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Historical climate trends, deforestation, and maize and bean yields in Nicaragua

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ABSTRACT

Nicaragua has already experienced substantial climate change, in part due to a loss of one half of its forest cover in the last half-century. In this study, we assess the extent to which historical climate trends have contributed to stagnating yields for maize (*Zea mays*) and bean (*Phaseolus vulgaris*), the two main staple crops in the country. We first analyze 40 years of historical weather data throughout Nicaragua to estimate trends, and assess the extent to which these trends correlate with spatial deforestation patterns. Then, we create a regression model linking department-level maize and bean yields with seasonal weather conditions, and use the model to estimate the impact of historical climate trends on yields. Regressions are run for yields on both harvested and sown area, with the latter accounting for the effect of complete crop losses. Results confirm strong warming trends throughout the country, with daytime temperatures in deforested areas warming at more than double the rate of global averages in the tropics. Decreases in rainfall frequency are also seen almost everywhere, along with an earlier end to the rainy season. Regression model results show, as expected, that red bean is a highly temperature-sensitive crop, and that maize is more water-limited than bean due to its longer seasonal duration. Warming temperatures and less frequent rainfall have led to drought-related losses for both crops in the main commercial production areas, while heavier rains at planting and harvest have also negatively affected yields, especially for bean. Moreover, reduced precipitation in December and January has negatively impacted production for bean in the commercially important apante, or dry season, on the humid Atlantic side of the country. In these areas, however, substantial model uncertainty remains for maize, with an alternative model formulation showing substantial benefits from drier and sunnier conditions. At an annual, national scale, beans have been more affected by climate trends since 1970 than maize, with −5% yield declines per decade on harvested area for bean and −4% for maize, and −12% and −7% yield declines respectively on sown area (with the alternative model showing gains for maize). Climate adaptation responses include government efforts to limit bean exports to control consumer prices, a switch from red to black bean for commercial sales and export, and area expansion and migration for bean in order to maintain production levels.

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1. Introduction

Despite technological advances around the world, agricultural production still remains highly dependent on the weather. In addition to the risk of crop losses from year-to-year weather variability and extreme events, a non-stationary climate with slowly shifting weather patterns (i.e. climate change) requires proactive planning, given that the long-term suitability of growing crops in certain locations will likely change. However, future projections of climate change impacts on agriculture have multiple layers of uncertainty which complicate efforts for proactive planning (Challinor et al., 2009; Hoffmann and Rath, 2013; Koehler et al., 2013; Vermeulen et al., 2013). One approach that may help to better understand the mechanisms of climate change impacts on agriculture is to look backwards in time for a certain region and set of crops, in order to understand how climate trends have already impacted yields to date, and how farmers have started to confront these impacts.

This study focuses on agricultural production in Nicaragua, a tropical country in Central America that relies mainly on rain-fed

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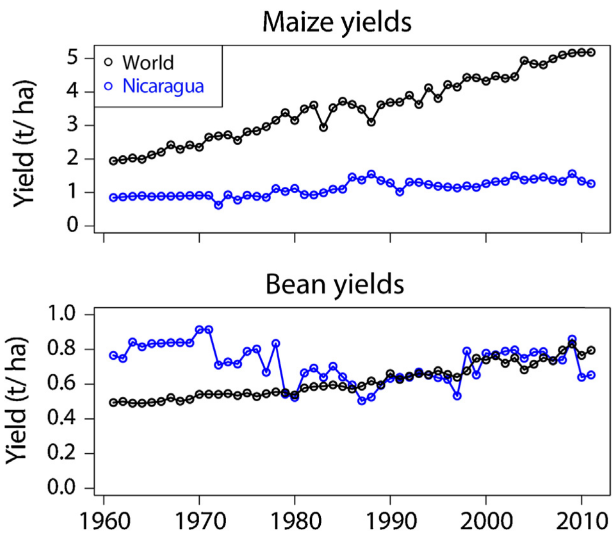

Fig. 1. Maize and bean yields in Nicaragua from 1960 to the present, as compared to world averages.
Source: FAOSTAT.

production on small farms to grow two key staple crops: maize (*Zea mays*) and bean (*Phaseolus vulgaris*). Maize and bean are grown both for home consumption and commercial sales, with roughly a fifth of national bean production exported to countries like El Salvador, Venezuela and the United States (Food and Agriculture Organization, 2012).

Nicaraguan maize and bean yields are low compared to world averages, and yield growth has also been relatively stagnant in the last half-century, especially for bean (Fig. 1). Maize yields have nearly doubled since 1960, although they were still less than a third of world averages in the 2000s. In contrast, bean yields, while closer to world averages in recent years, have actually fallen since the 1960s! Yield stagnation in Nicaragua has a number of causes which include political instability in the last half-century (wars and trade embargoes), natural disasters (both earthquakes and extreme climate events like hurricanes and droughts) (Kinzer, 2007; LeoGrande, 1996; Pielke et al., 2003), declining soil fertility (Stoorvogel and Smaling, 1998), and limited access to improved seed and inputs (Food and Agriculture Organization, 2012). Today, between a third and a half of Nicaraguan farmers use chemical fertilizers (CENAGRO, 2010), especially for maize production. However, input use still remains low, mechanization is almost non-existent, and less than 3% of farms in the country are currently equipped for irrigation (Food and Agriculture Organization, 2012). To cope with stagnating yields, aggressive expansion of the agricultural frontier toward the Atlantic Coast has helped to increase production, with a loss of more than a third of Nicaraguan forest cover since 1980 (Redo et al., 2012, Fig. 2).

Observational studies have demonstrated ongoing climate change in Central America in the last half century, principally warming, more intense and less frequent precipitation (Aguilar et al., 2005) and changes in the timing of the rainy season (Ray, 2013), related to both global greenhouse-gas induced warming and regional deforestation. In rain-fed farming systems, farmers have always faced production risk due to inter-annual variability in precipitation, in total volume as well as in timing, frequency and intensity. However, increasingly erratic and unpredictable rains at the start of the season are affecting the ability of farmers to determine appropriate planting dates and manage risk (Eakin, 1999; Simelton et al., 2013). Moreover, as warming progresses and rain events become less frequent, evaporative losses are increasing and soil moisture is declining, which is consistent with anecdotal reports of increasing drought by many Nicaraguan farmers.

The yields of both maize and bean are temperature-sensitive (Hatfield et al., 2011) through heat effects on crop duration, transpiration, and flowering and grain formation. High night temperatures are thought to be especially harmful for bean (Konsens et al., 1991), through negative effects on pod production. Also, compared to maize, bean has a lower temperature optimum (Hatfield et al., 2011; Prasad et al., 2002), and is therefore already grown at high altitudes and cooler temperatures within Nicaragua (Table 1). In particular, further warming is expected to substantially shrink suitability for bean cultivation within Central America without aggressive adaptation and crop breeding efforts to improve heat and drought-tolerance in the germplasm (Schmidt et al., 2012). In contrast, maize, with a higher temperature optimum, is grown on almost all arable land in Nicaragua. However, some studies have also suggested large projected impacts of climate change on maize, principally under rain-fed conditions (Jones and Thornton, 2003; Lobell et al., 2011a) and especially with low soil fertility (Schmidt et al., 2012), as is typical in Nicaragua.

In order to better understand yield stagnation and help guide future climate adaptation efforts for maize and bean production in Nicaragua, this study looks retrospectively to ask the question: to what extent have long-term climatic trends in recent decades retarded yield growth for maize and bean in Nicaragua? While acknowledging that yields are affected by many other non-climatic factors, this study helps to assess the extent to which climatic trends are stressing efforts to intensify production and increase yields. This study is complementary to the forward-looking Tortillas on the Roaster study (Schmidt et al., 2012) which analyzed future climate change impacts on maize and bean production in four Central American countries. However, this retrospective analysis represents the first attempt in the literature (that we are aware of) to identify the historical impact of climate trends on staple crop production in Central America, using similar methods as other studies that have focused on the United States, China and the globe (Lobell et al., 2011a; Maltais-Landry and Lobell, 2012; Tao et al., 2012).

The ultimate objective of this study is to assess the historical impact of climate trends on maize and bean yields in Nicaragua. Therefore, we perform three sequential analyses to arrive at this result. We first analyze a historical meteorological dataset from weather stations throughout the country to assess trends since 1970 in various seasonal weather variables. Second, we create a statistical model linking department-level maize and bean yields in the 2000s with reconstructed weather data in the principal growing areas for each crop. After interpreting estimated model coefficients, we finally use the model to back-cast the impact of historical climate trends on yields, allowing us to identify departments and growing seasons where farmers have likely experienced the most climatic stress on production. This work sets the stage for future work aimed at evaluating ongoing or future adaptation measures that could be adopted by farmers in these regions.

2. Methods and data sources

2.1. Maize and bean cultivation areas and growing seasons

Nicaragua can be divided into three principal climatic zones: the hot, dry Pacific coast, the cooler dry cultivation areas in the Central highlands, and the hot, humid, rainy and mostly forested Atlantic side (Figs. 2 and 3). The growing seasons in the Pacific and central zones typically follow the seasonal rains in May–July (referred to as the *primera*) and September–November (or the *postrera*), while in the rainier eastern half of the country, a 3rd crop is also grown in the dry season from December to March (the *apante*; Fig. 3).

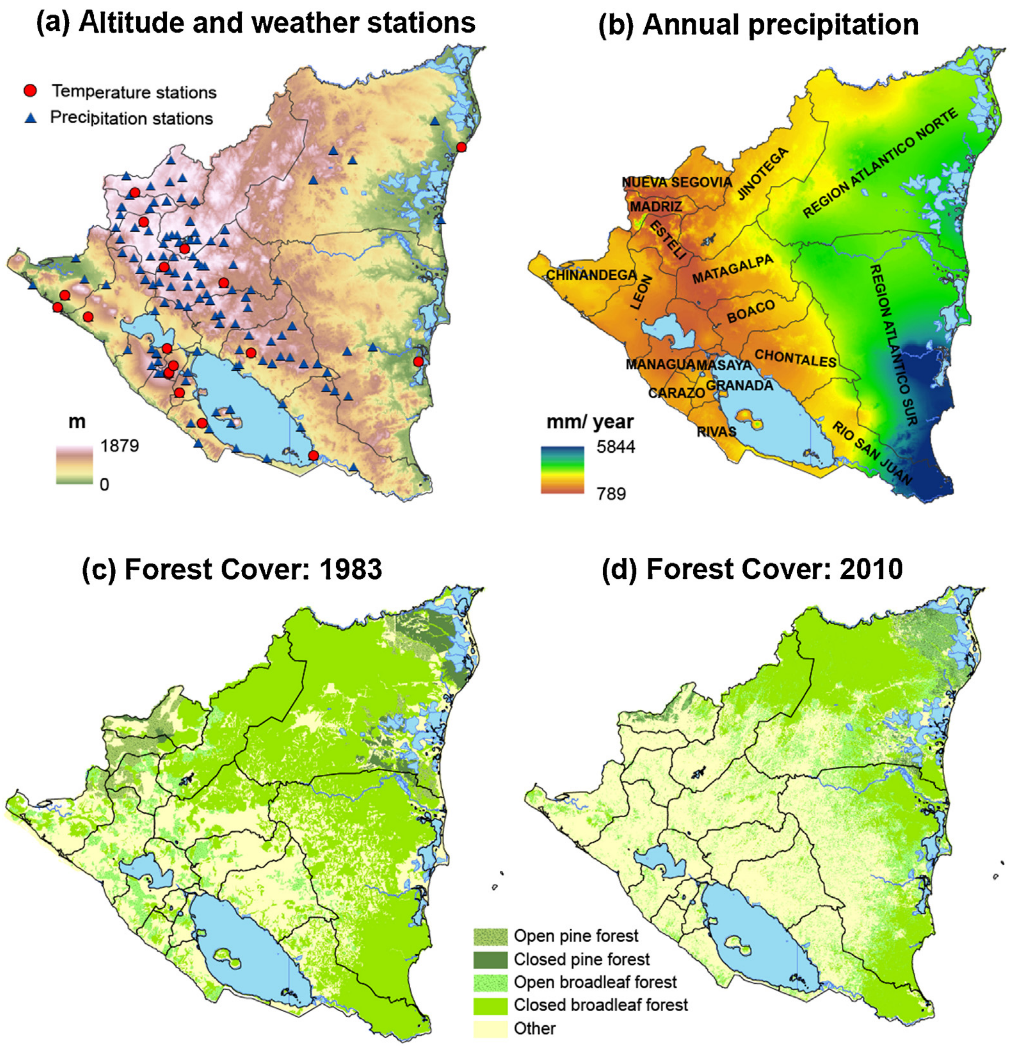

Fig. 2. (a) Altitude (m) with locations of temperature and precipitation weather stations. (b) Annual precipitation (mm/year). (c) Forest cover in 1983. (d) Forest cover in 2010. (Source: MARENA for forest cover, WorldClim for precipitation). Departmental boundaries are included on all maps, with names in (b).

The primary growing season for maize is in the primera, or 1st rainy season, for which planting occurs in almost all 17 departments in the country (Fig. 4). Bean production is highest in the apante, or dry season, followed by the postrera, or 2nd rainy season, with distinct growing areas for each season (Table 1, Fig. 4). Bean cultivation areas in the primera and postrera are centered in the northern Central highlands, and apante production for both crops takes place in the wetter, eastern half of the country. Planting occurs in all three seasons in only a limited number of departments, especially for bean (Fig. 4).

2.2. Regression model formulation

We create regression models pairing departmental yields with average weather data in cultivation areas using the model formulation defined here:

$$\begin{aligned}\log \mathit{Yield} = {} & \mathit{Average\ \ temperature} + \mathit{Diurnal\ \ temperature\ \ range} \\ & + \mathit{Planting\ \ precipitation} + \mathit{Seasonal\ \ precpitation} \\ & + \mathit{Seasonal\ \ precipitation}^2 + \mathit{Harvest\ \ precipitation} \\ & + \mathit{Dry\ \ days} + \mathit{Year} + \mathit{Department} + \varepsilon\end{aligned}$$

Using log yield as the response variable allows for the interpretation of model results as changes in yield relative to mean values. Estimating relative yield changes makes sense when average yields vary substantially across departments, as is the case here (Figure S1). We also create separate regression models with the two definitions of yield, dividing production by first, harvested area and second, sown area.

$$y_h = \frac{\mathit{production}}{\mathit{harvested\ \ area}}$$

$$y_s = \frac{\mathit{production}}{\mathit{sown\ \ area}}$$

Harvested area can be substantially less than sown area in any given season, due to crop losses from pests, disease or extreme weather. Therefore, the two types of yields calculated here alternately exclude and include the effects of these losses. We also run separate models for maize and bean, assuming that these two crops have structural differences in their response to weather, resulting in a total of four models for a given formulation.

The weather variables included in the models are defined for all departments using the sowing and harvest dates in Table 1. We assume fixed crop calendars here, although in reality, typical sowing dates vary by region of the country, and actual sowing dates vary inter-annually with the appearance of the rains. The use of fixed crop calendars likely contributes uncertainty to the regression results, particularly for the precipitation variables.

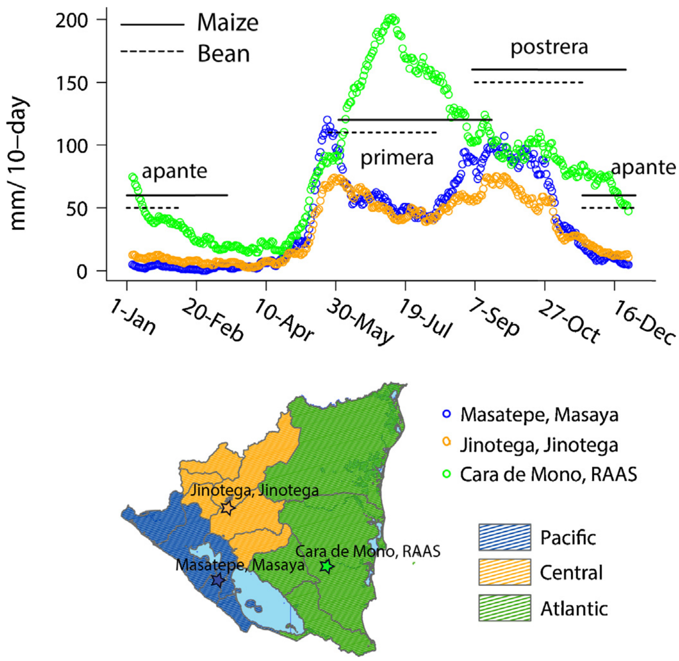

Fig. 3. Typical seasonal precipitation for weather stations in the three climatic zones of Nicaragua (Masatepe, Masaya in the Pacific, Jinotega, Jinotega in the Central zone, and Cara de Mono, RAAS in the Atlantic zone). Daily precipitation values represent 10-day moving sums, averaged from 1970 to 2007.

The two temperature variables, daily average temperature and diurnal temperature range (DTR, i.e. daily maximum temperature–daily minimum temperature) are both calculated as seasonal averages (in °C) from sowing to harvest. We also created separate temperature variables by growth stages, as in previous studies (Gourdji et al., 2013). However, we included this as a sensitivity test in the supplementary material given that these results are likely to be less reliable due to uncertainty in estimating the timing of the growth stages. Also, most temperature variability in the tropics is due to altitudinal gradients, with little temporal variability throughout the year.

For the precipitation variables (in mm), we divide the season into three time periods, including some weeks before sowing and after harvest. For the first and third time periods, we calculate planting and harvest precipitation by summing rainfall for 2 weeks before and after the planting and harvest dates. For the middle period, we include accumulated precipitation from 2 weeks after planting to 80% of the crop duration after sowing (just before physiological maturity, Table 1), which we refer to as seasonal precipitation. This is the time when sufficient rainfall is especially important for crop establishment and growth (Instituto Nicaraguense de Tecnologia Agropecuaria, 2012). For seasonal precipitation, we also include a quadratic term to account for non-linear relationships, and the differential response to precipitation changes in dry vs. wet regions of the country. Given that not just the total volume of precipitation is important, but also its timing and intensity (Barron et al., 2003; Biazin et al., 2012), we define a variable with the total number of dry days from planting to harvest, as we expect long dry spells to be associated with drought-related yield declines and losses.

In addition to the weather variables, we also include a year term and department fixed effects in the statistical models. The year term attempts to capture technological progress in yields over this short period (as in Lobell et al., 2011b), while department fixed effects represent estimated averages of relatively static soil and management differences that vary spatially across the country.

We also use an alternative model formulation with interaction terms as a sensitivity test, given that all of the weather variables are correlated and have mechanistic links between them, such as

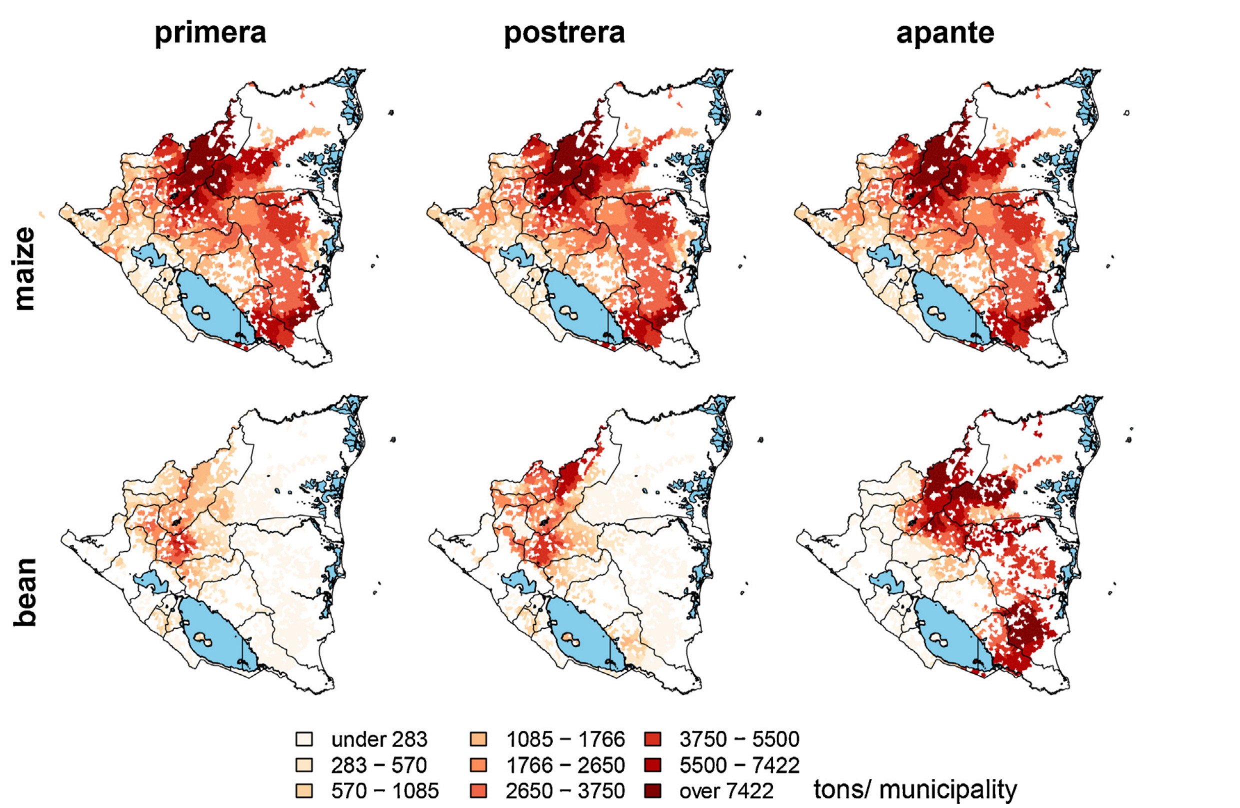

Fig. 4. Growing area maps for maize and bean by season. Non-white values represent municipal-level production (tons/municipality) projected to the census unit scale.

Table 1
Sowing and harvest dates, and length of crop cycle, for maize and bean as specified in the statistical models for the three growing seasons. Also shown are national yield (on sown area), production, altitude and seasonal precipitation and temperature averaged across cultivation areas from 2000 to 2007 for each crop and season, with inter-annual standard deviations in parentheses.

	Sowing date	Harvest date	Crop duration (days)	Yield (t/ha)	Production (000s t)	Altitude (m)	Seasonal precipitation (mm)	Seasonal temperature (°C)
Maize								
Primera	Jun. 1	Sep. 19	110	1.36 (0.15)	296 (52)	464	592 (54)	25.7 (0.2)
Postrera	Sep. 5	Dec. 24	110	1.66 (0.24)	165 (37)	370	452 (105)	25.5 (0.3)
Apante	Nov. 23	Mar. 13	110	0.87 (0.07)	63 (10)	203	240 (65)	25.4 (0.4)
Bean								
Primera	May 25	Aug. 10	77	0.62 (0.12)	36 (8)	644	287 (74)	25.0 (0.2)
Postrera	Sep. 7	Nov. 23	77	0.67 (0.12)	57 (14)	632	326 (98)	24.6 (0.4)
Apante	Nov. 23	Feb. 8	77	0.86 (0.06)	109 (18)	289	135 (30)	24.1 (0.3)

more water loss at high temperatures. Therefore, for our alternative models, we start with the same weather variables and then add in a number of interaction terms: seasonal precipitation (both linear and quadratic) multiplied by dry days, and average temperature multiplied by dry days. The alternative model formulation is defined as:

$$\begin{aligned}\log Yield = {} & Average\quad temperature + Diurnal\quad temperature\quad range \\ & + Planting\quad precipitation + Seasonal\quad precpitation \\ & + Seasonal\quad precipitation^2 + Harvest\quad precipitation \\ & + Dry\quad days + Seasonal\quad precpitation * Dry\quad days \\ & + Seasonal\quad precipitation^2 * + Dry\quad days \\ & + Average\quad temperature * Dry\quad days + Year \\ & + Department + \varepsilon\end{aligned}$$

The interaction terms capture our expectations that long dry spells are especially harmful with low seasonal precipitation, and that sufficient precipitation is even more important when rainfall is infrequent. Similarly, high temperatures (associated with water loss) are even more damaging with infrequent rain events. Alternative model results are discussed briefly in the main text, but are presented principally in the supplemental material.

We note here that these empirical models do not aim to capture all drivers of yield fluctuations and trends, such as input use or long-term soil degradation. However, in order to use the models to assess the impact of climate trends on yields, we only require that the unexplained variance in the model is uncorrelated with the weather predictor variables. For example, we assume that fluctuations in input use over time are uncorrelated with climate variability, or are themselves driven by climate variability (e.g. if more rainfall causes farmers to apply more fertilizer).

In order to assess model uncertainty, we use bootstrapping, a resampling procedure, to generate multiple estimates of each model coefficient, from which confidence intervals can be calculated. In this case, we use block bootstrapping, defining each block as a single production year from 2000 to 2007. By selecting an entire year at a time, this method accounts for spatial correlation across departments, and thus provides a more conservative estimate of standard errors than those from ordinary least squares regression (Hall et al., 1995). Each of our models are bootstrapped 500 times by randomly selecting production years, and then including all records for that year in each iteration.

2.3. Datasets

The weather dataset used in this study consists of long-term daily records collected from 18 temperature stations and 135 precipitation stations throughout Nicaragua (Fig. 2) which are maintained by the National Institute for Territorial Studies (abbreviated INETER in Spanish). The temperature stations, located in the capitals of each department, are sparsely located throughout the country. Precipitation station coverage is denser than for temperature, but there are still a limited number of precipitation stations in the Atlantic half of the country. We use historical precipitation and temperature data from 1970 to 2007 to assess long-term climate trends.

Department-level production and sown/harvested area data is from the Nicaraguan Ministry of Agriculture and Forestry (MAGFOR in Spanish), and goes from 2000 to 2011 (excluding 2008 and 2009) for 17 departments and 3 growing seasons per year. Unfortunately, we do not have daily precipitation data after 2007, so were not able to include production data for 2010 and 2011 in the statistical models, nor analyze the impact of recent severe weather events on both yields and long-term climatic trends. Given that in most departments, each crop is cultivated in only two of the three growing seasons, we use 272 data points for bean and 265 data points for maize from 2000 to 2007 in the statistical models (i.e. the time period of matching weather data). All datasets used in the study are further described in Table S1 in the supplementary material.

To identify growing areas for each crop by season, we combined municipal-level seasonal production data (averaged for the years 2000 and 2010) with static census data showing the number of maize and bean farms by census unit (in 2001) (Table S1), as described below.

2.4. Data processing and analyses

In order to identify cultivation areas, we mapped municipal seasonal production (normalized by area) to census units with at least one farm/km^2 for each crop (Fig. 4). Both sources of information were combined to take advantage of the relatively fine spatial scale of the census units (~25 km^2 vs. ~800 km^2 for the municipalities) and the seasonal-level information of the municipal data. The centroids of the census units with a minimal farm density and non-zero production for each season, were in turn used to represent points within the cultivation areas. With municipal-level production maps only for 2000 and 2010, we assumed fixed growing area maps for the period of the regression (2000–2007). However, in reality growing areas can shift from year to year, as farmers clear new land for cultivation, switch crops in existing cultivation areas, or convert from cropland to pasture or other uses. Despite some changes in departmental sown area from 2000 to 2007, this assumption is mostly robust for an 8-year period.

At each of the weather stations, we calculate the seasonal weather variables defined previously. These station-level variables are then interpolated to the cultivation area points using angular distance weighting (New et al., 2000) with a correlation decay distance of 150 km. Given that most spatial variation in temperature in Nicaragua can be explained by altitude, we combine the station temperature data with climate normals (from 1950 to 2000) at a 1 km resolution in the WorldClim (Hijmans et al., 2005) data product in order to better reconstruct historical temperatures across different regions of the country, as in Gourdji et al. (2013). By interpolating only the anomalies from "normal climate", this method avoids biasing the interpolation due to persistent spatial gradients in temperature associated with altitudinal variations.

Given that there are no simple correlations between precipitation and altitude, we interpolated the precipitation indicators "as-is". This should be reasonable at the seasonal or monthly averaged timescale of our weather variables, given that precipitation varies relatively smoothly in space at aggregated timescales.

Finally, after interpolating all weather variables to the selected points in our cultivation areas, we average interpolated values to the department-level, weighting by the municipal sown area by season at each cultivation area point. Non-linear weather variables in the regression models are then calculated from the linear terms at the department-level. (Mean values for the weather variables by department and season are shown in Figure S2 in the supplementary material.)

With reconstructed average weather data by department, we calculate long-term trends from 1970 to 2007, assuming the fixed cultivation areas in use in the 2000s. We then run the regression models for each crop, definition of yield and model formulation. Finally, we multiply the estimated model coefficients from each model with long-term trends in each of the weather variables to assess the impact of multi-decadal climate trends on yields by department and season.

3. Results and discussion

3.1. Estimated historical climate trends and relation to deforestation

Maize growing areas have seen substantial warming since 1970 across the country and for all seasons, but especially during the primera season (up to 0.4 °C/decade), and in the central and eastern departments as compared to the Pacific coast (Fig. 5). (Climatic trends for bean, shown in Figure S3 in the supplementary material, are similar to those for maize, despite a one month shorter growing season.) Increases in DTR for maize growing areas are also positive, which, along with higher temperatures, implies faster warming during the day than at night. The number of seasonal dry days has also been increasing almost everywhere, but with even faster increases along the agricultural frontier and during the primera season.

In contrast, the changes in planting, harvest and seasonal precipitation are in most cases insignificant, implying that rainfall is primarily changing in terms of timing and intensity, rather than total volume. There are a few significant ($p < 0.1$) changes in seasonal precipitation. These include increases along the Pacific Coast during the postrera due to increases in precipitation in October, and declines in the apante in most of the Central and Atlantic departments, associated with declines in precipitation in December and January. Precipitation in the planting month is declining almost everywhere in all seasons, pointing to delays in the start of the rainy season, although only a few of these changes are significant at the department-level. (At the station level, a clear shift toward a later start to the rainy season can be seen for some locations, Figure S4.) Harvest precipitation is principally declining in the postrera, which is the same as the planting month for apante (as defined here), implying a shorter overall rainy season. There is also evidence of a reduction in local rainfall throughout the rainy season in areas on the agricultural frontier that have experienced high levels of deforestation, e.g. in the Región Autónoma Atlántica del Sur (RAAS) and parts of Jinotega (Figure S4).

Along with more dry days, higher day-time temperatures and fewer clouds, there have been increases in surface shortwave radiation throughout the country, as seen in an analysis of radiation data from the NASA POWER dataset from 1983 to 2007 (Zhang et al., 2007). These increases are even higher in recently deforested areas in the central highlands and Atlantic forest regions. We did not, however, include this data in our regression model, given that we were unable to find a consistent data source for radiation from 1970 to 2007, as for the temperature and precipitation variables.

Global greenhouse gas-driven climate change as well as regional deforestation are both contributing to the climatic trends found here. In particular, day-time warming is especially associated with local deforestation (Castillo and Gurney, 2013; Houspanossian et al., 2013). In this study, we find that day-time maximum temperatures are rising ∼0.40 °C/decade in areas that have experienced rapid deforestation within a 50-km radius since 1983, a rate which is about three times the global average (Fig. 6). In contrast, night-time minimum temperature increases for all stations are ∼0.18 °C/decade, a rate more consistent with global averages.

The observed changes in precipitation found here are consistent with other studies of historical precipitation changes in the tropics due to both global drivers and regional land-use change. Global climate change has been used to explain wetter wet seasons and drier dry seasons (Chou et al., 2013), delays in the start of the rainy season in the Sahel (Biasutti and Sobel, 2009), and increases in precipitation in the latter part of the rainy season in monsoonal systems (Seth et al., 2011). However, deforestation also amplifies changes to large-scale forcing of the hydrological cycle (e.g. Zhang et al., 2009). In this study, we find that deforestation patterns have a high correlation with reductions in seasonal precipitation in the primera ($r = -0.76$; Figure S5), which may be due to a reduction in local feedbacks from forest cover that help to initiate the rainy season, as is well-documented in the Amazon (Fu and Li, 2004). In contrast, an increase in seasonal dry days has the highest spatial correlation ($r = 0.50$) with deforestation in the apante, or dry season. This is partly consistent with (Ray, 2013), who showed that changes in dry season precipitation in Central America are highly sensitive to deforestation.

The increase in dry days, along with rising temperatures (found here and consistent with the results of Aguilar et al. (2005)), are most likely increasing soil evaporation and reducing soil moisture in farmers' fields throughout the country. These findings can help to explain reports of increasing incidence of agricultural drought in the region. However, our findings of insignificant changes in total rainfall amounts are also consistent with the results of other studies of rainfall change in tropical regions (Kassie et al., 2013; Simelton et al., 2013). The minor changes in total annual precipitation imply some scope for capturing and storing runoff through rainwater harvesting projects in order to cope with drought periods (Rockstrom et al., 2002).

3.2. Results of regression models

The crop regression models explain a substantial amount of yield variability, with the maize models having a higher adjusted r^2 than those for bean (0.57 and 0.55 vs. 0.35 and 0.39, Table 2). The smaller amount of variability explained by the bean models may be due to the more specific and high-altitude growing areas for this crop relative to maize, which could imply potentially lower quality of the cultivated area maps and the reconstructed weather data. Bean growing areas have also been expanding rapidly in Nueva Segovia and the Región Autonoma Atlantico del Norte (RAAN) in the 2000s (MAGFOR, 2013), which could also introduce error into the

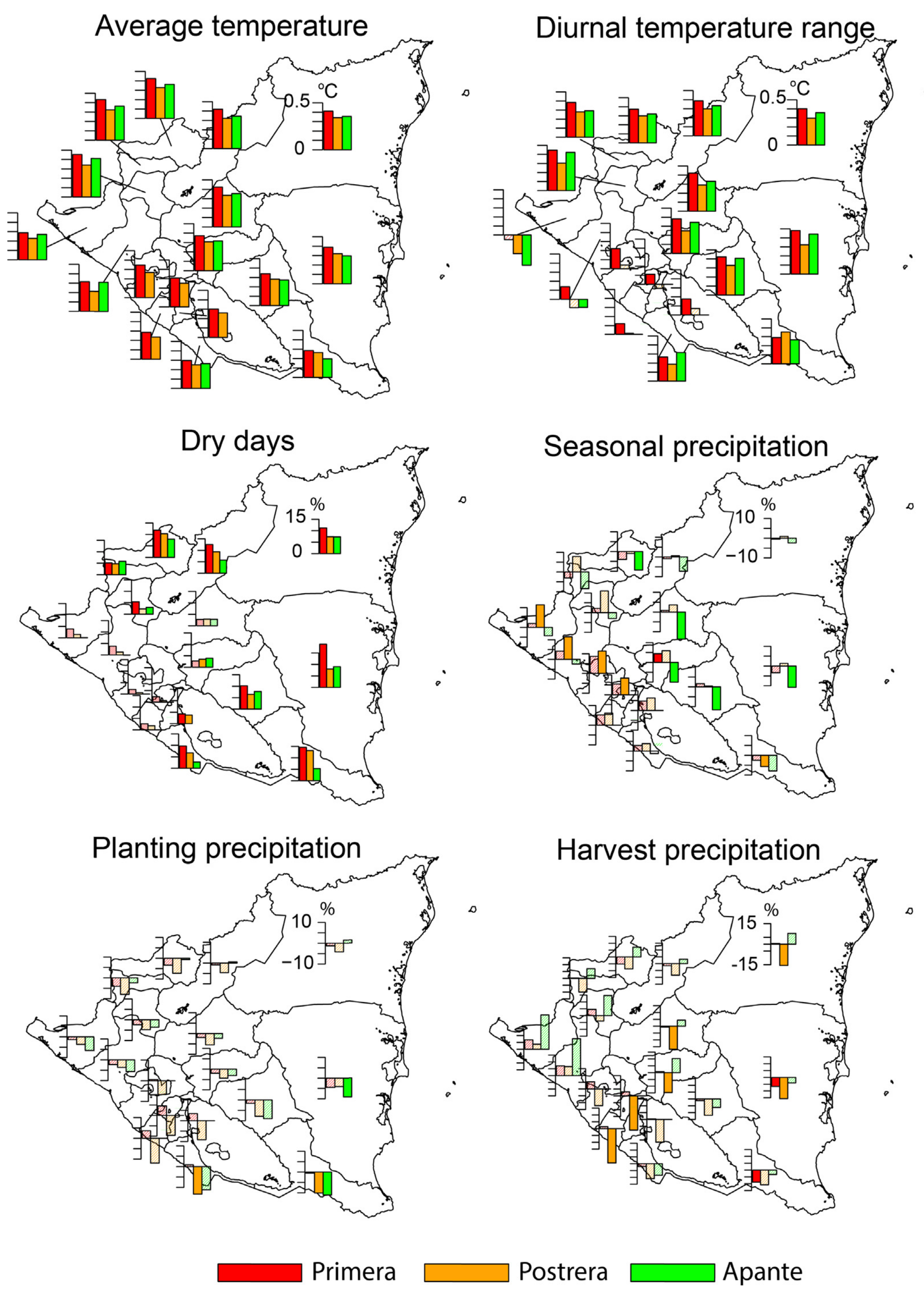

Fig. 5. Department-level decadal trends since 1970 for weather variables included in the maize models. (Climate trends for the bean models are shown in the supplemental material, Figure S1.) The temperature trends are expressed in °C/decade. The decadal trends for the dry days and precipitation variables (in days/decade) are expressed as a percent of their mean values from 1970 to 2007 to better represent relative changes. Solid bars represent significant trends ($p < 0.1$), whereas bars with hatching represent insignificant trends.

weather reconstruction, given our assumption of fixed cultivation areas.

For all models, the department fixed effects explain about half of the variability included in the model, with the weather variables explaining the other half. The weather variables show more significant effects for the models on sown area (i.e. y_s as the dependent variable), relative to those that consider yield only on harvested area (or y_h). The year coefficients, or derived technology trends, while slightly higher for maize than bean, are not significant for either crop ($p < 0.1$). From here-on, we will refer to the results of the models with y_s as the dependent variable, unless otherwise noted. Also, all percent changes in yield should be interpreted as changes relative to local mean values.

Model results show that bean is highly temperature-sensitive, with a decline of 21% yield relative to mean values per °C (90% confidence intervals: −47% to −4%). Maize is also sensitive to temperature, but less so, with losses of 14% yield per °C (90% confidence intervals: −34% to 4%). Both crops benefit from increases in the DTR,

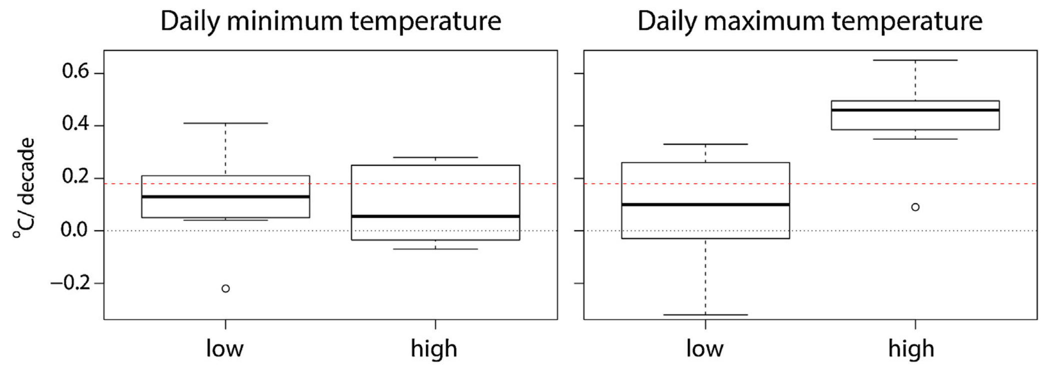

Fig. 6. Decadal trends in minimum and maximum temperatures from 1983 to 2007 for the 18 temperature stations in the department capitals. Station-level trends are binned by levels of deforestation within a 50 km buffer zone (with low defined as ≤25% loss of forest cover within the buffer zone during this period, and high as >25%). Red dashed lines represent the global average trends from stations in the tropics (23°N to 23°S) in the Global Surface Summary of the Day database (Smith et al., 2011).

but the effects are not significant, perhaps due to correlations with other weather variables in the regression (Tables S2 and S3). A high DTR is associated with more radiation and less humid conditions, which could be beneficial for crop growth given sufficient water supply, e.g. on the humid Atlantic side of Nicaragua. The sensitivity test using temperature and DTR variables by growth stage shows that temperature effects are most important in the grain-filling stage, followed by the reproductive stage for maize (Table S4).

Both crops have a strongly negative response to an increase in the number of seasonal dry days. The decline of 8–10% yield for a 10% increase in seasonal dry days is most likely associated with drought-related losses, given that the estimated coefficient on this variable is not significant for the models regressed on y_h. (We estimate yield changes as a function of relative precipitation changes, given that mean precipitation and dry days vary strongly across the country; see Figure S2 in the supplementary material.) While the inferred curves for seasonal precipitation show that both minimal and excess precipitation are problematic, both crops are currently more limited by a deficit than an excess of precipitation (i.e. 74% of maize data points and 68% of the bean points could benefit from an increase in the total volume of seasonal precipitation). At the median value for seasonal precipitation, the maize model is more responsive to a 10% increase than bean (5 vs. 1% yield gain), although this sensitivity varies along the inferred curves (Fig. 7). The models using y_s compared to those with y_h, are not surprisingly, more sensitive to too little and excess rainfall, as both extremes can lead to losses, especially for bean.

The inferred coefficients on planting and harvest precipitation are more negative for bean than for maize, although the effects are less statistically significant. This is partly consistent with farmer perceptions that bean is more sensitive to excess rainfall than maize, especially at harvest time. Regardless, the overall effects of planting and harvest precipitation on yield are relatively small in magnitude relative to the inferred coefficients for other variables in the model.

The results from the alternative model formulation (Table S5) are broadly consistent with those from the main model, but help to further elucidate mechanisms of weather impact on yields. First, temperature effects (accounting for the dry days interaction) are still significantly negative for both crops, and especially so for bean, but are worse at a high number of dry days. This emphasizes the likely pathway of temperature impacts through water loss. Also, the magnitude of the temperature effects is reduced relative to the main model, implying that the water loss mechanism is now better explained by other variables in the model. Second, as we might expect, the seasonal precipitation optimum goes up with the number of seasonal dry days (Figure S6; i.e. a higher volume of rainfall is needed when rain events are infrequent). The estimated seasonal precipitation curves with the interaction terms also show that bean is more sensitive to excess precipitation than maize, while maize tends to be more water-limited, especially with a high number of dry days and perhaps due to a longer season. The sensitivity of bean to excess precipitation is supported by discussions with agronomists and agricultural experts in the region.

3.3. Impact of historical climate trends on yields

We now use the statistical models to assess the influence of historical climate trends on yields by multiplying department-level climate trends since 1970 by inferred model coefficients for

Table 2

Estimated model coefficients, with significance levels, and adjusted r^2s for each model for maize and bean regressed on y_h and y_s. Units of the coefficients are log(yield in t/ha) per unit of the weather variable. Units of the weather variables are shown after their names. Department fixed effects, while included in the models, are not shown here. Significance levels for the coefficients are calculated using 1000 bootstraps, where $^{\dagger}p < 0.1$, $^{*}p < 0.05$, $^{**}p < 0.01$, and $^{***}p < 0.001$. Also shown in parentheses is the relative yield response to changes in weather variables, i.e. percent yield change due to a 1 °C temperature increase or a 10% increase for the precipitation variables relative to their median values in the 2000s.

	Maize		Bean	
	y_h	y_s	y_h	y_s
Average temperature (°C)	−0.06 (−6.1%)	−0.14 (−13.5%)	−0.09† (−8.4%)	−0.24* (−21.4%)
Diurnal temperature range (°C)	0.01 (0.6%)	0.09 (8.0%)	−0.02 (−1.7%)	0.02 (1.5%)
Dry days (days per season)	−0.006 (−3.1%)	−0.018*** (−9.7%)	−0.007 (−2.7%)	−0.021* (−8.2%)
Planting precipitation (mm)	−3.2e−4(−0.7%)	1.1e−4 (0.2%)	−4.9e−4†(−0.9%)	−7.8e−4 (−1.5%)
Seasonal precipitation[a] (mm)	2.3e−3***(2.6%)	4.3e−3*** (4.7%)	0.7e−3 (0%)	2.8e−3 (1.4%)
Seasonal precipitation^2 (mm^2)	−2.0e−6***	−3.9e−6***	−1.4e−6	−4.2e−6
Harvest precipitation (mm)	−0.1e−3(−0.1%)	−1.4e−3**(−1.4%)	−1.0e−3†(−0.6%)	−1.7e−3†(−1.1%)
Year	0.016 (1.6%)	0.018 (1.9%)	0.014 (1.4%)	0.017 (1.7%)
Adjusted r^2	0.57	0.55	0.35	0.39

[a] The relative change in yield is shown for the derived seasonal precipitation curve at the median precipitation value.

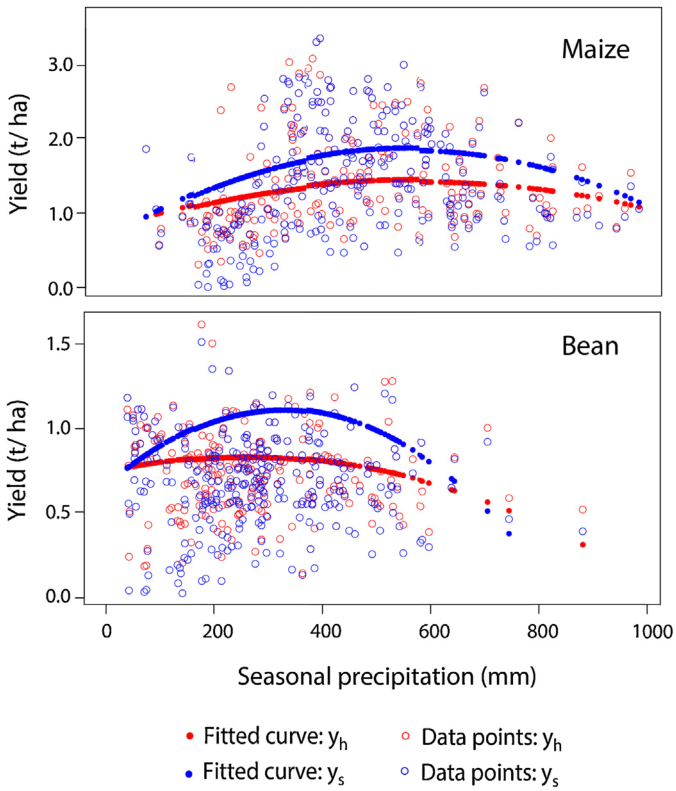

Fig. 7. Derived curves for yield response to seasonal precipitation from the maize and bean models with y_h and y_s. The filled circles represent the modeled yield response, and the open circles represent individual data points in the models.

the weather variables. Overall, both crops show yield declines for almost all departments and seasons due to climate trends, but with stronger and more significant impacts for bean relative to maize (Fig. 8). The estimated yield declines are always more severe when considering the impact of losses on sown area, and this is especially true for bean. This result is also consistent with higher actual losses in sown area in the 2000s for bean, with a ratio of harvested to sown area of 83% in the primera, and 86% in the postrera (vs. 90% and 93% for maize). Actual losses in the apante are minimal for both crops.

For the primera and postrera, climate trends have had the strongest negative impacts on yields in the Atlantic and central zones, with milder impacts on the Pacific coast near the capital. The yield declines in Jinotega, a department in the central and Atlantic zones and with the largest maize production and the 2nd largest bean production, are −9 and −8%/decade for maize in the primera and postrera, and −15 and −12% for bean. For maize, there appear to be relatively weak losses or even gains in the primera season in the Atlantic departments, e.g. the RAAS.

In the apante, impacts for both maize and bean are significantly negative in all departments where cultivation occurs, with losses reaching up to 13% per decade in Chontales and the RAAS for maize and −17 and −16% for bean in Nueva Segovia and Jinotega. This is primarily due to the drying in December and January throughout the country, and the negative response to drying in the model, especially with the lower seasonal precipitation amounts in the apante (typically less than one half that in the primera and postrera). However, it is also likely that the model has the least skill in the apante season, due to two factors. First, apante production relies on a declining soil moisture profile following the end of the rainy season, which may not be well-accounted for by the seasonal climatic variables included in the model. Second, there are limited weather stations in the eastern half of the country which reduces the quality of the reconstructed weather in the apante growing areas.

The alternative model with interaction terms shows less severe impacts of climatic trends on yields for both crops in all seasons relative to the main model. The alternative model results even show positive yield gains for maize in the primera and postrera in the Atlantic half of the country, including the two departments with the largest production (Jinotega and Matagalpa; Figure S7). In these areas, it is possible that maize cultivation has become more suitable due to deforestation-induced drying, which has reduced rotting and disease pressure and led to reduced cloudiness and higher radiation. An increase in climatic suitability for maize production is also consistent with the perceptions of agricultural experts in Nicaragua, who maintain that this improvement in climatic suitability can help to explain migration patterns eastward in the country (personal communication).

We also calculate the impact of climatic trends on yield at the national scale, weighting department-level estimates by their average production (Fig. 9). This exercise helps to assess how much overall supply may have been affected by these trends. For the models with y_s, we see that climate impacts on bean are significantly negative and roughly similar across seasons (−13, −11 and −14% yield declines per decade for primera, postrera and apante). In contrast, the climate impacts on maize are highest in the apante (−12%) and only half that in the primera and postrera (−6 and −7%). At the annual and national scale, the yield declines for maize and bean on sown area are −7 and −13% per decade, whereas for the models with y_h, national annual losses are −4% and −5% per decade.

It should be noted that results from the alternative model formulation show maize having significantly weaker yield declines, and even gains, at the national scale in all three seasons relative to the main model (Fig. 9). In fact, the estimated yield gains in the primera for maize with the alternative model are +16% per decade, due to the strong climatic gains estimated by this model in the central and eastern departments. Also, at the annual national scale, the alternative models show insignificant effects of climate trends on both definitions of yield for both maize and bean. However, the estimated error bars for these models are wider due to the reduced degrees of freedom associated with including the interaction terms, which could influence this result.

Despite uncertainty associated with model formulation for maize in the Atlantic half of the country, the estimated negative impacts of climate trends on yields for maize and bean estimated by the main models are principally driven by the strong warming trends and increases in the number of seasonal dry days throughout the country, which imply faster crop development and lower average levels of soil moisture. The strong negative impacts of warming in our models are consistent with previous work (Lobell and Burke, 2008; Lobell et al., 2011b) showing that temperature trends are especially important for the long-term impacts of climate change on agriculture, given high inter-annual variability in yearly precipitation. However, we show here that gradual changes in the timing and intensity of precipitation are also having substantial impacts on rain-fed cropping systems. Although not included in the models here, delays in the start of the rainy season are most likely introducing additional risk into production due to increased difficulty in choosing appropriate planting dates. In addition, increasing rainfall intensity may also be worsening soil erosion problems.

3.4. Comparison to other studies and observed yields; adaptation measures

Projections of future changes in crop yield due to climate change for this region were also made in the Tortillas on the Roaster (TOR) study using process-based crop models and future climate model simulations (Schmidt et al., 2012). The TOR report showed severe reductions in suitability for bean in the Pacific dry corridor in the primera, but increasing suitability for production on the Atlantic

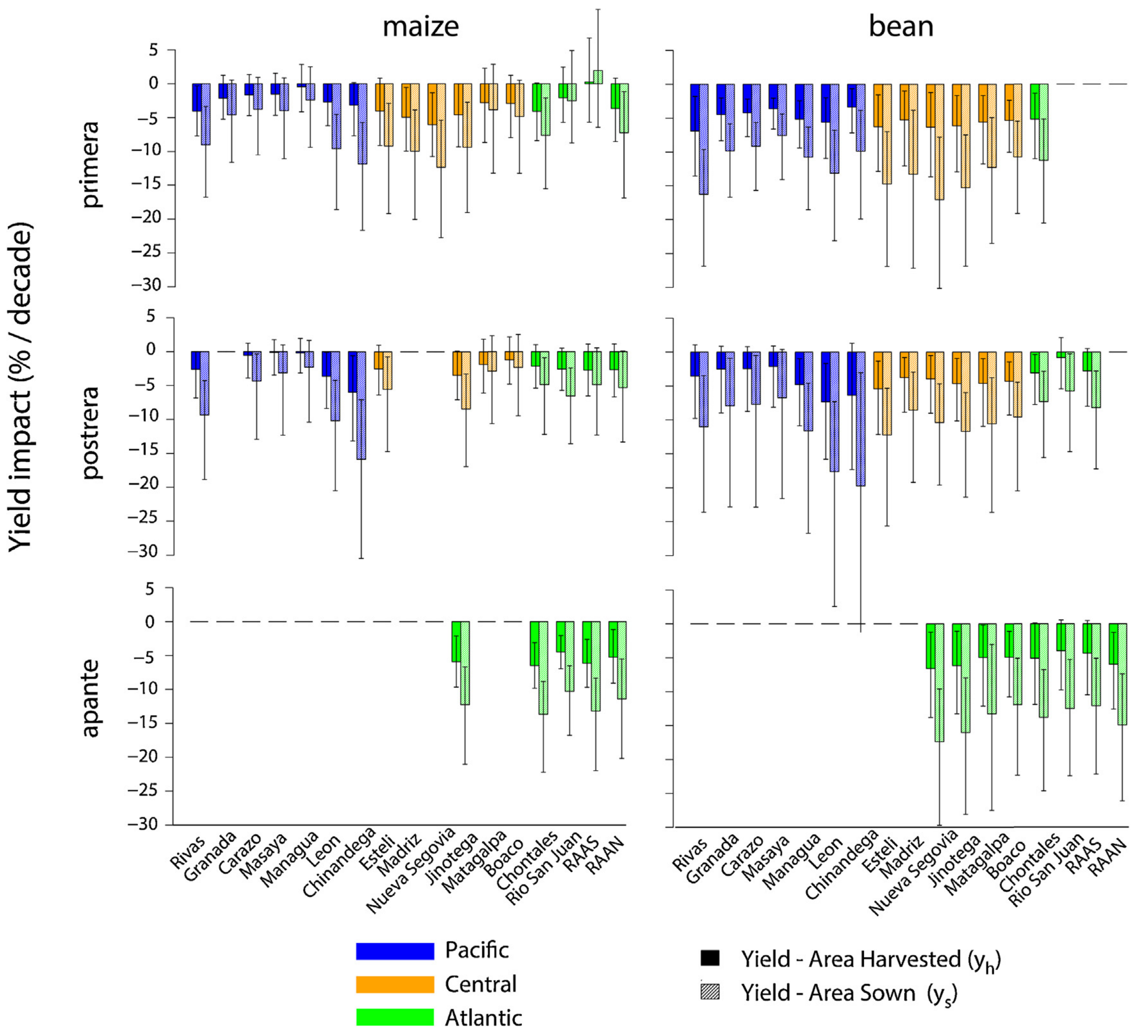

Fig. 8. Percent yield change per decade due to historical climate trends since 1970, shown by department & season for maize and bean models regressed on y_s (solid) and y_h (hatched). Results are shown with 90% confidence intervals derived from the block bootstrapping procedure. Departments are colored by Pacific (blue), Central (orange) and Atlantic (green) zones, and then ordered from south to north in the Pacific, north to south in the Central and south to north in the Atlantic zones.

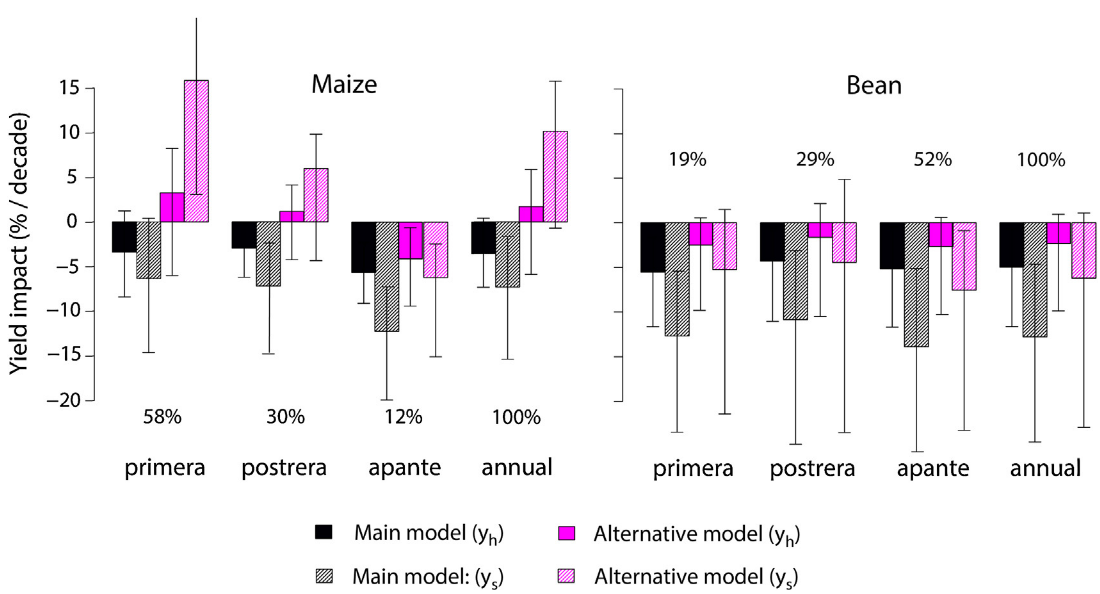

Fig. 9. Decadal impacts on maize and bean yields due to climatic trends at the national scale for the three growing seasons and at the annual timescale. Results are aggregated to the national scale by weighting by departmental production. Results are shown for both the main and alternative models regressed on both definitions of yield (y_h and y_s), and compared with 90% confidence intervals from the block bootstrapping procedure. The percent of production in each season is also shown for each crop.

side of the country by the 2050s. (Other seasons were not included in the study.) The TOR conclusions for the primera are mostly consistent with our empirically modeled results, although we only find increasing suitability on the Atlantic side for maize using the alternative model with interaction terms. Similarly to the TOR study, our results show maize as less impacted by climatic trends than bean, although we do not explicitly account for impacts in high vs. low-fertility soils. Our results reflect the current state of soils, which are generally low fertility in the region.

We also compare our model results to observed yield trends from 1970 to 2007 from the FAOSTAT database, which are −0.4% per decade for bean, and 16% per decade for maize in Nicaragua (Food and Agriculture Organization, 2012). Observed yields reflect the impact of not only climatic trends, but also trends in technology and input use, and other drivers like soil fertility declines and changes in agronomic management. The gap between the climatic impacts estimated here and observed yield trends should reflect the impact of these other factors. This comparison suggests that technological progress and management changes have been able to overcome climatic stresses more easily for maize than for bean in Nicaragua. It also suggests that yield benefits for maize on the agricultural frontier due to drying, as shown by the alternative model, are plausible.

Although it is beyond the scope of this study to examine climate adaptation responses, we briefly mention a few ongoing initiatives within the country to confront climatic stresses for maize and bean production. First, area expansion is helping to maintain production in the face of climatic pressures (e.g. a 50% increase in sown area for bean from 2000 to 2011). Interestingly, area expansion seems to be shifting overall production to higher altitudes with cooler temperatures, particularly for bean. Between 2000 and 2011, the production areas for bean migrated from an average altitude of 603 to 685 m for bean in the primera, and from 241 to 337 m in the apante, the two driest and most water-limited seasons. (There was little change for the postrera.) Maize similarly migrated upward in the primera and apante seasons.

Secondly, heavy crop losses for bean in 2009–2010 prompted a ban on red bean exports in order to address rising consumer prices and food security concerns within the country (Union Nacional de Agricultores y Ganaderos (UNAG), 2012). (Although not included in our models, 40% of the postrera sown area for bean was lost in 2009, followed by 37% losses in the primera of 2010, Figure S8.) Since then, more commercial farmers have also been switching from red to black beans, which are primarily exported to Venezuela (Union Nacional de Agricultores y Ganaderos (UNAG), 2012). Anecdotally, black beans are a hardier and more heat-tolerant crop than red bean, and can be grown in lower elevations.

Third, breeding programs in the region and at international centers like the Centro Internacional de Agricultura Tropical (CIAT) and the Centro Internacional del Mejoramiento de Maiz y Trigo (CIMMYT) have been working to develop improved germplasm with increased heat and drought-tolerance for decades (Beebe et al., 2008; Porch et al., 2007), a demonstrated need in the region. However, there is still limited uptake of improved seed within Nicaragua (∼18% in the 2011 census (INIDE et al., 2012)) due to a perceived lack of net financial benefits at the farm level. Finally, rainwater harvesting projects, agroforestry practices and soil conservation measures hold potential as means for farmers to buffer weather extremes, and additionally improve incomes and diversify risk (Holt-Gimenez, 2002; Lin, 2007; Rockstrom et al., 2002; Stroosnijder, 2009).

4. Conclusions

This study examines the impact of ongoing climate change on rain-fed production of maize and bean in Nicaragua, key staple crops in this country and more broadly in Central America. The analysis of historical weather records shows very strong climate trends in the last 40 years, principally warming temperatures, along with less frequent but more intense rainfall events. Warming is occurring throughout the country, but daytime temperatures have been warming at a rate more than double the global average in areas along the agricultural frontier experiencing substantial deforestation. There have also been changes in the timing of the rainy seasons, with a later start, earlier end and more rain in the middle of the season (especially in October) in many areas of the country. These changes, however, are not as spatially consistent throughout the country as the changes in precipitation frequency and intensity. One spatially consistent change in accumulated precipitation has been a drying trend in December and January throughout the country, or the end of the rainy season and start of the dry season. Given the importance of commercial bean production in the apante, or dry season, this represents an important challenge for maintaining farmer income and national food security.

Results from our empirical models confirm prior understanding that bean is a particularly temperature-sensitive crop, and maize, due to its longer season length, is especially susceptible to water stress and drought-related losses. Both crops are also sensitive to excess rain at harvest time. The alternative model with interaction terms shows a strong interaction between average temperature and the number of dry days in the season, implying that a key mechanism of heat stress impacts is through excess water loss on hot and dry days.

Results also show a clear impact of climatic trends on yields, especially for bean across seasons, and for maize in the primera and apante in the Pacific and Central zones. In general, the models that are regressed on y_s (and hence account for crop losses) show more negative and significant yield declines than those regressed on y_h. Bean yields on sown area seem to be particularly affected in the postrera, perhaps due to more extreme heavy rain events and losses during this season. The alternative model with interaction terms also shows positive gains for maize on the Atlantic side in the primera, pointing to some potential benefits from drying in humid areas.

At the aggregated annual and national scale, the main model results show yield declines for bean roughly double that for maize (−12 vs. −7% per decade for the models on sown area). Technology gains and input use have likely mitigated some of these climatic stresses on yields, particularly for maize, but increasing losses for bean in the 2000s, along with observed stagnating yields, imply increased risk of production for this crop.

Farmer adaptation to these climatic trends is already occurring in Nicaragua, for example with an ongoing switch from red to black bean for commercial farmers, and 50% area expansion for red bean since 2000. Future work will look into on-farm adaptation measures, such as adoption of improved seed, small-scale irrigation, and agroforestry and soil conservation measures that could help to mitigate the increasing impacts of climatic trends on staple crop yields and production in Nicaragua and other tropical farming systems confronting similar changes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2014.10.002.

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