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How do weather and climate influence cropping area and intensity?

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ABSTRACT

Most studies of the influence of weather and climate on food production have examined the influence on crop yields. However, climate influences all components of crop production, includes cropping area (area planted or harvested) and cropping intensity (number of crops grown within a year). Although yield increases have predominantly contributed to increased crop production over the recent decades, increased cropping area as well as increases in cropping intensity, especially in the tropics, have played a substantial role. Therefore, we need to consider these important aspects of production to get a more complete understanding of the future impacts of climate change. This article reviews available evidence on how climate might influence these under-studied components of crop production. We also discuss how farmer decision making and technology might modulate the production response to climate. We conclude by discussing important knowledge gaps that need to be addressed in future research and potential ways for moving forward.

1. Introduction

Numerous studies have suggested that climate variability and climate change can have adverse impacts on global food production and food security. Climate variability driven by major interannual-scale climate modes, such as the El Nino Southern Oscillation, has been playing a key role by often leading to droughts and decrease in crop yields that could further result in famine in some food insecure regions (Hansen et al., 2011; Maxwel and Fitzpatrick, 2012; Iizumi et al., 2014a). For example, droughts in the United States in 2012, heat waves and associated Russian wheat embargo in 2010/2011, and droughts in Australia in 2006/2007 and 2007/2008 led to low levels of cereal stock and steep increases in food prices, likely worsening the access to affordable food for many consumers, including the poor in import-dependent countries (Food and Agriculture Organization (FAO), 2007, 2010, 2012). Ongoing climate change and associated changes in the intensity, frequency and duration of weather/climate extremes, in conjunction with growing population, dietary shift and increasing biofuel demand, are additional concerns for global food security. For example, Lobell et al. (2011) estimated that climate change from 1980 to 2008 has already reduced global production of maize by 3.8% and wheat by 5.5% relative to a counterfactual without climate change.

Such studies, however, have mainly focused on estimating the climate impact on crop yields. Annual crop production, on the other hand, consists of two other components in addition to yield: harvested area (cropping area) and number of harvests per year (cropping intensity):

$$P = \sum_{i=1}^{n} A_i \times Y_i, \tag{1}$$

where P (tonnes) is the annual production of a crop of interest in a given year, A (hectares) and Y (tonnes per hectare per harvest) is, respectively, the harvested area and yield of an intended crop for the cropping season i in a given year and n (times) is the number of completed cropping cycles within a given year. Climate variability and change, along with other factors such as demand, price, policy and technology, can influence these other components of production as well. However, our current knowledge of the climatic impacts on cropping area and intensity is limited. The latest report of the Intergovernmental Panel on Climate Change (Porter et al., 2014) reminds us about this contrasting situation across the different components of crop production. Undoubtedly a major portion of the increase in crop production in the recent past owes to vast improvements in yield. However, the contribution of cropping area expansion to increased production and export in some regions (e.g., Brazil and Argentina, Schnepf et al.,

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2001) should not be underestimated. And the contribution of cropping intensity to production and export on at least a regional level is not negligible if we consider, for instance, the reported number of annual harvests of rice in the tropics (three times, Sakamoto et al., 2006; Kotera et al., 2014; Gray et al., 2014) and that of maize in Brazil (two times, U.S. Department of Agriculture (USDA), 2007).

Therefore, the main objective of this article is to review our current understanding of how weather and climate influences cropping area and intensity, through a literature review to piece together available information on the climatic impacts on the respective components of crop production in the historical past. We further consider how farmer decision making and technology can modulate how climate influences the different components of crop production. We end our review by outlining major knowledge gaps and suggesting potential ways forward.

We chose relatively broader definitions of cropping area and cropping intensity to help cast a wide net while reviewing the literature. Cropping area considered here includes both area planted (transplanted or sown) and area harvested. Cropping intensity includes both the cultivation of the same crop multiple times within a year (multiple cropping) and cultivating different crops in a sequence within a year (crop rotation).

2. Influence of weather and climate on different components of crop production

Climate and weather influence crop production in different ways. If a weather event that is fatal to crops takes place during the crop growth period, an indicator of the impact of the fatal event may be more relevant than that of growing-season mean climate to explain variations in crop production in that year. For example, the Missouri floods of 1993 in the United States that ruined extensive amounts of cropland in American Midwest fall into this category (Rosenzweig et al., 2002). However, if no fatal weather event occurred, then growing-season mean climate would explain the major variations in crop production, as seen in various crop progress reports.

The influence of weather and climate on the different components of crop production can vary, and often happen at the same time. Further, different types of climatic extremes can affect crop production differently. This makes it difficult to understand the climatic impacts on respective components of crop production. To take an extreme hypothetical case for the purpose of illustration, let us say a landslide associated with a tropical cyclone occurs and a portion of cropland is buried in dirt; in this case harvested area would decrease, but yield in the harvestable area would not necessarily decrease. In another extreme case, an unfavorable growing-season climate, such as insufficient solar radiation associated with modulated monsoon, would lower yield, but not necessarily decrease harvested area. Both cases would result in a decreased production, but the affected component of crop production is totally different.

However, actual climatic influences are far more complex. For instance, in the Philippines, wet-season (July–December) rice yields in rainfed conditions show a strong positive correlation with rainfall at the beginning of crop growth period (thus the availability of soil moisture in the earlier growth stage) (Koide et al., 2013). But the same factor seems to influence planted (and harvested) area also. The strong dependency of planted area on accumulated rainfall around the beginning of crop duration is observed for both wet- and dry-season rice in the Philippines (Koide et al., 2013) and wet-season rice in Java, Indonesia (Naylor et al., 2001). In addition to year-to-year variations in monsoonal rainfall, varying topographic conditions and resultant variations in rainfall accumulation rate in June–July, the typical peak of monsoonal rainfall in Northeast Thailand, influences the progress of transplanting and thus the extent of transplanted area completed for a certain time interval in rainfed lowland rice cropping system in that area (Sawano et al., 2008).

An unfavorable climate, such as too wet or too dry condition, affects the cropping intensity as well. For instance, in the Vietnam Mekong Delta where triple rice cropping system is operated, the annual number of completed cropping cycles is affected by variations in the timing and areal extent of flooding in wet season as well as those of salinity intrusion in dry season (Sakamoto et al., 2006; Kotera et al., 2014). Due to the severe floods in 2000, the second-season rice (planted in the middle of dry season and harvested before the onset of wet season) in that year grown in the upstream area of this region was fully and continuously submerged immediately after the heading, leading to crop failure except for the floating rice varieties (Kotera et al., 2014). In contrast, the below-normal seasonal rainfall in 2004 reduced water availability for irrigation due to high salinity, and the dry-season rice in that year could not be harvested. Another example is a severe flood that occurred in Mekong and Chao Phraya river basins in Thailand in 2011, and ruined 14% of rice paddies, had little impact on the Thai national production, export and domestic stock of rice in that year, although it was one of the severest floods in terms of the amount of discharged water and affected number of people (FAO, 2011). In fact, the Thai annual rice production in 2011 hit a record high despite the floods due to compensating increased production during the second-season (January–June) rice (Sinpeng, 2012).

As seen above, climate evidently affects cropping area and intensity. A few studies have estimated the separate responses of production, harvested area and yield to climate (Lobell et al., 2008; Koide et al., 2013). Although the difference in these responses potentially informs about the varying climate impacts across the components of crop production, this was not analyzed. In addition, most available information is based on regional studies. A global overview of climatic impacts is available only for yield, but not for cropping area and intensity. This is mainly because a global data set of yield for different crops at subnational spatial resolution has only recently been developed (Ray et al., 2012; Iizumi et al., 2014b) while a global data set of cropping area and intensity and their changes do not yet exist.

3. Influence of farmer decision making and technology

The agronomic technology available to farmers can influence how climate influences different components of production. For instance, direct seeding, which is a more time- and labor-saving planting method than transplanting, is often used in Northeast Thailand to compensate for the delayed seedbed preparation when the monsoon onset is late (Sawano et al., 2008). Because of the photoperiod-sensitive rice varieties used in that area, the crop duration of directly-seeded rice is always shorter than that of transplanted rice and the shorter crop duration leads to lower yield. Another example is that rice varieties used – floating type or non-floating type – affect harvestable area, number of harvests and yield after floods, as reported in Kotera et al. (2014). These facts suggest the importance of knowing the technology used by farmers to improve our understanding of how climate affects respective components of crop production. It is also worth emphasizing that the technology available for farmers is linked with their economic conditions and affects their decision making on how to deal with climate risk.

Farmer decision making also greatly influences which component of crop production is affected by climate. On the one hand, some farmers may harvest only crop plants that are less damaged. This decision would lead to decreased harvested area, but not decreased yield. On the other hand, other farmers may harvest all crop plants including damaged ones and this leads to decreased yield, but not decreased harvested area. Importantly, both decisions can be reasonable under different economic conditions. The former decision could be expected when the crop price is high enough to compensate for the decreased production. The latter decision would be expected when crop production is covered by crop insurance or governmental subsidy, wherein insurance payouts are calculated based on yield anomaly deviations from a predefined normal yield (Roberts et al., 2006). Among others, the type of marketing channels is a key economic factor. For instance, the reactions of apple producers in Japan to the delayed maturity and delayed reddening of apple fruits associated with the recent temperature rise are largely different across the producers' marketing channels (Fujisawa and Kobayashi, 2011). Producers who directly sell their products to consumers delayed the timing of harvesting to ensure full maturity as their consumers put more value on the palatability than on coloring. In contrast, those who sell apple fruits via the wholesales markets accelerated the coloring by placing reflective materials on ground and/or picking off leaves around the fruits to ensure the timing and prerequisite of the shipment.

Another example describing the impacts of decision making and technology on cropping area is the selection of crops grown in relation to water availability. Farmers in the southeastern part of Australia had increasingly grown rice using irrigation until 2001. However, because of the persistent droughts in the 2000s and associated restriction on water intake and increased water price, they switched their crop from rice to wine grapes which require less water than rice (Bradsher, 2008). In contrast, in the Philippines where abundant water is available, the empirical relationship between rainfall and rice planted area – wetter condition in the beginning of cropping season leading to larger planted area – becomes weaker in the presence of irrigation (Koide et al., 2013).

4. Shift in cropping areas due to gradual climate changes

The large influence of decision-making and technology on crop production poses a major challenge for detecting, attributing and understanding climate change impacts of cropping patterns in the historical past. For instance, the potential contribution of climate change in the last decades to the expansion of cropping area to higher latitudes and altitudes has been hypothesized for a long time and suggested by many studies exploring agro-climatic indices (e.g., growing-season degree-days with a certain base temperature), but few studies have corroborated this hypothesis. For instance, the cropping area in central Siberia approached its peak in 1960–1980 due to growing industrialization and urbanization and decreased after the downfall of the Soviet Union in 1991, although the thermal condition became more suitable for crop production over time (Tchebakova et al., 2011). The cropland expansion in the continental United States in 1850–2000 is mainly attributed to change in the population density, although the biophysical factors, including climate, play a certain role to explain the historical cropland trajectories in some biophysically-marginal regions (Kumar et al., 2012).

Zhang et al. (2013) is the only study we know of demonstrating the vertical and horizontal expansions of cropland in the Brahmaputra River and its two tributaries in Tibet Autonomous Region on the basis of intensive field survey. The observed cropland expansions are accompanied by improved thermal conditions as suggested by an agro-climatic index, but are most likely driven by increasing food demand in that region and farmer response to increase their income. Interestingly, the cropping intensity in the region in 2000s increased horizontally and vertically compared to those in 1970s primarily due to temperature rise. The warmer climate in spring allows farmers to plant the first crop (winter barley) earlier than before and this allows farmers to grow the second crop (rapeseed) for the remaining portion of the growing season to improve soil fertility and income. However, the agricultural expansion and intensification is currently limited to a certain distance from major river channels because the availability of water and fertile soil (soil deposition is driven by water transportation) is another limiting factor of cropland expansion in the area.

5. Knowledge gaps

As this review shows, we know little, especially on a global level, about how weather and climate, modulated by farmer decision making and available technology, influence cropping area and intensity. We now consider some specific knowledge gaps that need to be addressed to deepen our understanding of the climatic impacts on crop production. Also some specific topics for future research are noted. Given global climate change, globalization of food trade, and the increasing importance of food imports to maintain national food balance in many countries, we argue that it is crucial to address these knowledge gaps globally.

5.1. *Extent of crop failure from weather extremes and other shocks*

Temporal changes in cropped area during crop growth from planting to harvest have not yet been well documented, although severe weather events during crop growth period (as well as insect outbreaks and other shocks) and subsequent farmer response certainly may decrease the extent of harvestable area. For instance, the extent of rice area damaged due to tropical cyclones in Japan can be explained by the intensity of tropical cyclones (a function of wind speed and accumulated rainfall) and growth stage of rice when the cyclones hit (Masutomi et al., 2012). Also the reduction in yield and harvested area of maize in the United States due to hail (through reduced stands and defoliation) varies depending on the growth stage when hailstorms hit and producer's decision on replanting (Vorst, 2002). However, due to lack of information, many economic models empirically estimate harvested area in a given year using the crop price in the previous year alone (e.g., Furuya and Kobayashi, 2009). Although it is partly true that price influences the extent to which a farmer plants a crop, this approach ignores the reduction of harvestable area due to severe weather events. To address this knowledge gap, better techniques need to be developed to estimate the spatial extent of crop failure due to severe weather events and other disasters and associated change in harvested area.

5.2. *Influence on crop production through work calendar and field workability*

The progress rate of planting determines the extent of area planted in a given time interval and thus partially explains year-to-year variations in cropped area. While there have been attempts to explain global planting date by climate (Deryng et al., 2011; Waha et al., 2012), the large errors between the estimated and reported planting dates reconfirm the fact that climate is an important, but not sole determinant of planting date (Kucharik, 2006; Sacks et al., 2010). The timing and number of planting (and thus harvesting) in a year substantially depends on both economic and climate conditions (i.e., the availability of labor and fresh water and seasonal pattern of rainfall and inundation for the Vietnamese Mekong Delta, Kotera et al., 2014).

In addition, weather-induced limitation on workability is a key factor. The delay of some operations (seedbed preparation, planting, harvesting, etc.) could lead to crop failure and decreased number of harvests (Sawano et al., 2008). The timing of operations, including of planting and harvesting, is affected by that of the previous operation in a work calendar (Kotera et al., 2014) and need to fulfill the field workability when heavy machines are used (Cooper et al., 1997). Operating heavy machines on wet soil that has low bearing strength is problematic and field workability for some operations (e.g., spreading of farm waste to land) is constrained by weather to avoid watercourse pollution (Cooper et al., 1997). Also the initiation of maize planting in the central United States is influenced by the sequence of weather patterns and the level of soil "trafficability" because the soil is too wet just after spring melt (Kucharik, 2006). The first steps toward a global analysis would require the development of detailed information on the work calendar for multiple crops grown in a farm, allowing for an improved understanding of the sequence of operations and weather-related workability in specific regions.

5.3. Information on cropping intensity

Cropping intensity is clearly an important component of crop production at least in regions where multiple cropping is operated (USDA, 1994). However, there is no adequate global data set of cropping intensity and no studies explicitly examining the relationships between climate variability (and change) and cropping intensity. Satellite remote sensing is a potential source of information on the cropping intensity on a regional to global level. However, remote sensing has difficulty distinguishing individual crop types and misses entire cropping cycles in areas where extensive cloud cover during the monsoon limits satellite observations (Gray et al., 2014). Available regional studies (Sakamoto et al., 2006; Kotera et al., 2014; Qiu et al., 2014) suggest that merging agricultural census data and/or crop model output with satellite data is vital to derive crop-specific information. In line with this finding, future research developing a methodology to derive global historical subnational crop-specific information is important.

The Food and Agriculture Organization of the United Nations (FAO) statistical database (known as FAOSTAT) is the most comprehensive source of information on global crop production. The cropping intensity information is implicitly reflected in the aggregated annual value of crop production and harvested area in the database. However, separate information on cropping intensity is not available. As already shown in regional studies, the climate influences on the cropping intensity as well as cropping area and yield vary greatly within a country and by season (Naylor et al., 2001; Sakamoto et al., 2006; Koide et al., 2013; Kotera et al., 2014). And the local impacts of some weather extremes (e.g., hail and heavy rainfall) on crop, work calendar and field workability are substantial (Cooper et al., 1997; Vorst, 2002). For these reasons, cropping intensity data (as well as cropping area and yield data) on a subnational level and finer is key to improve our understanding of the cropping intensity response to climate.

5.4. Interactions among technology, decision making and climatic impacts

In order to aid climate adaptation and improve food security, we need to improve our understanding of the interactions among technology, farmer decision making and climatic impacts on cropping area and intensity as well as yield. While climate adaptation potential has been tested using crop models, technology considered in these assessments is limited to shifting planting date, changing varieties, introducing irrigation, increasing fertilizer and so on (Challinor et al., 2014; Porter et al., 2014). These assessments tell us about the upper limit of adaptation potential assuming no limitations to accessing technology. However, the actual relationships among technology, farmer decision making and climatic impacts are complex. For example, the availability of labor or seeding machine shared among agricultural cooperative members may limit the ability to shift planting dates, or farmers may be too poor to purchase additional fertilizer and/or agricultural chemicals. Another example is the case of Northeast Thailand, described earlier, where direct seeding instead of transplanting during late monsoon onset can lead to shortened crop duration and lower yield (Sawano et al., 2008). This underlines the importance of knowing the type of technology used, for instance the extent of planted area by planting method when analyzing climatic impacts on crop production because climate during the planting window influences the selection of planting method and thus yield even though the total planted area remains unchanged. Further, crop varieties used – floating or non-floating type – affect harvestable area, number of harvests and yield after flooding (Kotera et al., 2014). By knowing the relationships among climate, technology and decision making, we can obtain more accurate estimates of the adaptation potential, limitations and costs, and ultimately shift crop production systems to more climate-smart one (Lipper et al., 2014). A first step of future research might be to develop a global dataset of economic variables at fairly fine resolution (e.g., subnational level) that provides information on farmer access to different levels of technology.

5.5. Impacts of weather/climate extremes other than temperature

The impacts on yield due to high temperature extremes have been modeled or empirically estimated at the global scale during the last years (e.g., Gourdji et al., 2013; Deryng et al., 2014). However, the impact of other weather extremes, such as tropical cyclones, are not well quantified, although the influence of tropical cyclones on yield and harvested area in some regions are evident (Iizumi et al., 2008; Masutomi et al., 2012; Koide et al., 2013). Crop damages due to tropical cyclones include many factors, such as salt injury due to blowing tides inland, insufficient oxygen caused by overhead flooding, flash floods, wind injury to plant organs and water stress induced by enforced respiration, all of which occur at the same time (Iizumi et al., 2008; Masutomi et al., 2012). Similarly, the different impacts of many weather/climate extremes, including floods, hail, etc., on each component of crop production is poorly understood or not well quantified compared to other large-scale climate extremes such as droughts. The development of new global data sets tracking crop losses from extreme weather events would be beneficial. For instance, EM-DAT (http://www.emdat.be/database) is an excellent global database cataloguing various disasters and their human impacts; however, while human lives affected and total economic damage is reported, crop losses are not. Future studies also need to focus on gaining a process-based understanding of how the under-studied weather extremes influence the respective components of crop production, beyond what is currently achieved using empirical approaches.

6. Conclusions

Climate and weather influences cropping area, intensity and yield in different ways. Farmer decision making and technology modulate these influences. Improving our knowledge of climate influences on and management contributions to cropping area and intensity as well as yield is important to reduce the uncertainty of future climate change impacts on crop production and develop more targeted climate adaptation responses. It may facilitate the development of strategies to deal with the influence of typhoons, heavy rain, floods, and hail storms on cropping systems, or the influence of early snow melt on the ability to operate farm machinery, issues which have hitherto received far less attention compared to developing strategies to deal with the influence of extreme heat stress and/or drought on crop yields.

To develop a more comprehensive response strategy to deal with the multitude of ways in which climate change may influence crop production, more research is needed to improve our understanding of: (1) the impacts of relatively less studied extreme weather events on crop area, intensity, and production; (2) climate impacts on crop production through changes in the work calendar and field workability; and (3) farmer responses to climate shocks under various economic conditions and varying access to technology. A global analysis of these issues is critical to the development of more climate-resilient crop production systems.

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