Climate change-based modeling of potential land use arrangements for coffee (*coffea arabica*) and forest in Costa Rica

Alberto Coto-Fonseca[1*], Carlos Rojas[1,2], Sergio Molina-Murillo[2,3]

(1. *Department of Biosystems Engineering, University of Costa Rica, San Pedro de Montes de Oca, 11501, Costa Rica*;
2. *Engineering Research Institute, University of Costa Rica, San Pedro de Montes de Oca, 11501, Costa Rica*;
3. *Department of Environmental Sciences, National University of Costa Rica, Heredia, 30101, Costa Rica*)

Abstract: Besides the need to reduce its own emissions, the challenge of the agricultural sector worldwide is also to adapt to a changing and more variable climate. Coffee is an important crop in Costa Rica based on cultivated area and the number of families connected to this activity that has a long historical tradition. In this context, the potential distribution shifts of coffee production based on climate change scenarios have been identified and targeted in this study. Bioclimatic variables along with elevation were used to evaluate changes in suitable areas for coffee production under the framework of four climate change scenarios for the year 2070. Results suggest that the highlands have a high probability of being suitable for coffee under all four scenarios, and unsuitability seems to be associated with the lowlands. All four climate change scenarios showed high overlap between the projected suitable areas for coffee and current forested areas. This investigation suggests that the long-term management of coffee production in Costa Rica should carefully consider climate change given its potential conflict with other land uses and associated socioeconomic implications.

Keywords: climate change, coffee, models, forests, land use

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1 Introduction

Climate change is affecting fundamental aspects of modern life style, including agriculture (Rosenzweig, 2011). The adaptation of agricultural systems to climate change is paramount to ensure food security, poverty alleviation, and the sustainable use of natural resources (FAO, 2016; Smith and Olesen, 2010).

Climate-driven variables such as temperature and precipitation; as well as human-influenced atmospheric greenhouse gas concentrations impose external forces on crop development (Streck, 2005; Porter and Semenov, 2005; Benton, 2012). As a direct consequence of the later, recent research has shown that some crops have a high probability of shifting their geographical extent based on climatic suitability over the next decades. This has been shown in both commercial (Evangelista et al., 2013; Davis et al., 2012) and non-commercial crops (Khanum et al., 2013).

In this manner, researchers have developed a series of computational programs (i.e., ECOCROP, CaNaSTA, DSSAT) intended to integrate ecological modeling, plant physiology and socioeconomic planning by first demonstrating the effects of climate change on crop distribution and then interpreting results in a context of development. A popular modeling technique currently used around the world is the maximum entropy (Maxent) approach, which was originally developed for ecological purposes (Loarie et al., 2008; Van Gils et al., 2014) but has been widely used to assess geographical and climatic viability of commercial crops as well (Estes et al., 2013).

In the case of Costa Rica, coffee agriculture has been shown to have a positive effect on the economic

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*** Corresponding author: Alberto Coto-Fonseca,** Department of Biosystems Engineering, University of Costa Rica, San Pedro de Montes de Oca, 11501, Costa Rica. Email: alberto.cotof@gmail.com, Tel: (506) 2511-6643 (506) 2511-6657.

development of rural areas (Wollni and Zeller, 2007) but little has been published on the use of ecological modeling to assess potential shifts in the optimal distribution of crops. Even though some larger scale studies under the climate change framework (Ovalle-Rivera et al., 2015) are in place for coffee; these do not show the higher resolution needed for country-level assessments. Given the importance of such integration between economic development and climate change drivers at different scales (Van Vuuren et al., 2011), the Intergovernmental Panel on Climate Change (IPCC) has included four different representative concentration pathways (RCP) in its fifth assessment report in 2014 (Intergovernmental Panel on Climate Change, 2014). These RCPs are intended to provide modelers with standard scenarios for the development of potential future climate change effects.

In the present study, the potential suitable area of coffee distribution in Costa Rica for the year 2070 under four climate change scenarios was determined using the Maxent protocol. Besides contributing to the limited published information on this topic for such country and the Central American region, the approach took herein also contributes in terms of generating information to consider agriculture-based climate change potential vulnerability for administrative divisions in Costa Rica.

2 Materials and methods

The study area of this work encompassed all the Costa Rican territory. All the compilation of data and spatial analyses were carried out in 2015.

First, a database of geographical locations pertaining private lands used for coffee agriculture was created using 2012 information from the Coffee Research Center (CICAFE). This database, consisting of 4034 individual locations across Costa Rica, was used to create a baseline distributional map for the subsequent analyses. Such map was considered in the present investigation to depict the current distribution of coffee lands in the country.

Second, a series of bioclimatic data rasters at a spatial resolution of 30 arc seconds for 1) the current global climatic condition (average between 1950-2000) and 2) for the four different scenarios centered on 2070 (average between 2061-2080) were obtained from the databases of the WorldClim (www.worldclim.org) and the Consultative Group on International Agricultural Research (CGIAR, www.cgiar.org) databases, respectively. For the latter, two general circulation models (GCM), Miroc-ESM and Hadgem2-ES; and two RCPs, the 4.5 and 6.0 options, were selected.

The choice of the year 2070 was made based on the available projections for bioclimatic data according to the fifth report of the IPCC. Both GCM were selected because of their use in the analysis of ecological systems and of the high probability of continuing to be used in the future (Nygaard, 2015; Betts et al., 2015). Miroc-ESM predicts relatively dry scenarios, while Hadgem2-ES foretell moderate scenarios (moderate reduction of precipitation and increase in the temperature). Regarding the RCP, Collins et al. (2013) establish that those two concentration pathways assume moderate carbon emission curves, which stabilize until the year 2150, while the RCP of 8.5 stabilizes near 2250 (low confidence) and 2.6 for the 2070 (unreal).

Third, in order to evaluate which variables (represented by the individual rasters) could be considered for modeling, a preliminary assessment of their predictive relative importance was carried out based on the original distribution map. For this task, all 19 original bioclimatic rasters plus an extra elevational set were clipped for Costa Rica and loaded in the software Maxent (v.3.3.3k) to generate a first ecological model of coffee based on 100 replicates. Using the resulting model, the non-correlated variables that accumulated up to 70% of the total variation associated with the predictive power of the model were selected (minimum temperature of the coldest month, elevation, and mean diurnal range). For the latter selection, after the original results including all variables were obtained, a statistical analysis of all variable correlations was carried out on ArcGIS (v.10.2) with a cutoff value of 0.80 for the Pearson´s r correlation estimator associated with the lower ranked variables. In this manner, when two variables showed an r value higher than 0.80, the one with the lowest cumulative importance according to the original Maxent model was eliminated.

Forth, the selected variables were used to construct all the models presented herein in order to minimize errors in the calculations that could be the product of different sets of variables used for different scenarios. In all of the successive ecological models, most standard options in Maxent were applied. One hundred runs and the bootstrap replicated run type were used. When all probability rasters were obtained, the 10-percentile training presence threshold was used to define the suitable/unsuitable areas. With that information, a series of binary maps were created to determine the zones where the crop could have a high probability of ecological expansion and contraction. Furthermore, in order to provide detail for local governance, a layer of administrative municipalities was used in conjunction with the probability rasters, generating a category based determination of crop production suitability in comparison with the current state.

Finally, the percentage of crop overlap with the current forest cover was obtained by generating a forest cover map that considered mature, successional, deciduous, and mangrove swamp forest types. This forest cover layer was created from the 2012 dataset of the Costa Rican Forest Resources Information System (SIREFOR). This comparison was made in order to determine the forest areas with potential threats of coffee expansion based on the climate change models created. Dairy farming in the highlands is another competing land use with coffee; however, we focus the study on forest-land since it is a critical land-use for a national conservation strategy not competing in a market system but in a policy realm.

3 Results and discussion

For coffee in Costa Rica, the preliminary bioclimatic assessment showed that only three variables were required to explain over 70% of the structure associated with the current distribution of the crop. In fact, the three selected variables explained over 85% of the variability associated with the models constructed herein. This result is an indication of the ecological and climatic homogeneity of the areas currently used for coffee production, which in the case of Costa Rica typically corresponds with intermediate elevations in moist to wet tropical forest zones. The area under the curve (AUC) values obtained for both the current distribution model and all four future scenario models were calculated in 0.86. According to Baldwin (2009), such a high magnitude of the estimator reflects the potential accuracy of the models since AUC values near 0.50 indicate an adjustment better than expected by chance, and thus, values close to 1.00 would reflect a perfect adjustment.

Figure 1 shows that all four models evaluated herein, and contrasted with the current distribution of coffee lands, predicted an expansion in the northwestern part of the country and a contraction along the Caribbean highlands. Interestingly, such expansion of potential areas for coffee production was mainly located at intermediate elevations of the windward side in both the Tilaran and Guanacaste mountain ranges, where national parks currently exist. The Miroc-based models were the ones that showed the strongest contraction of suitable areas; however, for all four scenarios evaluated, the net predicted change was positive with values between three and eight percent of net gain in suitable areas for coffee production in Costa Rica by the second part of the XXI century.

Since coffee agriculture is a relevant economic activity in rural intermediate elevations of Costa Rica (Instituto del Café de Costa Rica [ICAFE], 2015), it is important to note that potential changes in the optimal areas for coffee production may impact the life style of the people living in those areas. For all future scenarios, the central zone of Costa Rica showed a high probability to continue sustaining the crop (Figure 2). Interestingly, the same pattern was observed in areas of the country where coffee production is already an important agricultural activity (e.g., counties of Tarrazú, Naranjo and Poás). This is relevant because those areas are strategic for the international trade of Costa Rican coffee.

It is likely anyway, that in the predicted unsuitable areas farmers will continue to grow coffee, even if the bioclimatic conditions do not favor its production. This can be related to the cultural value of coffee in the collective memory of Costa Ricans since this crop was an engine in the construction of the national identity (Peters, 2001). For instance, despite that coffee represents the single largest extension of any agricultural crop (Instituto Nacional de Estadística y Censos [INEC], 2015), coffee exports only represented 0.34% of the gross domestic production (GDP) and 2.46% of the total revenue from exported goods in 2014 (ICAFE, 2015). This low relevance of coffee for the overall national economy is yet important for the economy of local farmers and their families, which farms represented in the same year about a quarter of the total nationally (INEC, 2015).

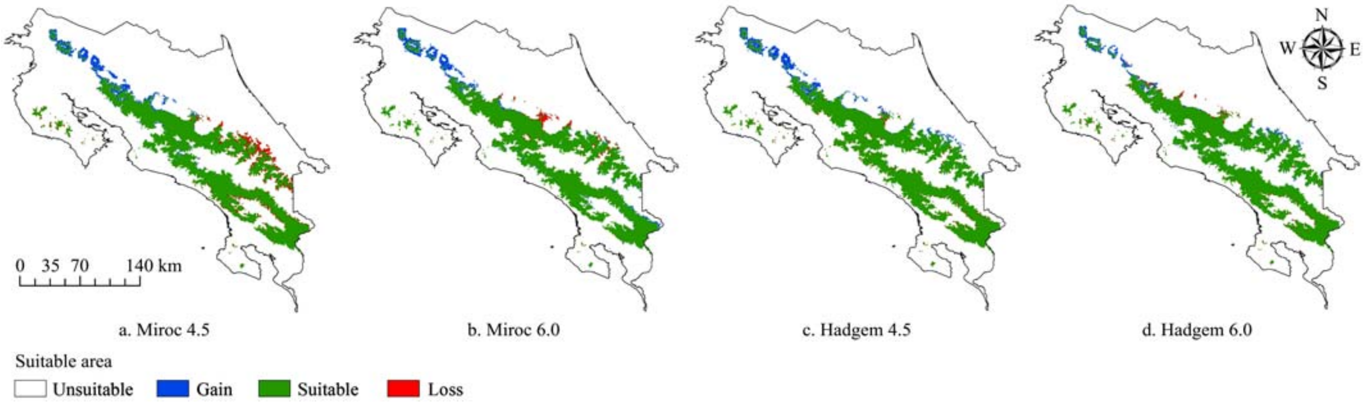
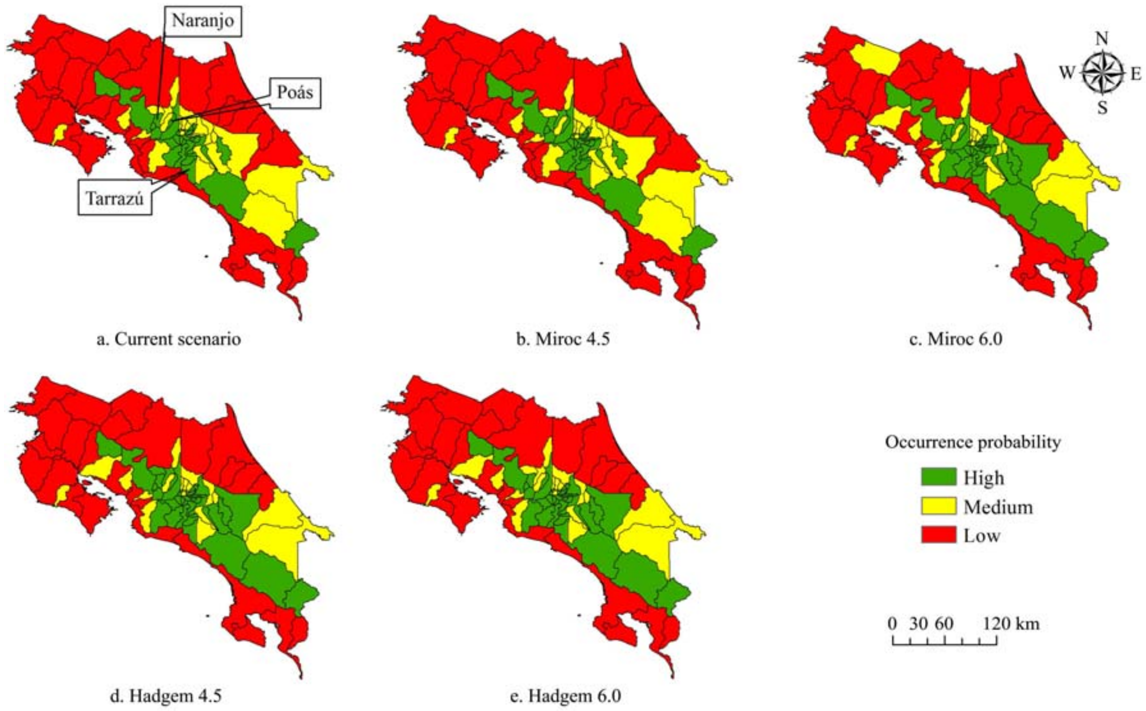


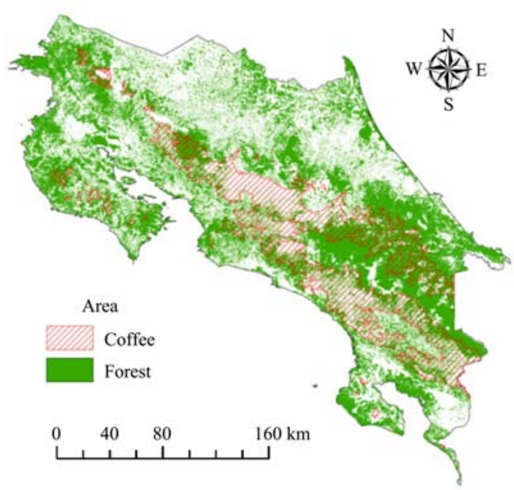
Figure 1 Maps of Costa Rica showing the gain and loss areas for the suitability of coffee production according to the 2070 scenarios evaluated in the present investigation



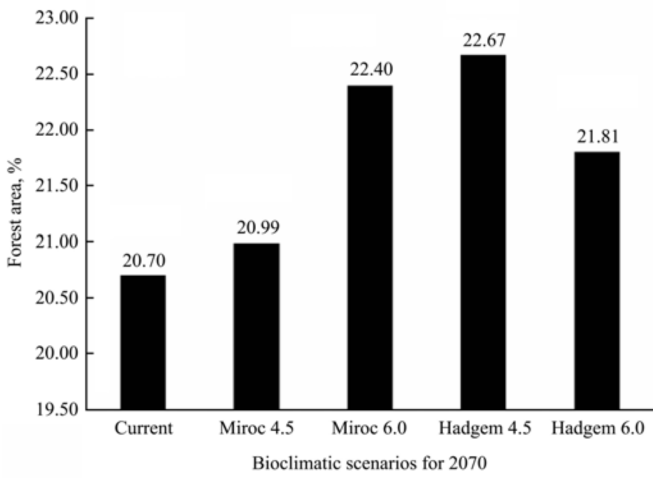
Note: Administrative divisions at the county-equivalent level are shown and three important counties for coffee production are labeled in the upper left.

Figure 2 Maps of Costa Rica showing the probability of occurrence for coffee production according with current scenario, Miroc 4.5, Miroc 6.0, Hadgem 4.5 and Hadgem 6.0.

As observed in Figure 3, all the models studied during this investigation showed an increase in the overlap between suitable areas for coffee production and the current forest cover in Costa Rica. In this sense, it is important to consider the environmental viability of future coffee production because most of the higher elevation lands, where the overlap occurs in our models, provide a series of key ecosystem services and serve as a shelter to preserve the biodiversity of the country (Laderach et al., 2011). For instance, the surroundings of the capital city, where coffee production has been a key economic activity over the years, have been transformed into suburban areas. This kind of situation will surely continue to take place in detriment of the suitable areas for coffee production, which in turn, may generate pressure to enter the protected higher-elevation national forests. This is problematic since water quality and quantity in the metropolitan area of Costa Rica depend on the protection of these forest areas, putting at risk the long term wellbeing of over 60% of the country population.



a. Coffee production areas and forest cover



b. Percentage of overlap calculated

Figure 3 Map of Costa Rica showing the current overlap between coffee production areas and forest cover and percentage of overlap calculated for all four climate change scenarios evaluated herein

An additional source of conflict might be the protection of forests in private lands in an economically efficient manner. Since 1997, Costa Rica established the Program of Payment for Environmental Services (PPES), the first of its kind in a developing country. The PPES has been a key strategy to deter deforestation over the last two decades. However, in a situation of increasing competition with agricultural production, the opportunity cost for such forest protection is making it progressively more difficult to manage forests along with their associated goods and services (Murillo et al., 2014). In this manner, the results presented herein are helpful to inform the different stakeholders of conservation production sectors about the potential land use changes associated with new climate scenarios.

Finally, the ecological modeling developed in this study has great relevance for the coffee sector of Costa Rica, since it shows potential suitable areas for the production of such product under the framework of climate change. The latter is relevant in the successful adaptation of the agricultural sector to different climate change-driven pressures. In this manner, the use of tools such as the ones used in this study along with the generation of public policies might provide effective strategies for the Costa Rican coffee supply chain to prepare for such expected changes. These types of approaches could sustain the relevance of the coffee sector for the local economy in rural areas and maintain the cultural importance of the product in Costa Rica.

4 Conclusions

It is very likely, according to the approach and models used in this investigation, that the Costa Rican highlands will continue to be suitable areas for coffee production in the future. Our models showed however, a series of expansions and contractions that may pose challenges to local populations that rely on coffee for income generation. The net change of the potential area for coffee production was predicted to be positive, and protected areas in the higher elevations seemed to be the target locations for a potential expansion. The type of modeling used in this study may provide relevant elements for the implementation of management and adaptation strategies of current and future land use arrangements in Costa Rica. In the case of coffee, such a situation can derive in the maintenance of the sector given its historical and cultural importance, but in the case of highland forests, it may trigger a sign of attention due their increasing risk in the future, a public-policy challenging endeavor. In either way, the approach used in the present investigation may be used for the correct planning of coffee-related activities and the promotion of sustainable coffee practices.

References

Baldwin, R. A. 2009. Use of maximum entropy modeling in wildlife research. *Entropy*, 11(4): 854–866.

Benton, J. 2012. *Plant Nutrition and Soil Fertility Manual. Second Edition*. Florida: CRC Press.

Betts, R. A., N. Golding, P. Gonzalez, J. Gornall, R. Kahana, G. Kay, L. Mitchell, and A. Wiltshire. 2015. Climate and land use change impacts on global terrestrial ecosystems and river flows in the HadGEM2-ES Earth system model using the representative concentration pathways. *Biogeosciences*, 12(5): 1317–1338.

Collins, M., R. Knutti, J. Arblaste, J. L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W. J. Gutowskiet, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A. J. Weaver, and M. F. Wehneral. 2013. Long-term climate change: projections, commitments and irreversibility. In *Climate Change 2013: The Physical Science Basis*, eds. T. F. Stocker, D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, ch. 12, 1029–1136. Cambridge, United Kingdom and New York, USA: Cambridge University Press.

Davis, A. P., T. W. Gole, S. Baena, and J. Moat. 2012. The impact of climate change on indigenous arabica coffee (*Coffea arabica*): predicting future trends and identifying Priorities. *PloS One*, 7(11): e47981.

Estes, L. D., B. A. Bradley, H. Beukes, D. G. Hole, M. Lau, M. G. Oppenheimer, R. Schulze, M. A. Tadross, and W. R. Turner. 2013. Comparing mechanistic and empirical model projections of crop suitability and productivity: implications for ecological forecasting. *Global Ecology and Biogeography*, 22(8): 1007–1018.

Evangelista, P., N. Young, and J. Burnett. 2013. How will climate change spatially affect agriculture production in Ethiopia? Case studies of important cereal crops. *Climatic Change*, 119(3-4): 855–873.

Food and Agriculture Organization. 2016. *State of the World's Forests*. Rome: FAO.

Instituto del Café de Costa Rica. 2015. *Informe Sobre La Actividad Cafetalera De Costa Rica*. Heredia, CR: ICAFE.

Instituto Nacional de Estadística y Censos. 2015. *Resultados Generales VI Censo Nacional Agropecuario*. San José, CR: INEC.

Intergovernmental Panel on Climate Change. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland: IPCC.

Khanum, R., A. S. Mumtaz, and S. Kumar. 2013. Predicting impacts of climate change on medicinal asclepiads of Pakistan using Maxent modeling. *Acta Oecologica*, 49: 23–31.

Laderach, P., M. Lundy, A. Jarvis, J. Ramirez, E. P. Portilla, K. Schepp, and A. Eitzinger. 2011. Predicted impact of climate change on coffee supply chains. In *The Economic, Social and Political Elements of Climate Change*, ed. W. L. Filho, ch. 42, 703–723. Berlin, Heidelberg: Springer Berlin Heidelberg.

Loarie, S. R., B. E. Carter, K. Hayhoe, S. McMahon, R. Moe, C. A. Knight, and D. D. Ackerly. 2008. Climate change and the future of California's endemic flora. *PloS One*, 3(6): e2502.

Murillo, S. A. M., J. P. P. Castillo, and M. E. H. Ugalde. 2014. Assessment of environmental payments on indigenous territories: the case of Cabecar-Talamanca, Costa Rica. *Ecosystem Services*, 8(1): 35–43.

Nygaard. L. P. 2015. *Climate Change in the United States: Benefits of Global Action*. Washington, D.C.: United States Environmental Protection Agency.

Ovalle-Rivera, O., P. Läderach, C. Bunn, M. Obersteiner, and G. Schroth. 2015. Projected shifts in Coffea arabica suitability among major global producing regions due to climate change. *PloS One*, 10(4): e0124155.

Peters, G. S. 2001. *Café de Costa Rica: un viaje a lo largo de su historia*. (*No. 633.73 P481 c*). San José, CR: Instituto del Café.

Porter, J. R., and M. A. Semenov. 2005. Crop responses to climatic variation. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 360(1463): 2021–2035.

Rosenzweig, C. 2011. Climate change and agriculture. In *Extreme Environmental Events: Complexity in Forecasting and Early Warning*, ed. R. A. Meyers, 31–41. New York, NY: Springer New York.

Smith, P., and J. E. Olesen. 2010. Synergies between the mitigation of, and adaptation to, climate change in agriculture. *The Journal of Agricultural Science*, 148(5): 543–552.

Streck, N. A. 2005. Climate change and agroecosystems: the effect of elevated atmospheric CO2 and temperature on crop growth, development, and yield. *Ciência Rural*, 35(3): 730–740.

Van Gils, H., E. Westinga, M. Carafa, A. Antonucci, and G. Ciaschetti. 2014. Where the bears roam in Majella National Park, Italy. *Journal for Nature Conservation*, 22(1): 23–34.

Van Vuuren, D. P. V., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J. F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. J. Smith, and S. K. Rose. 2011. The representative concentration pathways: an overview. *Climatic Change*, 109(1): 5–31.

Wollni, M., and M. Zeller. 2007. Do farmers benefit from participating in specialty markets and cooperatives? The case of coffee marketing in Costa Rica. *Agricultural Economics*, 37(2-3): 243–248.