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Analysis

Climate change driven shifts in the extent and location of areas suitable for export banana production

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ABSTRACT

Species distribution modeling (SDM) is used to map areas predicted to be suitable for commercial banana production in Central and northwestern South America. Using the downscaled climate projections for 2060 from seven leading global climate models we then predict the geographical shifts in areas suitable for banana production. We repeat this process for conventional and organic banana production. Approximately half of the existing conventional plantations included in the analysis are located in areas predicted to become unsuitable for banana production by 2060. The overall extent of areas suitable for conventional banana cultivation is predicted to decrease by 19%, but all countries are predicted to maintain some suitable areas. The extent of areas suitable for organic banana cultivation is predicted to nearly double due primarily to climatic drying. Several countries (e.g., Colombia and Honduras) are predicted to experience large net decreases in the extent of areas suitable for banana cultivation. Some countries (e.g., Mexico) are predicted to experience large net increases in the extent of suitable areas. The shifts in the location of areas that will be suitable for banana cultivation are predicted to occur mainly within areas outside of protected areas and that are already under agricultural production.

1. Introduction

Large expanses of lowland tropical forests have already been converted to agriculture (Wiley, 2008), causing widespread losses of biodiversity and carbon stores (Brook et al., 2003; Defries et al., 2002; Turner, 1996). Conversion of tropical forests to agriculture is ongoing, and is currently the leading driver of tropical deforestation and land conversion worldwide (Achard et al., 2002; Mayaux et al., 2005; Veldkamp et al., 1992). Due to increasing population sizes and affluence, the extent of land areas converted to agriculture is predicted to increase by approximately 18% by 2050. This equates to a loss of one billion ha of natural habitats — an area larger than the United States — in less than 50 years (Tilman et al., 2001).

Future agricultural production will depend on many complex factors. These include required increases in crop production to meet growing demand, increasing land scarcity, globalization (Lambin and Meyfriodt, 2010), competing conservation needs, and global climate change (Fischer et al., 2005; Iglesias et al., 2011; IPCC, 2001). Climate change can potentially affect agriculture in many ways, for example by driving geographic shifts in the suitability and yields of key crop species (Jones and Thornton, 2003; Tubiello et al., 2002) and varieties (White et al., 2006), as well as geographic shifts in the occurrence of the diseases and pests that affect crops (Cintra de Jesus et al., 2008). If the potential effects of climate change are not accounted for through appropriate shifts in farming techniques, changes in the locations where different crop species and varieties are planted, and/or advances in agricultural technology such as abiotic-stress resilient genetically-modified crops (Hu et al., 2006; Vij and Tyagi, 2007), decreasing yields will lead to heightened risk of food insecurity for large portions of the global population (Nelson et al., 2009). Although impacts of global climate change are expected to strongly affect the subsistence, or smallholder, farmers found predominantly in developing countries (Morton, 2007), large-scale multinational agricultural industries will also be affected.

Adaptation of large-scale agricultural systems to climate change can potentially be addressed through a variety of strategies including the movement of crop production systems to follow suitable climatic conditions (Howden et al., 2007; Iglesias et al., 2011; Smit and Skinner, 2002). As such, it is essential that we develop models which can be used to predict how the locations and extents of areas suitable for the production of focal crop species will change under future climate change scenarios.

One tool that can potentially be used to help predict the locations of areas that will be suitable for the cultivation of specific crop species in the future is species distribution models (SDMs). SDMs are a general suite of models that relate the locations of a species' known occurrences to sets of underlying environmental and/or climatic variables (e.g., mean annual temperature, annual precipitation, seasonality, slope, etc.) (Pearson and Dawson, 2003; Phillips et al., 2004). The probability of occurrence in relation to the environmental variables can then

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be interpolated and extrapolated across the broader landscape to produce maps of the species' predicted potential geographic distributions (Anderson and Martınez-Meyer, 2004). Due to their power and relative ease of use, SDMs have become one of the most widely-used tools in conservation biology, biogeography, and ecology (Franklin, 2009; Richardson and Whittaker, 2010). For example, SDMs are used to generate predictions of where invasive species may occur under present climatic conditions (Ficetola et al., 2007; Giovanelli et al., 2008; Guisan and Thuiller, 2005; Peterson and Vieglais, 2001) as well as shifts in species' geographic distributions under future climatic change scenarios (Feeley and Silman, 2010; Hijman and Grahams, 2006; Kearney et al., 2010).

Despite their wide application in ecological and biogeographic studies, SDMs have rarely been applied to agricultural systems or crop species (Beck, 2012; Beck and Sieber, 2010; Bradley et al., 2012; Hijman and Grahams, 2006; Trnka et al., 2007). Instead, process based models (e.g., the International Model for Policy Analysis of Agricultural Commodities and Trade [IMPACT]; Rosegrant and The IMPACT Development Team, 2012), spatial analog models (e.g., the Future Agricultural Resource Model [FARM]; Darwin et al., 1996, 1995), and integrated assessment models (e.g., the Agro-Ecological Zone model [AEZ]; IIASA/FAO, 2012), have been more extensively applied to model current and future crop production scenarios. SDMs differ from these models in that they focus solely on geographic distributions and thus require relatively little system-specific information other than the location of existing production areas and underlying environmental variables. Perhaps one reason that the agricultural community has been slow to adapt SDMs is the perception that SDMs are limited in their ability to accurately predict the distributions of areas suitable for agricultural crop species since the environmental conditions on farms can be modified through active management practices such as irrigation, thereby enabling crop species to grow in areas that are unsuitable based on ambient climate alone (Jensen, 2002; Wittwer and Castilla, 1995). For example, most crop species can theoretically be grown almost anywhere on the planet given sufficient environmental controls, such as externally supplied light, heat, irrigation, and soil amendments. However, these controls involve economic costs which are likely to increase in direct relation to the degree to which the natural ambient environment is unsuitable. Thus, while the potential distributions of many crop species are theoretically boundless, SDMs can be used to model the potential economically-viable distributions of focal crop species. For example, if a crop species is not currently grown in dry areas, then a safe assumption may be that it will not be economically viable to grow that species in similarly dry areas in the future even if it could potentially be grown there under intensive irrigation practices. Other geographic variables that are important in defining economic limitations on production, such as distance to market and/or transportation centers, can also be incorporated into SDMs as additional "environmental" variables, thereby potentially increasing the ability of SDMs to predict suitability of areas for crop production.

In this study, we use SDMs to predict the locations of areas that are currently suitable for commercial banana production in Mexico, Central America, and western South America (Colombia, Ecuador, and Peru), as well as the locations of areas that will be suitable for banana production in the future (the 2060s). We focus specifically on export banana plantations, typically grown by large multinational companies in monoculture plantation settings, as they are one of the most economically important food crop systems in the world and are of heightened conservation concern since they are grown exclusively in the tropics (see discussion on bananas below). More specifically, we use the MAXENT SDM to produce current and future suitability maps for conventional banana plantation production as based on a sample of existing plantation locations, select climatic and economic variables, and spatially explicit spatially explicit general circulation models (GCMs). We then examine the predicted current and future suitability maps in relation to the distribution of different land cover classes and protected areas in order to investigate how climate change and food production needs may intersect with conservation priorities. Finally, a similar SDM analysis is performed to predict areas suitable for the production of organic bananas under current and future conditions.

2. Methods

2.1. Bananas (*Musa acuminata* Colla)

Bananas (*M. acuminata* Colla) are the developing world's fourth most valuable food crop, following only rice, wheat, and maize in terms of gross value of annual production (Frison et al., 2004), and are the 12th most globally-important plant crop by value and quantity (FAOSTAT, 2010). Globally, over 100 Mt of bananas are grown annually on an estimated area of approximately 5 million ha, with production concentrated in Africa, Asia, India, the Caribbean, and Latin America (FAOSTAT, 2010). Furthermore, bananas are a leading tropical agricultural export crop with export volumes of > 15 Mt per year and an annual export value of approximately $5 billion per year. Indeed, for many decades, bananas have been the leading fresh fruit imported into the USA (FAO, 2003a; Huang and Huang, 2007). Nearly all of internationally traded bananas are the Cavendish variety (Robinson and Sauco, 2010).

Overall, over 80% of banana exports come from Latin America where banana production is an important component of local and national economies (Evans and Ballen, 2012; FAO, 2009; Robinson and Sauco, 2010). In 2010, Ecuador was the world's largest exporter of bananas, with an annual export production exceeding 5 Mt and $2 billion in export value. This is nearly three times the quantity produced by Costa Rica, which ranks as the world's second largest exporter, followed by Colombia and the Philippines (FAOSTAT, 2010). In contrast to most other export countries, farms in Ecuador are relatively small-scale; most farms are in the range of 10–50 ha and are owned and managed by local producers that sell to intermediaries or international companies (UNEP, 2002; Wunder, 2001). In other Latin American countries, export bananas are produced primarily on large-scale plantations (commonly exceeding 1000 ha) that are controlled by private producers or large multinational companies (Robinson and Sauco, 2010; Wiley, 2008).

Although bananas are often grown by smallholder farmers in intercropping formats for consumption at home or in local markets, export banana plantations, especially conventional plantations, are primarily monocrop systems. Conventional export plantations use large amounts of nutrient inputs and agrochemicals to control diseases and pests. On average, almost 1/3 of production costs in commercial plantations are allocated to fungicidal applications to control the leaf fungus Black Sigatoka (*Micosphaerella fijiensis*) which is considered to be the most damaging and costly threat to bananas (Marin et al., 2003). While organic banana production offers an alternative, less chemical intensive, production method, they currently account for only ~1% of world trade (FAO, 2003b) and approximately 3% of the total volume of fresh banana imports to the USA (Evans and Ballen, 2012). The Dominican Republic is the largest producer of organic bananas with an annual production of $200 million in 2011 (Elnuevodiario, 2012), exceeding its conventional exports. This accounts for 40% of the global organic market volume (FAO, 2003b; Frundt, 2009), with 90% of the country's exports going to Europe (Elnuevodiario, 2012). The second largest global supplier of organic bananas is Ecuador, where output has grown at high rates (Evans and Ballen, 2012; FAO, 2003b). Likewise, Peru is rapidly expanding its production of organic bananas: exports grew significantly between 2000 and 2007, in terms of both net value (from $264,000 to $31 million) and volume (from 856 tonnes to 64,586 tonnes) (COPLA, 2009). Other major suppliers of organic bananas are Mexico, Colombia, Honduras, Guatemala and the Canary Islands (Spain) (FAO, 2003b). Previous studies have