The Impact of Rainfall Frequency on Coca (*Etythrozylum coca*) Production in the Chapare Region of Bolivia

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ABSTRACT
The impact of weather and climate on agricultural production has been primarily explained in terms of plant response to environmental stimuli. The production and harvest of certain crops, however, may be linked more directly to anthropogenic response to climatic fluctuations than to the plant's physiological response. This study shows that the production of Bolivian coca leaves is highly linked to the frequency of rainfall events and, to a lesser degree, total precipitation. Temperature variability appears not to be related to production during the high sun rainy season. The relationship between rainfall frequency and coca leaf production is negative in that as the number of days of rainfall increases, the volume of harvested and dried leaves sent to market decreases. This study suggests that a critical factor in coca leaf production related to climate may be the ability of farmers to harvest and dry coca leaves, which is dependent on the regular occurrence of dry periods.

> It is dusk in the *Villa 14 de Septiembre*, a village at the dark heart of Bolivia's Chapare jungle. As clouds roll in, a Ford Bronco pulls up outside the local market. Within moments, a crowd of cocaine traffickers pounces on the driver, who is wrestling with his load: two 50 pound bags of coca leaves. The buyers grab and pull some leaves to taste, then stuff the man's pockets with bills in an attempt to pre-empt the competition. It's a good batch of leaves, and the local *narcos* know that the coming rainstorm will bump up the price. (Larmer 1992, 23).

The production of crops in the wet tropics, such as coca (*Etythrozylum coca*) leaf, may be dependent on a sufficient number of rainless days to allow for harvest and drying procedures (McGlade et al. 1993). However, the mechanisms explaining this statistical link between the production of such crops and precipitation frequency have not been well-established. In this case study, analysis of climatic data for a set of selected Bolivian weather stations is expanded to examine the relationship between three climate parameters and coca leaf production. Production-climatic relationships found in this study do not appear to relate to the physiological growth and development of the coca leaf bush, but rather to the ability of farmers and farm workers to harvest and dry the leaves.

AGRICULTURAL PRODUCTION, RAINFALL AND HARVEST

Variations in crop production related to climate have often been linked to the physiological response of the crop to climate. Many assessments of climatic change on crop production, such as greenhouse warming, have been based on the physiological response of the crop to the projected change (e. g. Drake and Leadley 1991; Kimball 1983; Lawlor and **[end p. 97]** Mitchell 1991 ; Mabbutt 1989). Study and discussion of these projected changes are undoubtedly important in formulation of future agricultural policy. However, this study proposes that factors beyond the physiological response of a crop to climate change may also affect the production of a crop.

The production of a crop is fundamentally linked to the ability to harvest that crop. Previous studies have suggested that significant crop losses in coca leaf production in central Bolivia are associated with poor weather, specifically heavy rains (Figueras 1978; Delaine 1979). Clearing land for coca cultivation, the weeding of the fields and particularly, the drying of the harvested coca leaf during the high-sun season (November-February) of the year, is seriously jeopardized by heavy rains (Henkel 1971). Surveys of coca production in Bolivia estimate the harvest loss due to heavy rains at 20 to 50 percent (Carter and Mamani 1978; Henkel 1971; WeiI 1980). In this study, variations in coca leaf production in central Bolivia as specifically influenced by various climate variables are investigated. Coca was chosen because (a) any projected changes in coca production are of global importance as Bolivian coca comprises about 40 percent of the world's supply of illicit cocaine (NICC 1990; Smith 1992), and (b) coca production in Bolivia is a very labor-intensive activity that may be significantly linked to the ability to harvest and dry the crop (Delaine 1979; Weil 1980; Blanes; 1983).

Coca leaf yield (Y) is a function of a variety of economic, physiological and environmental factors (Brooner et al. 1981) such that:

$$Y=f(age) + f(management) + f(soils) + f(market\ price) +f(geography) +f(climate)$$

where age refers to the age of the bush. A mature coca bush (age> 7 years) produces a consistent yield from harvest to harvest while bushes from 18 months to 7 years experience a near-linear increase in yield each year. Yields remain fairly constant from 7 to 11 years then yields begin to decline due to soil improvishment and disease (Keller and Aitken 1974). Coca bushes younger than 18 months produce little or no coca leaf-yield. Management in the equation refers primarily to field weeding, bush pruning and harvest procedures. Greater pruning and more frequent weeding generally results in higher yields. Coca production occurs on a wide range of soils but there is little available information on yield variations associated with soil type in Bolivia (OTA 1992, 40; Henkel 1993, 6; Alvarado 1986).

Market price in the yield equation can influence yield by promoting more capital intensive management practices, including fertilization. Geography refers to the yield differences associated with the two main coca producing regions of Bolivia. Production in the Chapare region accounts for approximately 90 percent of the Bolivian production while the Yungas region accounts for approximately 10 percent (Orellana and Zanier 1982, 211-212; Pando et al. 1989, 134; Quiroga 1990, 88). Coca yields are also much higher in the Chapare, averaging approximately 2.76 metric tons per hectare as compared to the Yungas region's 0.94 metric tons per hectare. In addition, the cocaine content of the leaves is much higher in the Chapare. The cocaine content of Chapare leaves averages 0.52 percent of dry weight, while those of the Yungas average 0.34 percent (Plowman and Rivier 1983). This has contributed to the Chapare becoming the main center of cocaine production in Bolivia (Henkel 1986, 55). Over 90 percent of the cocaine produced in Bolivia is produced in the Chapare (Pando et al. 1989,134). The Chapare production is estimated to be approximately 40 percent of the total cocaine available on the world cocaine market (NICC 1989).

For the above reasons, the Chapare was selected as the focus of this study rather than the Yungas. Climate in the yield equation refers to the influences of temperature, precipitation, cloud cover and other atmospheric factors on coca production. Excessive rainfall during the dryer season in the Chapare from June to August restricts to some extent the clearing and burning of primary and secondary forest to create fields for planting coca. High rainfall also results in the rapid growth of weeds in the fields resulting in higher labor requirements and to some extent yield reduction. However, the most significant impact of climate on production appears to be the lack of sufficient days without rainfall to dry the leaves in the peak harvest season of December through February (Henkel 1971, 191-192; Delaine 1979, 82; Figueras 1978, 152; Flores and Blanes 1984, 75-76). **[end p. 98]**

RAIN AND HARVEST / DRYING

Because of the scarcity of coca leaf production data, the individual impact of the variables in the coca yield equation described above are poorly understood. McGlade et al. (1993) recently conducted systematic research on the subject and documented a strong negative relationship that exists between rainfall days and coca leaf production. This study explores additional aspects including the management and post-harvest practices related to this inverse relationship and a relationship between temperature fluctuations and coca leaf production. If heavy rainfall occurs during the dry season of June to August in the Chapare, farmers will not be able burn the vegetation on land cleared for coca. A period of approximately 14 days without rain is required for downed trees and shrubs to dry sufficiently for burning (Henkel 1971, 142-144; Flores and Blanes 1984). Experience in the Chapare suggests that increases in rainfall lead to increases in the growth of weeds in coca fields (Henkel 1971, 202). This accelerated weed growth forces corresponding (a) increases in labor hours spent weeding and/or (b) decreases in the growth of coca leaves due to increased competition for nutrients and light.

More importantly, increases in the number of days with rainfall results in additional difficulty in harvest and post-harvest drying. Coca harvesting is very labor intensive. Coca leaves are picked by hand, placed in baskets, and spread out on tarps or the ground to dry (Figure 1). Extended periods of rainfall and related high humidities cause the leaves to loose their quality and eventually spoil. In general, about three rain less days are needed to dry the leaves (Henkel 1971; Rodriquez 1967; WeiI1980). In some cases, the tarps containing the coca leaves are rolled up as the rain begins to minimize spoilage of the leaves. Prolonged rainy periods may curtail the harvest completely and can leave migrant and local workers without employment or income (Sanabria 1986). In fact, farmers and migrant laborers who work in the Chapare, the site of this study, have been known to migrate back to the Altiplano and transitional valleys regions in highland Bolivia when rainfall inhibits coca leaf harvest activity in the Chapare region (Blanes 1983, 82).

Figure 1. Coca leaf drying in the Chapare.

METHODOLOGY

In this study which extends the earlier work of McGlade et al. (1993), monthly data (1976-1981) of coca production for the Chapare region of Bolivia are statistically compared to corresponding datasets of temperature, precipitation, and raindays. Monthly coca leaf production values exist for the 72-month period between January 1976 and December 1981. These data are derived from Bolivian governmental records (DNCPFC 1983) compiled from the coca checkpoint located on the single road out of the Chapare region. Coca was primarily produced during this period for the legal and relatively stable domestic market (Campodónico 1989). Although some coca leaves were being used in the manufacture of cocaine, these leaves also passed through the check point on the road out of the Chapare with their ultimate destination being the cocaine factories in the Cochabamba Valley and Santa Cruz regions (Gill 1986, 183-193; LAB-Iepala 1982). Subsequent official production values (after 1981) may be under **[end p. 99]** -estimated due to the illicit un-documented harvests and processing of coca leaves into coca paste and cocaine in the Chapare that resulted from an increase in world-wide demand during the 1980s (Henkel 1986; Healey 1986; Eastwood and Pollard 1986).

Coca leaves are harvested throughout the year and the amount of coca produced follows an annual cycle. The months November-February constitute the major harvest period of coca averaging between 40-50 percent of the total annual production (Orellana and Zannier 1982). Data used in this study have been standardized to individual months over the length of record to remove the influence of this annual cycle on the cocaine production data. In addition, the study is restricted to the part of the year when a strong upper-tropospheric anticyclonic cell develops over the Altiplano and the southern Amazon basin (Aceituno 1988) and an intense thermal low develops over much of the interior continent (Schwerdtfeger 1976). This is the height of the summer rainy season in the southern hemisphere (November-February).

Climate in this study is represented by three different variables. The first is average monthly temperature at nine Bolivian stations (Figure 2). The second is total monthly precipitation and the third variable is the number of days with precipitation greater than 1 mm. (hereafter referred to as "raindays"). The number of raindays is used as a climatic variable to test observations suggesting that coca production is related to available leaf drying time (Figueras 1978, 153; Henkel 1971, 191), and hence may be more strongly linked to the number of raindays rather than the total amount of precipitation. As with the coca data, all climatic data have been standardized by month to the length of record available for these variables (1961-1986) as documented in *Monthly World Weather Records* with the exception of La Jota, a station located within the Chapare coca-producing region. Climatic data for this station were obtained from the Bolivian *Servicio Nacional de Meteorología e Hidrología*. La Jota precipitation and raindays, also standardized, were available from January, 1978 to December, 1984. Specific stations used in this study are listed in Table 1 and mapped in Figure 2.

Weather Station	Geographical Land Type	Temperature	Precipitation	Raindays
Camiri	transitional valleys	-0.41 (20)	-0.59 (20)**	-0.47 (20)*
Cochabamba	transitional valleys	0.36 (21)	-0.37 (20)	-0.46 (20)*
La Jota	tropical lowland	NA	-0.68 (14)**	-0.77 (20)**
Rurrenabaque	tropical lowland	0.02 (20)	-0.03 (19)	-0.80 (20)**
Santa Cruz	tropical lowland	0.03 (21)	-0.16 (20)	-0.72 (20)**
Sucre	transitional valleys	0.10 (21)	-0.57 (20)**	-0.70 (20)**
Tarija	transitional valleys	-0.37 (20)	-0.41 (20)	-0.46 (20)*
Trinidad	tropical lowland	0.03 (21)	-0.02 (20)	-0.63 (20)**
Yacuiba	tropical lowland	0.11 (20)	-0.27 (20)	-0.75 (20)**

Table 1. Pearson product-moment correlation (r) coefficients between high-sun (November-February) coca production in the Chapare region of Bolivia and three climatic variables recorded at 15 Bolivian cities. Note: The numbers in parentheses refer to the number of available months used to compute the coefficient. The symbol (*) indicates the coefficient is significant at a = 0.05. The symbol (**) indicates the coefficient is significant at a = 0.01.

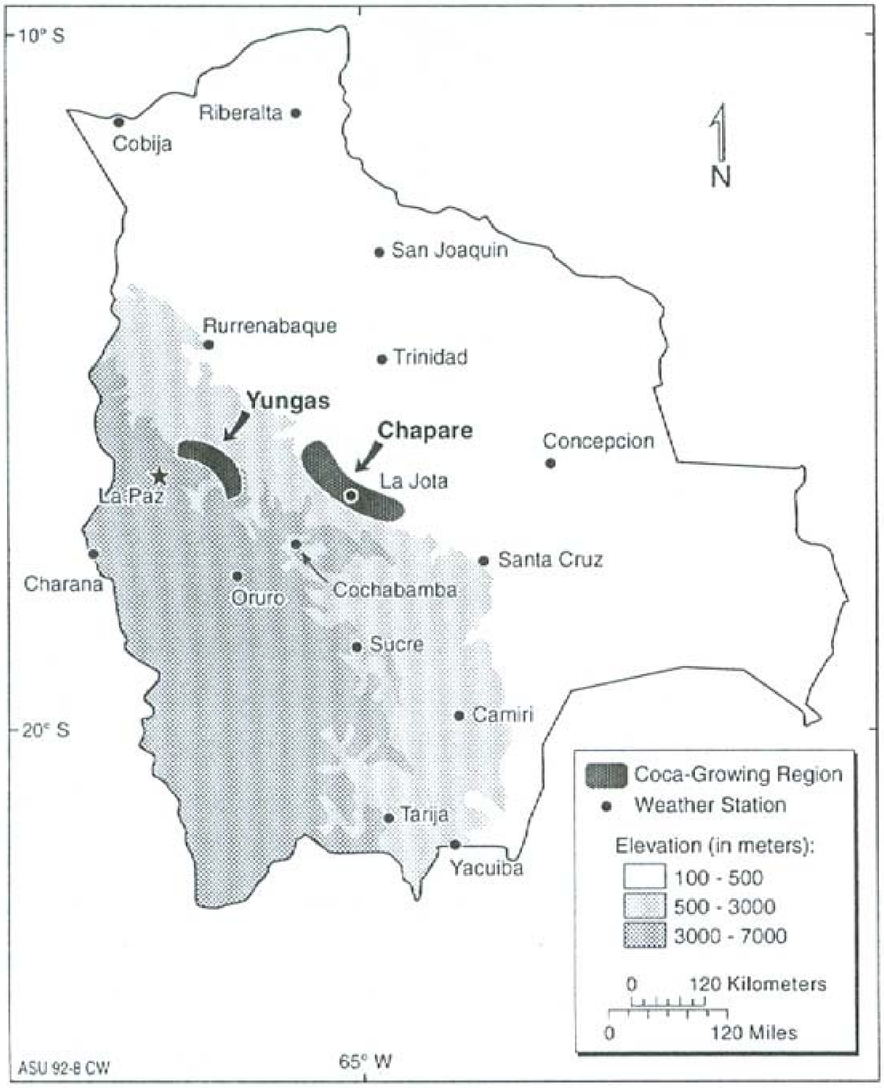


Figure 2. Map showing the meteorological stations for this study, the two primary coca-producing regions (the Chapare and Yungas regions) of Bolivia and selected important geographical features of Bolivia.

Temperature is not a primary controlling variable on coca production during the high-sun season. Although six of the stations used in the study display some relationship between coca production and temperature, none are significant at the ∞ = 0.05 significance level (Table 1). This is not surprising considering the lack of significant day-to-day temperature changes during the austral tropical summer. This absence of large temperature variations appears to be due to the extensive latent heat release associated with convective activity, which counteracts any cold advection or radiative cooling (Schwerdtfeger 1976).

Monthly precipitation, in contrast, is significantly linked to coca production. Five stations show correlations between the amount of precipitation and the coca production in the Chapare that are signifiicant at ∞ = 0.05; four of those cities' precipitation/ coca relationships are significant at ∞ = 0.01. The relationship is negative such that Chapare coca prooduction is reduced when higher amounts of precipitation are received at these distant stations.

The number of raindays per month is the climate variable linked most closely to coca production in the Chapare (McGlade et al. 1993). All Bolivian **[end p. 100]** weather stations in this study demonstrate a significant at ∞ = 0.05) inverse relationship between the number of raindays during the wet season and the coca production for that season (Table 1). Coca production decreases as the number of raindays in the month increases. This relationship between coca production and the number of raindays is significant at six Bolivian locations at ∞ = 0.01. A scatterplot (Figure 3) of the standardized number of raindays at Rurrenabaque to the standardized coca production is representative of this strong negative relationship. In the case of Rurrenabaque, the number of raindays accounts for 64 percent of the variance in Chapare coca production. As an additional test of the hypothesis that raindays significantly influence coca production, a chart showing standardized rain days and coca leaf production at La Jota is presented (Figure 4). La Iota is a weather station near the center of the Chapare coca producing region. **[end p. 101]**

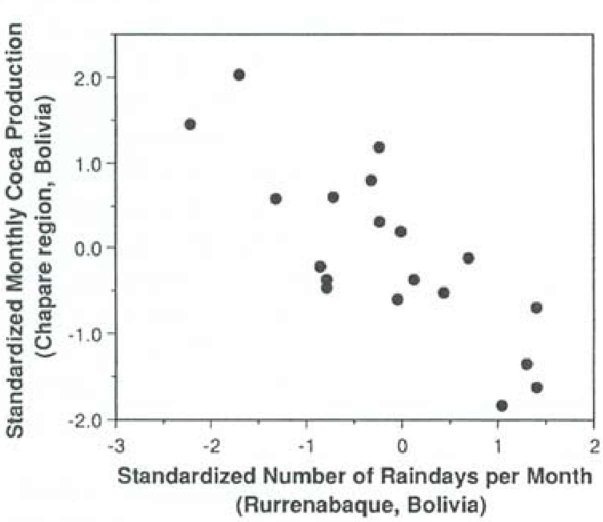
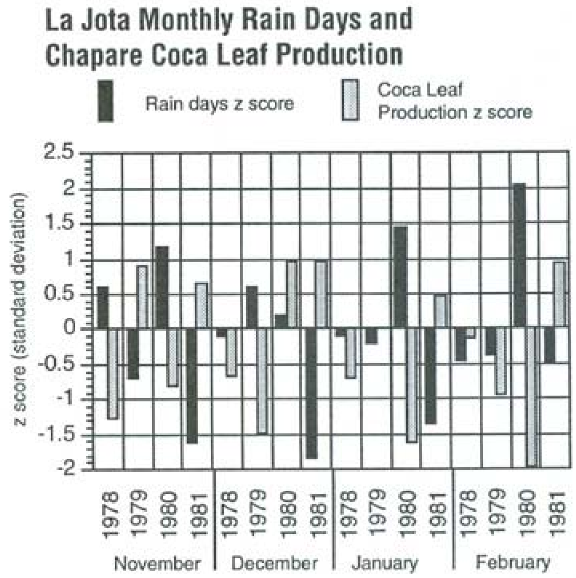


Figure 3. Scatterplot showing relationship between the standardized Chapare coca production during the high sun season and the standardized monthly number of raindays for Rurrenabaque, Bolivia. Pearson product-moment correlation (r) = -0.80.



note: coca leaf production data for December 1979 missing

Figure 4. Bar chart showing the relationship between the z scores (standard deviations) of La Jota raindays per month and Chapare coca leaf production.

The strength of the raindays/coca production relationship is not a measure of the total amount, but rather of the actual occurrence, of precipitation. As discussed previously, the number of raindays constrains the harvest by decreasing the time available per month to dry the picked coca leaves. In order to properly dry leaves without loss due to spoilage, two to three sunny days without rainfall is required (Henkel 1971, 191; Rodríguez 1967, 41). Analysis of the climatic data for the La Jota weather station in the Chapare indicates that during most years only two rainless periods of two days of more occur during each month in the wet season of November-February. Consequently, coca production is frequently severely curtailed during the rainy season due to the lack of rain days but also by the difficulty in obtaining sufficient labor to harvest the leaves during the brief periods of sunshine (Sanabria 1986).

In addition, raindays are more highly correlated to coca production than are precipitation totals because raindays are more closely linked to the overall regional meteorological pattern. Individual convective thunderstorms may produce variable precipitation totals; yet the regional nature of the meteorological situation favoring those convective thunderstorms suggests that, although precipitation values may vary widely, the basic occurrence of precipitation (i. e. a "rainday") will be linked between stations (Schwerdtfeger 1976). The results from the present study confirm this reasoning; precipitation totals among the Bolivian stations exhibit greater variability than do the number of raindays.

The strength ofthe inverse relationship between the number of raindays at various Bolivian cities and coca production is linked to Bolivian geography (McGlade et al. 1993). Three geographical constraints appear to link rainday totals to Chapare coca production. Specifically, these constraints are (a) close geographical proximity to the coca-producing region (e. g. La Jota, Trinidad); (b) similar climate patterns, specifically the climatic region defined by the large transition zone of valleys between the lowland rainforests and the Altiplano region (e. g. Santa Cruz, Rurrenabaque, or Yacuiba) (Schwerdtfeger 1976, 159); or (c) locations in the same regional moisture flow as the coca-producing area such that the precipitation is derived from the same source region (Schwerdtfeger 1976, 158).

However, Altiplano stations such as La Paz are not included in this study. Cochabamba raindays, although showing the same inverse correlation as the other cities, are not as strongly correlated to coca production. While Cochabamba is closer in geographical space to the coca fields than are most other cities in the region, it is also isolated from the climate regime of the coca fields by the eastern cordillera of the Andes (Figure 2). While the advection of Amazonian moisture apparently produces similar occurrences (but not necessarily equal amounts) of precipitation at such varied locations as Santa Cruz and Rurrenabaque, the mountainous terrain to the northeast of Cochabamba isolates the city from the convective/orographic climate of the Bolivian transition zone between the Altiplano and tropical lowlands.

SUMMARY AND CONCLUSIONS

The analyses between climate variables and coca leaf production identify a very strong inverse relationship with the number of days of measurable precipitation, a strong link with precipitation and no significant association with temperature. The strong inverse relationship between coca production and rainfall at a number of Bolivian cities is not apparently tied to the physiological response of the crop to precipitation. Research by McGlade et al. (1993) suggested that coca leaf production is significantly linked to the need for adequate drying time. In general, a two to three day drying time is needed to ensure a good harvest. Therefore, the strong inverse relationship described above indicates that if a given month experiences a high number of rain events, coca producers do not have a sufficient number of dry days to insure a large market supply of leaves. Consequently, harvest amounts are lower and prices will be higher. Although academic research regarding this point is limited, journalists have observed that cocaine traffickers in the Chapare know that the arrival of heavy rains will "bump up the price" (Larmer 1992).

This study suggests that researchers should consider ramifications of climatic change beyond the immediate physical response of a plant. Although increases in precipitation enhance the yields of some crops up to a certain point (Nix 1985; Thompson 1975), this study suggests that other factors may reverse the expected relationship such that increases **[end p. 102]** in precipitation may substantially decrease the harvest of specific crops. The impact of these factors on the harvest of various crops is a separate issue unrelated to physical damage caused by excessive rainfall (e. g. Lomas and Herrera 1985, 140; Radulovich 1987,312). This study suggests that for researchers to adequately assess the impact of environmental factors on the production of some crops, an understanding of local factors important in the production and harvesting of the crop of interest is necessary. As with harvesting, planting may also be impacted by climatic conditions and, consequently, impact yield. For example, if weather during June through August is not favorable for clearing land for planting of coca fields, the yield of harvested coca will be diminished.

The lack of recent coca harvest data (GAO 1988) prevents independent prediction of coca production based on statistical equations derived with raindays or precipitation. However, because of the strong relationship between raindays and coca, this study may initiate discussion of alternative methods of monitoring and predicting the yields of clandestine crops such as coca.

Given that a number of Bolivian weather stations exhibit climatic variations that correlate very significantly with coca production, first-order approximations of coca production may be achieved by monitoring rainfall at these stations. Because current data of Boli vian coca production are difficult to obtain due to increased leaf use in the illicit cocaine industry, such approximations may be critical to monitoring coca leaf supply. In conjunction with suchtechniques, utilization of modem methods of estimating rainfall, such as from satellite imagery (Durana et al. 1987) may substitute for the scarcity of on-site climatic information for the coca-producing areas.

This study also implies that coca leaf production and hence cocaine production may be grossly overestimated for the Chapare. Previous estimates of coca production have been based on multiplying yield per acre by total acreage using the assumption that all coca is harvested as soon as the leaves reach maturity (SRA 1993; Brooner 1981; NICC 1990; OTA 1993; GAO 1988). The findings of this study indicate that this is unlikely to be the case and that much coca remains in the fields due to climatic restraints on harvesting and drying. This study focuses only on climatic restraints on harvesting and drying and its relation to coca production. It has not addressed the restraints imposed by climate on clearing land for coca, increased weed growth, and effective use of labor, issues worthy of future research.

NOTE

[1] The Chapare coca control checkpoint is operated by La Dirección Nacional del Control de la Producción y Fiscalización de la Hoja de Coca.

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RESUMEN
EI impacto del clima en la producción agrícola ha sido explicado principalmente en términos de la reacción de las plantas a los estímulos ambientales. Sin embargo, la producción y cosecha de ciertos cultivos pueden ser relacionados más directamente con factores antropogénicos, por ejemplo los problemas de cosechar con fluctuaciones rápidas de mal tiempo. Este estudio muestra que en Bolivia, la producción de hojas de coca está altamente relacionada con la frecuencia de lIuvias, y menormente con el total de precipitaciones. La variación de la temperatura no parece estar relacionada con la producción durante la estación lIuviosa de alta intensidad lumínica. La relación entre la frecuencia de lIuvias y la producción de hojas de coca es negativa: en cuanto al número de días de lIuvia aumenta, el volumen de las hojas cosechadas disminuye. Este estudio sugiere que un factor crítico en la relación entre la producción de las hojas de coca y el clima es la habilidad de los campesinos para cosechar y secar las hojas lo cual depende de la ocurrencia de cortos períodos secos.**[end p. 105]**