure 2 shows the box plots for precipitation. The plots reveal that forests are strongly favored as the region becomes wetter. Across the range of rainfall on the continent, forests-only, crops-forests, and crops-livestock-forests enterprises all increase, with crops-forests recording the largest growth. In contrast, crops-only and crops-livestock enterprises decline with higher precipitation. The livestock-only alternative also gradually falls in most zones until monthly rainfall reaches 200 mm. Livestock enterprises may fall because of the reduction of pasturelands or the increased frequency of livestock disease outbreaks that accompany wetter conditions, which are the severe constraints in Africa's subsistent livestock management.[39] The gradual decrease in a crops-only choice contrasts with agronomic studies reporting beneficial effects of increased rainfall on crops.[40] Again, when the alternative model is used, the plots overall show more variance, as captured by the vertical length of the boxes. In addition, crops-forests enterprises fall in the wettest zones, as do livestock-only ventures.

Since the expected impact of disturbances in the current climate on natural resource enterprises is not obvious from tables 3 and 4, I calculate the changes in choice probabilities of the six enterprises when climate is disturbed marginally. Table 6 shows the marginal effects of changes in temperature and

38. Adams and others (1990); Reilly and others (1996); Magrin and others (2007); Hahn (1981).

39. Sankaran and others (2005); Committee on Foreign and Emerging Diseases (2007); Seo and Mendelsohn (2008b).

40. Reilly and others (1996); Magrin and others (2007).

precipitation. When temperature increases by 1 degree Celsius, there is a large decrease in crops-only and crops-forests enterprises. The decrease in the former amounts to 3.6 percent. Livestock-only and crops-livestock-forests enterprises increase under a hotter climate, with more than 3.0 percent in the former. When precipitation increases by 1 mm per month, crops-only and forests-only enterprises decline, with a drop of more than 1.0 percent in the case of the former. Livestock-only, crops-livestock, crops-forests, and crops-livestock-forests enterprises all increase in response to the small increase in precipitation.

Climate Simulations

The current distributions of natural-resource-intensive enterprises across climate zones analyzed in the previous section signal potential shifts of these enterprises in the future if the current climate were to be substantially altered. The changes in the future choice of enterprises would not result solely from climate change, however. Social, economic, and policy parameters—such as economic growth, population growth, changes in agricultural policy and trade regimes, agricultural price adjustments, dietary shifts, and technological advances—will play a large role in the transition.[41] My aim in this section is therefore more modest: I want to isolate the impacts of climate change on future enterprise choices, taking the present conditions as the baseline.

I employ a set of climate scenarios in forecasting the changes in enterprise choices due to climate change. Specifically, I examine A1 emission scenarios from the following atmospheric-oceanic general circulation models (AOGCM): the Canadian Climate Centre (CCC) model, the Center for Climate System Research (CCSR) model, and the Parallel Climate Model (PCM).[42] These scenarios cover the range of climate predictions reported in the most recent Intergovernmental Panel on Climate Change report.[43] As shown in table 7, the PCM scenario predicts an increase in summer temperature of 0.6° Celsius by 2060; CCSR, 2.2° Celsius; and CCC, 2.8° Celsius.

41. Although price change is likely a key factor in the choice of a selected crop in the future (Cline, 1996), this paper only models the changes in the crop enterprise, which comprises a full set of crops.

42. See Boer, Flato, and Ramsden (2000); Emori and others (1999); Washington and others (2000).

43. Solomon and others (2007).

TABLE 7. Scenarios Used for the Atmospheric-Oceanic General Circulation Models (AOGCM)

Scenario	*Current*	*2020*	*2060*
Summer temperature			
ΔCCC	18.65	1.65	2.85
ΔCCSR		1.30	2.15
ΔPCM		−0.16	0.52
Winter temperature			
ΔCCC	13.90	1.27	2.42
ΔCCSR		1.11	2.01
ΔPCM		1.41	2.04
Summer precipitation			
ΔCCC	129.40	−5.65	−13.88
ΔCCSR		−1.74	5.67
ΔPCM		−5.95	−5.67
Winter precipitation			
ΔCCC	73.32	−1.91	2.00
ΔCCSR		0.29	−2.02
ΔPCM		10.22	6.60

The differences in the model predictions are much smaller for winter temperatures. For precipitation, winter rainfall decreases by 2 mm per month by 2020 under the CCC model, but it increases by 10 mm per month under the PCM. Summer rainfall decreases by 14 mm per month by 2060 under the CCC, increases by 5.6 mm under the CCSR, and decreases by 5.6 mm under the PCM. One consequence of selecting these well-recognized climate models is that this simulation excludes the possibility of catastrophic events due to climate change within the half century time frame.[44]

Based on each of these scenarios, I calculate the changes in choice probabilities of the six enterprises in the coming half century (table 8). By 2020, under a hotter and drier CCC scenario, the crops-only specialization decreases by more than 6 percent, while livestock-only enterprises increase by as much as 5 percent. Crops-livestock and crops-livestock-forests enterprises increase, though to a lesser extent. This may be attributable to portfolio diversification benefits.[45] The changes magnify through 2060. The decrease in crops-only enterprises reaches 13 percent, while the increase in livestock-only enterprises reaches 8 percent. The combined crops-livestock alternative also grows substantially, reaching 5.4 percent by 2060.

44. Weitzman (2009).
45. Markowitz (1952); Tobin (1958).

TABLE 8. Dynamic Impacts of Climate Scenarios on Enterprise Choice
Percent

Scenario	*Crops only*	*Livestock only*	*Forests only*	*Crops + livestock*	*Crops + forests*	*Crops + livestock + forests*
Baseline	41.83	29.17	0.31	20.21	4.21	4.27
2020						
ΔCCC	−6.35	5.49	0.05	0.83	−0.67	0.65
ΔCCSR	−6.40	5.36	0.04	1.03	−0.50	0.47
ΔPCM	7.05	−3.90	0.03	−2.80	0.23	−0.61
2060						
ΔCCC	−13.17	8.16	0.11	5.49	−1.34	0.74
ΔCCSR	−9.05	9.74	0.09	−1.19	−0.69	1.10
ΔPCM	5.35	−1.41	0.05	−4.01	0.10	−0.07

Predictions of enterprise choice are quite different under the milder and wetter PCM scenario. By 2020, specialization in crops only increases by 7 percent, while livestock-only enterprises decrease by 4 percent. Forests-only and crops-forests enterprises also increase, though by smaller percentages. The crops-livestock option also falls. By 2060, crops-livestock enterprises decrease by as much as 4 percent. There is little effect on crops-livestock-forests enterprises. The predictions under the CCSR scenario are qualitatively similar to those of the CCC scenario, but the magnitudes of the expected changes are smaller. One exception is the decrease in crops-livestock enterprises by 2060 due to increased summer rainfall.

These estimates at the continental level provide valuable summary information on how South American households will adapt to the changes predicted by climate models. They are not particularly useful, however, for implementing adaptations on the ground, since they only provide continental-level information. Table 9 reports adaptive changes in the six enterprises by vegetation type, as described in the empirical section, assuming the CCC scenario. In xeromorphic shrublands (a major vegetation across Argentina), livestock-only enterprises increase by 13 percent, while crops-only ventures decrease by more than 10 percent. Changes in other enterprises are dwarfed by the large shifts in these two major enterprises. In xeromorphic forests (a major vegetation in eastern Brazil), the livestock-only choice increases by 20 percent, but crops-livestock enterprises decrease by 3 percent and crops-only options fall by 17 percent. In tropical rainforests (northern Brazil and equatorial Andean countries), crops-forests and crops-only enterprises fall by 2 percent and 9 percent, respectively. Livestock-only and crops-livestock-forests enterprises increase by 7 percent

TABLE 9. Impacts of Climate Scenarios on Enterprise Choice in 2060, by Land Cover
Percent

Scenario	*Tropical rainforest*	*Subtropical rainforest*	*Tropical/ subtropical dry forest*	*Temperate rainforest*	*Evergreen broadleaf forest*	*Cold deciduous forest*	*Xeromorphic forest*	*Xeromorphic shrubland*	*Grassland with woody cover*	*Grassland with little woody cover*	*Grassland with shrub cover*	*Medium grassland*	*Tall grassland*	*Water body (oceans, rivers, or lakes)*
Crops only	38.15	18.71	17.38	22.18	51.80	66.19	33.33	56.73	5.97	52.10	48.84	42.56	32.46	38.90
ΔCCC	–8.89	–17.03	–13.67	–13.39	–22.80	–2.61	–17.44	–10.47	–1.94	–7.80	–21.62	–16.91	–14.02	–13.31
Livestock only	45.93	32.05	47.64	61.98	29.64	11.84	30.29	28.18	6.90	25.82	30.19	28.76	24.42	41.65
ΔCCC	7.38	–30.18	–3.07	14.30	16.74	1.15	20.18	12.82	–5.11	6.42	10.36	11.81	4.61	12.52
Forests only	0.16	0.04	1.22	0.24	0.26	0.10	0.46	0.23	0.20	0.40	0.33	0.83	0.23	0.09
ΔCCC	0.04	–0.04	–0.15	–0.03	0.17	–0.02	0.15	0.02	–0.08	0.22	0.25	0.35	0.03	0.04
Crops-livestock	2.43	22.33	27.17	6.38	6.59	16.48	33.39	5.33	85.66	11.13	12.07	18.95	36.41	12.97
ΔCCC	0.34	72.79	19.94	0.00	6.40	2.80	–2.92	–1.10	7.94	3.14	11.56	4.37	8.30	–1.91
Crops-forests	9.83	26.86	3.90	7.34	3.86	2.77	2.37	5.33	1.26	4.79	4.16	3.45	2.45	4.33
ΔCCC	–1.73	–25.55	–1.91	–2.46	–0.71	–0.43	–0.24	–1.18	–0.80	–1.78	–1.18	–0.42	–0.80	–0.85
Crops-livestock-forests	3.49	0.00	2.69	1.87	7.85	2.62	0.16	4.21	0.00	5.75	4.41	5.45	4.03	2.05
ΔCCC	2.86	0.00	–1.13	1.58	0.20	–0.89	0.26	–0.09	0.00	–0.21	0.64	0.79	1.89	3.52

and 3 percent, respectively, under this hotter and more arid scenario. In the medium grasslands with no woody cover (the upper Andean region of Chile), the choice of crops only decreases by as much as 17 percent. Large increases in livestock-only and crops-livestock enterprises would occur to offset the move away from specialization in crops. The grasslands with woody cover (southern inland Brazil) are currently characterized by a large concentration of crops-livestock enterprises, which would increase further by 8 percent under a hotter and drier condition. Specialized enterprises either in crops or in livestock would fall. In tropical/subtropical drought-deciduous forests (southern Brazil), mixed crops-livestock enterprises would increase by large percentages, offsetting the decreases in crops-only and livestock-only alternatives. In grasslands with shrub cover (Uruguay), a crops-only enterprise falls by more than 20 percent, which is mostly offset by the increase in a livestock-only enterprise as well as a crops-livestock enterprise. The widespread increase in livestock enterprises across vegetation conditions is likely due to the expansion of pasturelands in a hotter and drier climate.[46] However, in cold deciduous forests (central and southern Chile), where crops-only enterprises account for a large share of rural employment, the hotter and drier conditions would lead to a relatively smaller contraction of only 2.6 percent.

Discussion

This paper has developed an integrated model of natural-resource-intensive enterprises to examine behavioral adaptation to climate change in South America. Based on the observed choices of about 2,000 households in seven countries, I modeled six specialized and diversified natural resource enterprises across climatic zones. The three specialized enterprises exploit crops only, livestock only, and forests only. The three diversified enterprises combine crops and livestock, crops and forests, and crops, livestock, and forests. I estimated both fixed and random coefficients of climatic parameters with a mixed logit model.

The results reveal that climatic variables are highly significant determinants of the choice of enterprise after controlling for geographic variables, socioeconomic variables, and country dummy variables. A slight perturbation in temperature or precipitation will motivate people to switch

46. Sankaran and others (2005).

over to other enterprises. A slightly warmer temperature by 1° Celsius would decrease crops-only enterprises by 4 percent and crops-forests choices slightly, whereas livestock-only ventures would increase by more than 3 percent. Mixed enterprises such as crops and livestock or crops, livestock, and forests also increase, though by smaller margins. A slight increase in precipitation of 1 mm per month would decrease crops-only enterprises by more than 1 percent, while livestock-only and crops-livestock-forests enterprises would increase.

I dynamically simulated future distributions of these enterprises in 2020 and 2060 based on three climate scenarios: CCC, CCSR, and PCM. By 2020, under a hotter and drier CCC scenario, crops-only and crop-forests enterprises are predicted to fall by 6.2 percent and 0.6 percent, respectively. Offsetting these losses, livestock-only enterprises increase by 5.5 percent and crops-livestock-forests enterprises expand by 0.7 percent. These changes would magnify over time: by 2060, crops-livestock enterprises increase by more than 5 percent. The adaptations are drastically different under the milder and wetter PCM climate scenario.

These adaptive changes would also vary across the land covers found in South America. Although specialization in crops only would decrease across all land covers, the shift is greatest in grasslands and xeromorphic forests. Livestock-only enterprises would increase in most zones, but especially in xeromorphic forests, temperate forests, and xeromorphic shrublands. The mixed crops-livestock enterprises would see large increases in grasslands, as well as in subtropical rainforests and dry forests. The most diversified crops-livestock-forests alternative would increase in tropical rainforests, coastal zones, and grasslands with some tree cover. Crops-forests enterprises would decline under this hot and dry climate, especially in tropical and subtropical forested zones.

The results presented in this paper provide valuable information for policymakers and rural residents who need to take action against climate change. This paper analyzes all enterprises that are highly intensive in natural resources and thus climate sensitive. If the crop sector becomes less productive in the future in comparison with the livestock sector, people will switch from the former to the latter to reduce the damage from climate change. Since the loss of productivity in the crop sector without adaptation is likely to be large, adaptation will be inevitable for both individuals and policymakers.

Several qualifications should be attached before closing. This paper does not model the direct impacts of elevated CO_2 concentrations on crops, animals, and forests.[47] A carbon doubling may benefit one sector over the others, which would then affect optimal adaptation strategies. In addition, this paper assumes use of technologies that are available now in South America. Any significant technological progress, such as the development of a new crop or livestock species, would lead to different adaptations than those presented in this paper.[48] Moreover, while the paper controls for policy factors using country dummy variables, distance to the coast, and land tenure, it does not separate out the influence of a specific policy distortion.[49] Finally, given the current state of science, it is impossible to tell with certainty which climate scenario will come to pass. However, climate models provide reliable estimates of temperature predictions, and precipitation predictions will likely improve over time. This will help farmers and policymakers develop future adaptation strategies.

47. Reilly and others (1996); Ainsworth and Long (2005).
48. Evenson and Gollin (2003).
49. Anderson (2009).

Appendix: Supplemental Tables

TABLE A1. A Parsimonious Model with Climate Only

	Crops + livestock		*Crops + forests*		*Crops + livestock + forests*		*Livestock only*		*Forests only*	
Parameter	*Estimate*	*P value*	*Estimate*	*P value*	*Estimate*	*P value*	*Estimate*	*P value*	*Estimate*	*P value*
Intercept	−1.9077	0.07	−2.8292	0.12	−4.5207	0.05	−1.3841	0.37	−25.0521	0.04
Summer temperature	0.0749	0.49	−0.1369	0.48	−0.478	0.03	−0.2477	0.10	1.5097	0.17
Summer temperature squared	0.000269	0.92	0.00559	0.27	0.0145	0.01	0.0129	0.00	−0.0314	0.22
Summer precipitation	0.00619	0.02	0.0159	<.0001	0.00768	0.06	0.0363	<.0001	0.0169	0.30
Summer precipitation squared	−0.00001	0.04	−0.00002	0.03	−7.45E−06	0.43	−0.00008	<.0001	−0.00005	0.31
Winter temperature	−0.0649	0.20	−0.1325	0.13	0.4887	0.00	−0.4585	<.0001	0.1906	0.54
Winter temperature squared	0.00203	0.18	0.00323	0.20	−0.0124	0.00	0.011	<.0001	−0.00428	0.64
Winter precipitation	0.000469	0.88	0.0262	<.0001	0.0182	0.01	0.025	<.0001	0.0111	0.37
Winter precipitation squared	0.000031	0.02	−0.00008	0.00	−0.00005	0.17	−0.00008	<.0001	7.84E−06	0.87

Comment

Subhra Bhattacharjee: The discussion on climate change is fraught with controversies, largely because of the uncertainties associated with its causes and consequences. This paper is part of the relatively recent and growing body of literature that seeks to quantify the possible effects of climate change, particularly in the farm sector. It is extremely difficult to quantify the extent of climate change in any particular geographical region, and only recently have there been systematic empirical analyses of the economic impacts of climate change. The usual practice in these studies is to use changes in long-run averages and variability in weather patterns to stand in for the changes in climate. This paper takes the same approach to model the impact of climate change on choice of enterprise by households in South America.

Agriculture, livestock, and forestry are among the most weather-dependent enterprises, and thus they display the earliest impacts of climate change. Changes in land use, primarily in agriculture and forestry, also account for about 20 percent of global greenhouse gas emissions. As a result, the majority of empirical economic analyses of climate change are concentrated in this area. Most studies focus on one side of the two-way causality—either the impact of climate change on one or more of agriculture, livestock, and forestry or the impact of land use changes on total emissions.

In most of the literature on the impact of climate change on agriculture, livestock, and forestry, the dependent variable is land values, yields, or farm profits, with a range of climate, soil, market, and farm characteristics as the independent variables.[1] Many of these studies rely on pooled or panel data sets, though some studies also use cross-sectional data. Niggol Seo's paper is among the smaller body of work that uses the choice of enterprise—or land use—as the dependent variable. It is a logical next step for the author

1. Schlenker, Hanneman, and Fischer (2005, 2006); Schlenker and Roberts (2009); Kurukulasuriya and Mendelsohn (2008).

after his earlier work on crop choice, livestock choice, and choice of agricultural systems in South America using the same data set.

The strength of this paper lies in its focus on enterprise choice rather than land value or farm profits. From the policymaker's perspective, understanding the impact of climate change on land use or choice of enterprise could be of more direct use than the impact of climate change on land values or farm profits because a policymaker would be concerned about changes in farm profits and land values largely to the extent that they affect farmers' choice of land use, input use, or demand for insurance. The value of modeling the impact of climate change on enterprise choice lies in informing policy that seeks to affect either the product mix from the agriculture, livestock, and forestry sectors or their total emissions. This paper, in predicting the impact of changes in temperature and precipitation on enterprise choice, could inform those policy efforts. Moreover, this exercise is undertaken for a large region spanning seven countries and a wide range of soil and weather conditions.

A weakness of the exercise, however, is that it seeks to model enterprise choice without using any choice-specific variables. The independent variables in the paper can be categorized under four headings: climate-related variables (such as temperature, precipitation, and functions thereof); soil type; geographical variables (including flat land, altitude, distance from port, and country of location); and farm or household characteristics. All of these variables remain the same for a household or farm regardless of its choice of enterprise. The set of independent variables does not include any variable that is different for different enterprises. Furthermore, other than access to electricity, this set does not include any variable that can be changed by policy.

This compromises the usefulness of the work for policymakers. If the enterprise mix is expected to shift over time on account of climate change and if a policymaker, concerned about food security or carbon emissions, wants to prevent such a shift, the first instrument of choice would likely be the relative price or the price of a key input. The sensitivity of enterprise choice to prices would then provide a clear idea of the magnitude of taxes or subsidies required to steer an adequate number of households toward or away from a particular enterprise choice.

A number of sophisticated land-use models can map specific policy changes into changes in land use and from there into changes in output and emissions while controlling for a wide range of factors.[2] These models can make

2. For example, FAPRI (2004); Tyrell and others (2004).

predictions about the impact of changes in weather-related variables and also provide predictions on responses to policy changes in the short term, conditioning for climate, geographic, use-specific, and sociodemographic variables. The approach used in this paper requires less data than these models, but the exclusion of choice-specific variables buys the lower data requirements at the cost of usefulness for policy. Including one or more such variables would enhance the usefulness of the work and also refine the paper's econometrics by allowing the identification of the individual parameters.

Another area in which this approach could be extended is in modeling risk aversion. The latent variable underlying enterprise choice in this paper is profit from an enterprise, not utility from profit. Modeling behavior in terms of utility maximization rather than profit maximization will enable the author to model risk aversion without requiring any additional data.

Latin America is likely to be very strongly affected by climate change in the short to medium term. The impact of climate change is already showing up in the more frequent incidence of extreme weather events. Not only are land use patterns going to change in response to climate change, but such changes in land use patterns will likely affect the pace of climate change through emissions. In parts of South America, land use changes account for as much as 50 percent of total greenhouse gas emissions. A shift from crops or forestry into livestock would sharply increase the emission of these gases. This work complements the existing literature by exploring the direction and implications of these changes.

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