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Article

Decadal Variations in NDVI and Food Production in India

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Abstract: In this study we use long-term satellite, climate, and crop observations to document the spatial distribution of the recent stagnation in food grain production affecting the water-limited tropics (WLT), a region where 1.5 billion people live and depend on local agriculture that is constrained by chronic water shortages. Overall, our analysis shows that the recent stagnation in food production is corroborated by satellite data. The growth rate in annually integrated vegetation greenness, a measure of crop growth, has declined significantly ($p < 0.10$) in 23% of the WLT cropland area during the last decade, while statistically significant increases in the growth rates account for less than 2%. In most countries, the decade-long declines appear to be primarily due to unsustainable crop management practices rather than climate alone. One quarter of the statistically significant declines are observed in India, which with the world's largest population of food-insecure people and largest WLT croplands, is a leading example of the observed declines. Here we show geographically matching patterns of enhanced crop production and irrigation expansion with groundwater that have leveled off in the past decade. We estimate that, in the absence of irrigation, the enhancement in dry-season food grain production in India, during 1982–2002, would have required an increase in annual rainfall of at least 30% over almost half of the cropland area. This suggests that the past expansion of use of irrigation has not been sustainable. We expect that improved surface and groundwater management practices will be required to reverse the recent food grain production declines.

Keywords: GIMMS NDVI; water-limited tropics; agricultural production; climate; irrigation

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1. Introduction

In the last 40 years, global crop production has more than doubled, supporting an increase in population of 3.2 billion people. This growth has been mainly possible through the innovations introduced by the Green Revolution, such as the use of high-yielding varieties of grain, massive increases in chemical fertilization (≈700%) [1], in irrigated area (100%) [2], and mechanization, and a modest (12%) increase in global cropland area. In the next 40 years, humanity will be challenged to continue increasing global crop production to meet the dietary requirements of an additional 2.5 billion people and help achieve food security to the existing one billion hungry people, while at the same time limiting cropland expansion and containing damages to natural resources and other ecosystems [3,4]. A key aspect of this challenge is that nearly all of the said population growth will occur where the majority of the hungry live today, and where ongoing and future climate changes are projected to most negatively impact agricultural production; the water-limited tropics (WLT) [5]. The WLT span over 40 developing countries, comprising a growing population of over a 1.5 billion people, many of which face problems of absolute poverty, and strongly depend on agriculture that is constrained by chronic water shortages. In spite of concerted international efforts to increase global food security [6], aggregated agricultural production statistics indicate that rates of food grain production have recently stalled or declined in several WLT countries [7,8], escalating concerns about matters of food security—the availability of food and access to it in a region where many people live in extreme poverty and depend on agrarian economies and local food production.

Crop production statistics offer limited opportunities to attributing the causes of declines in crop production, in particular to environmental drivers, as they often lack adequate spatio-temporal information required for this task. Sub-national and seasonal crop production data are often difficult to access for the WLT countries. Satellite remote sensing offers an effective means to compensate for, at least partly, the lack of consistent spatially detailed ground reporting of agricultural conditions, thus, allowing to independently monitor large crop area and production—with the added advantage of providing spatial and temporal information on the location and state of crop vigor [9]. A number of empirical relationships between various vegetation indices and yields have been developed to estimate and forecast crop conditions and production from remote sensing [10-13]. Among these, the most commonly used is the Normalized Difference Vegetation Index (NDVI), which is based on the property of the leaves of green vegetation to absorb incident solar radiation in the red (RED) spectrum band through the chlorophyll and scatter in the near-infrared (NIR) spectrum band through the spongy mesophyll [14], being calculated as:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

For large scale applications, time integrated series of NDVI offer a practical approach to measure crop production as they relate to the overall plant vigor, water stress, and photosynthetic activity during the growing season [15-17].

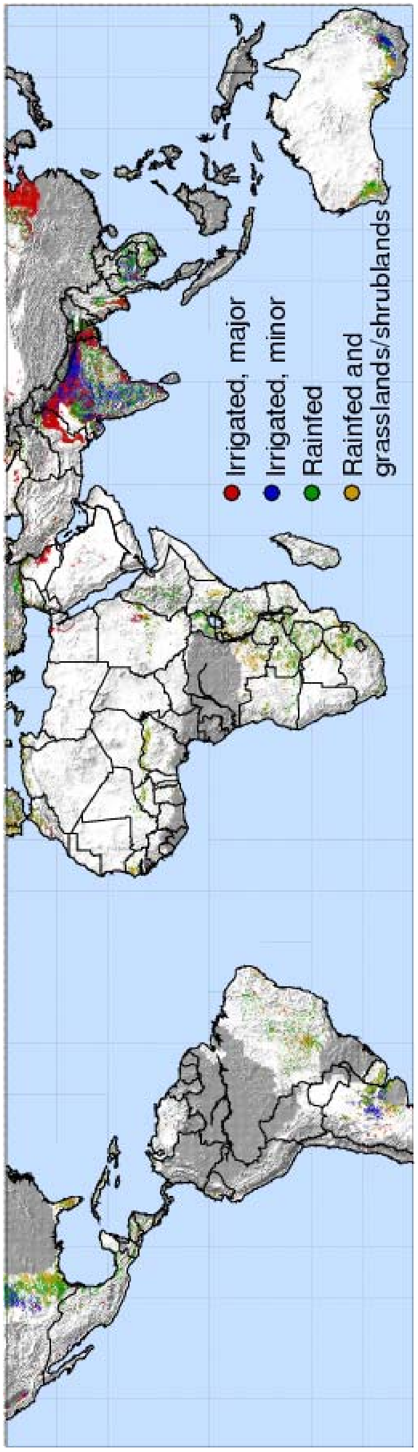
In this study, we analyze the entire long term (1982–2006) record of the Normalized Difference Vegetation Index (NDVI) from the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA/AVHRR), together with climate, land use, and aggregated crop production statistics to provide independent evidence of the agricultural deceleration in the WLT and improve our understanding of its environmental drivers. We discuss the prospects for reversing these trends by examining the deceleration in food grain production in India, the country with the world's largest population of food-insecure people and largest WLT croplands.

2. Data and Methods

2.1. Study Region

The analysis in this article is limited to irrigated and rainfed croplands in the WLT countries (Figure 1) and is carried out at a spatial resolution of 8 km by 8 km. In this study, we categorize all the grid cells where the precipitation has been found to be the primary climatic limitation to vegetation productivity and located between 40°N and 40°S as WLT. For this purpose, we use the dominant climatic controls on vegetation productivity [18]. These dominant climate controls were defined using long-term (1960–1990) monthly climate data of maximum/minimum temperatures, cloudiness, and rainfall [19], and developing scaling factors between 0 and 1 to indicate the reduction in growing potential from its maximum in each month. The maximum growing potential was determined through the comparison of monthly potential evapotranspiration (PET, estimated with the Priestley-Taylor method) with monthly rainfall, and assuming that when rainfall is greater or equal to PET, the maximum growing potential is reached. This method provides a biophysical definition of WLT rather than one based on precipitation amounts alone and includes areas that extend beyond the arid and semi-arid tropics (less than 800 mm of annual rainfall) but where, nevertheless, vegetation growth is primarily constrained by insufficient rainfall rather than low temperatures or insufficient solar radiation. The method also establishes a baseline of vegetation water-limitations against which we can compare the impacts of more recent changes in precipitation.

Figure 1. Map of the distribution of irrigated and rainfed croplands in the WLT. *Irrigated, major* refers to croplands irrigated with surface waters; *Irrigated, minor* refers to cropland predominantly irrigated with ground water, small reservoir, and tanks. The WLT where the land cover within the grid cell is not dominated by crops are shown in white. Areas outside of the WLT are colored in gray.



We then defined the geographic distribution of the irrigated and rainfed croplands of the WLT by overlaying the global irrigated [20] and rainfed cropland area maps [21] with the WLT mask. In the calculations we include only the grid cells in which cropland is the dominant land cover (*i.e.*, cropland occupies more than 50% of the pixel). This region covers over 40 countries and represents 40% of the global cropland and rainfed area mapped by [20,21].

2.2. Food Production Statistics

Spatially aggregated annual food grain production statistics were assembled for countries with at least 90% of the surface area of their irrigated and rainfed croplands within the WLT mask. This ensured that the food grain production statistics would be geospatially consistent with the gridded precipitation and NDVI datasets. Food grain production refers to the total production of rice, wheat, corn, coarse grains (sorghum and millet), and pulses (beans, dried peas, and lentils). The data were assembled from the FAOSTAT database [7]. For all-India, these data are available for the two main cropping seasons, namely kharif (June-October, rainy season), and rabi (November-May, dry season) for the period 1966–67 to 2006–07 from the Ministry of Agriculture of the Government of India [22].

2.3. Climate Data

We use precipitation data from different sources, since no single data set is available to cover the entire study period over the WLT. We assembled precipitation data from the CRU TS 2.0 (0.5° resolution) data [23] for the years 1966–2000 and TRMM 3B43 (v6, 0.25° resolution) data [24] for the years 2001–2006. These data sets were joined together at 0.5° resolution to create a time series for the period 1966–2006. Total annual precipitation was calculated for each year. Then trends in total annual precipitation for 1966–1996 and 1996–2006 were calculated by ordinary least squares. The 1966–1996 trend was subtracted from the 1996–2006 trend and divided by the 1966–2006 mean total precipitation and aggregated over the WLT croplands.

For India, we also obtained all-India rainfall [25] and surface temperature [26] monthly dataset. These data area available both as all-India aggregated monthly data and regional monthly data. We calculated 1960–2005 rainfall anomalies and 1960–2002 average surface temperature anomalies for kharif and rabi seasons. Annual rainfall anomalies during the two seasons were calculated for each year as the difference between seasonal total rainfall and 1960–2005 seasonal average total rainfall. Annual surface temperature anomalies during the two seasons were calculated for each year as the difference between seasonal average surface temperature and 1960–2002 seasonal average surface temperature.

2.4. NDVI Data

We used the Global Inventory Modelling and Mapping Studies Group (GIMMS) NDVI data set version G [27] for the period July 1981 to December 2006. To map the geographical distribution of crop production we calculated the annual sum of the 12 monthly values of maximum NDVI for each pixel (iNDVI). Bare soil pixels were excluded by including in the calculation only pixels with monthly maximum NDVI values larger than 0.1. For each pixel, linear time trends in iNDVI for the periods 1982–1992 (b_1) and 1996–2006 (b_2) were estimated by ordinary least squares and used to calculate percent change in growth rates (ΔGR) in iNDVI for the two periods as following:

$$\Delta GR = \frac{(b_2 - b_1)}{b_1} \quad 100 \tag{2}$$

We tested for significance of the change in trend over the two periods by calculating the Student's *t* score for change in slopes, such as:

$$t = \frac{(b_2 - b_1)}{S_{b2-b1}} \tag{3}$$

where b_2 and b_1 are the linear time trends in iNDVI for the periods 1996–2006 and 1982–1992, respectively, and S_{b2-b1} is the standard error of the difference between the trends.

For India, the same procedure was applied to NDVI data seasonally integrated over the rabi (November–May, dry) and kharif (June–October, rainy) seasons to calculate the change in relative growth rate of rabi iNDVI and kharif iNDVI, respectively.

2.5. Estimation of Relative Increase in Water Consumption Due to Increased Rabi Crop Production

To grasp the magnitude of the impact on water consumption of past increases in dry season crop production, over India we calculated a conservative estimate of the relative NDVI-driven increase in actual evapotranspiration during the rabi season. For this purpose, we used a modified version of the FAO-56 model for crop water consumption assessment of wheat, based on a relationship between the basal crop coefficient (*Kcb*) and NDVI [28], where *Kcb* is the crop coefficient component that corresponds primarily to transpiration. First, Kcb_m for each month *m* is calculated as:

$$Kcb_m = 1.07 \left\{ 1.0 - \left[(NDVI_{\max} - NDVI_m)/(NDVI_{\max} - NDVI_{\min}) \right]^{0.84/0.54} \right\} \tag{4}$$

where $NDVI_{\min}$ and $NDVI_{\max}$ are the minimum (bare soil) and maximum (dense vegetation) values of NDVI over the cropland area of India during the rabi season, and $NDVI_m$ is the monthly peak NDVI. 1.07, 0.84 and 0.54 are coefficients empirically relating *Kcb* to NDVI [28].

For each grid cell, annual actual evapotranspiration, AET, was calculated as

$$AET = \int_{m=1}^{m=12} Kcb_m \; PET_m \tag{5}$$

where PET_m refers to Thornthwaite Potential Evapotranspiration for month *m*. For each grid cell, the increase in water consumption ΔWC during the rabi season was then calculated as a function of local annual precipitation as:

$$\Delta WC = \left[(AET_{trend} \; nyears)/(P_{mean} \; E) \right] \tag{6}$$

where AET_{trend} is the 1982–2002 linear trend in *AET*, P_{mean} is the 1982–2002 average annual precipitation calculated from the CRU TS 2.1 data set, and *E* is the irrigation efficiency. Irrigation efficiency changes by crop and during the growing season, and can range from 25–35% for canal irrigation and 80% for groundwater irrigation [29]. Here, for simplification, we conservatively assume a constant efficiency of 60%. ΔWC represents the increase in water consumption required to sustain an increase in vegetation production as measured by the change in iNDVI. ΔWC can be satisfied either by irrigation or by increases in precipitation.

3. Results and Discussion

3.1. Patterns of Decline in Food Grain Production Growth Rates in the WLT

Between 1996 and 2006, data from the FAOSTAT database show food grain production rates have decelerated in 31 of the 40 countries that hold 90% of the WLT croplands (Figure 2). The pattern of decline in food grain production rate is corroborated by trends of satellite records of iNDVI. During the period 1982–1992, 32% of the WLT had a significant trend in iNDVI ($p < 0.10$), with a mean trend of 0.062 and standard deviation of 0.032. During the period 1996–2006, 22% of the WLT had a significant trend in iNDVI, with a mean trend of 0.058 and standard deviation of 0.042. The difference in trends of iNDVI for the two periods expressed in terms of percent change (Equation 2), shows that during 1996–2006 the growth rate of iNDVI declined by more than half over 58% of the WLT croplands compared to the first period, most prominently in India, Pakistan, Australia, United States, Iraq and Thailand (Figure 3). A one-sided test of significance for the change in slopes (Equation 3) shows that for 23% of the area the decline is statistically significant ($p < 0.10$). In contrast, 16% of the WLT the growth rate of iNDVI over the last decade increased by more than half, of which less than 2% is statistically significant ($p < 0.10$).

Figure 2. Change (%) in rate of food grain production (left) and in trend of total annual precipitation (right) during 1996–2006 relative to 1966–1996 in major WLT countries. For each country, the change (%) in rate of food grain production is weighted by the relative cropland area in WLT (identified in Figure 1).

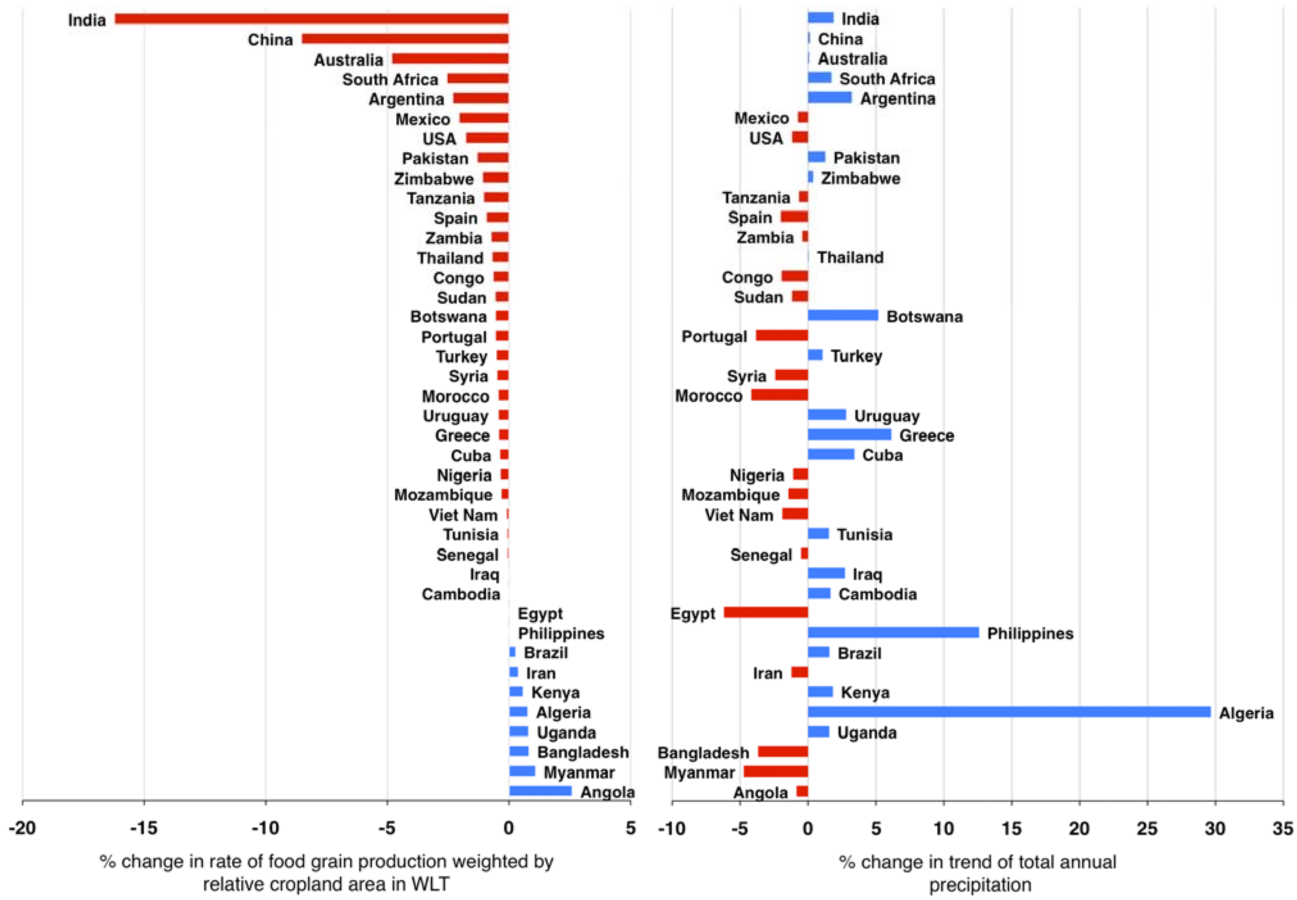
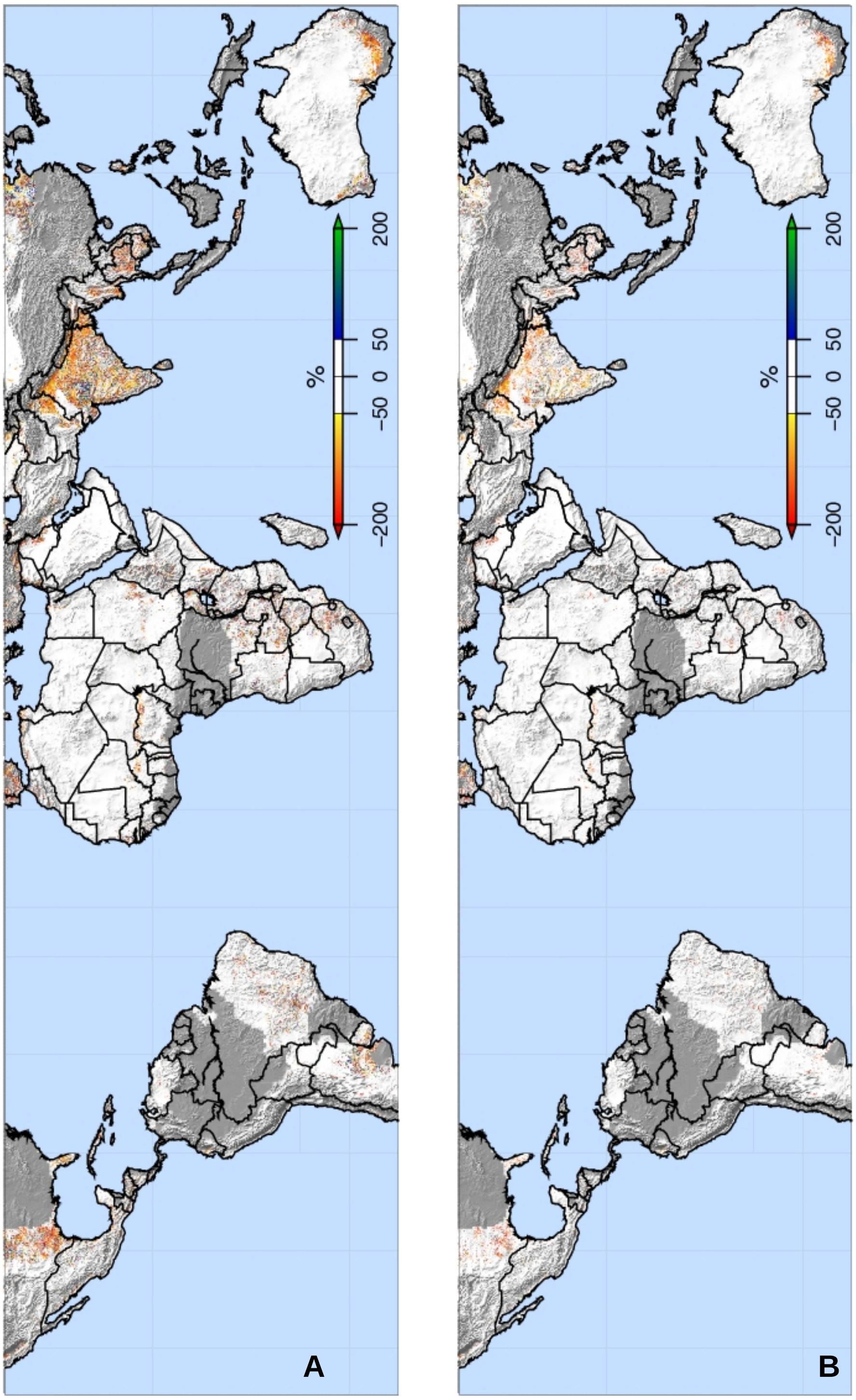
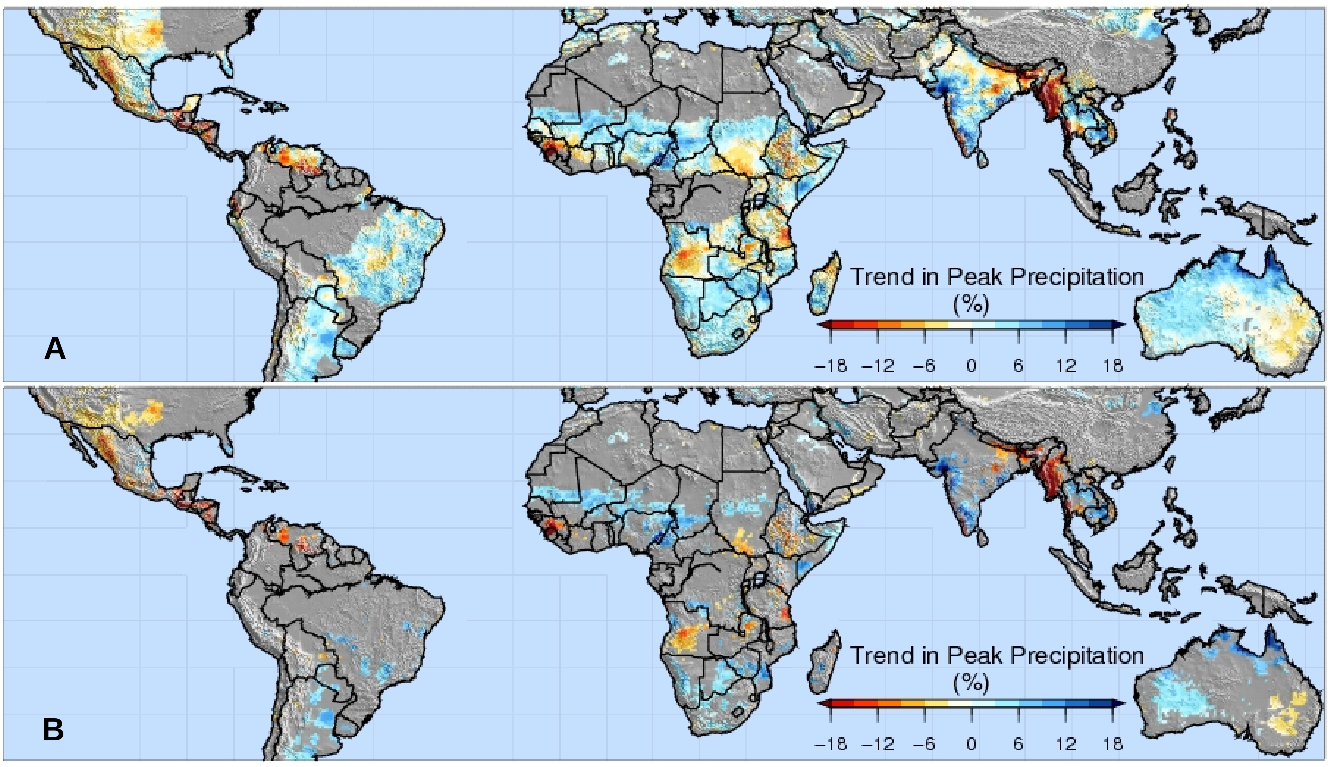


Figure 3. Distribution of changes in growth rate (%) of cropland iNDVI for the period 1996–2006 compared to the period 1982–1992 in the WLT croplands. (A) All pixels with more than ±50% change in growth rate of cropland iNDVI. (B) Only statistically significant pixels ($p < 0.10$).



The modest annual rainfall in these regions is delivered in the few months of the rainy season and the water-limited vegetation tends to respond rapidly to variations in precipitation [30]. Therefore, we may expect variations in precipitation trends (Figure 4) to be a key driver of changes in food grain production rates in the WLT. However, the lack of quantitative correspondence between variations in food grain production rates and precipitation trends (Figure 2), suggests that factors other than rainfall, such as irrigation, soil fertility, and other climatic factors, have played a role in shaping the observed decadal declines in food grain production rates.

Figure 4. Trend in wet season precipitation (peak precipitation, %) for the period 1982 to 2006 for (A) all pixels of the WLT and for (B) statistically significant pixels only ($p < 0.1$).



3.2. Decline in Food Grain Production Growth Rates in India

India, with the world's largest population of hungry people, is a particularly striking example of the recent deceleration in food grain production (Figure 2 and Figure 3), with one quarter of all the statistically significant declines in growth rate of iNDVI of the WLT occurring here. In India, 52% of the total area is devoted to croplands [7], of which close to 90% falls within the WLT region. There are two cropping seasons in India, namely, kharif and rabi. In Figure 5 we plot the time series of food grain (rice, wheat, maize, coarse grains, and pulses) production for the period 1966/67 to 2005/06 along with the record of iNDVI anomalies available since the rabi season of 1981–82. Figure 5A,B show that the satellite data capture well the interannual variability in food grain production, with a strong correlation between the two time series (Pearson's r = 0.87 during kharif and r = 0.82 during rabi). Food grain production has generally increased in both cropping seasons since the mid 1960s [22]. This increase has been made possible through the technological changes brought about by the Green Revolution, such as the diffusion of improved seeds, fertilizers and mechanization, which became widely accessible through increased government subsidies. However, the rate of increase has dropped by over 50% since the early 1990s during the kharif season. The rabi season rate has also flattened around the same period. These changes are also evident in the time series of satellite data shown in these figures—the anomalies of kharif- and rabi-season integrated vegetation greenness are stalled around 0.05 and 0.1 units above the 25-year average.

Figure 5. Total food grain production (rice, wheat, coarse cereals, and pulses) during the (A) kharif (summer, rainy) and (B) rabi (winter, dry) seasons in India over the past four decades. Food grain production (Million tons/yr; blue, left axis) and corresponding growth rates are displayed for the period 1966/67 to 2005/06. Also shown are anomalies of seasonally integrated satellite vegetation greenness (iNDVI) over the croplands of India for the kharif and rabi cropping seasons from 1981/82 to 2005/06 (green, right axis). The insets of **A** and **B** show the correlation between food grain production anomalies and rainfall anomalies (during kharif r = 0.76, rabi r = 0.11). (C) Annual cropped area under food grains during kharif (blue) and rabi (red) seasons, annual net irrigated area (green squares), and population (brown). (D) % of cropland irrigated across the main agricultural states of India and % of irrigated cropland area relying on groundwater use.

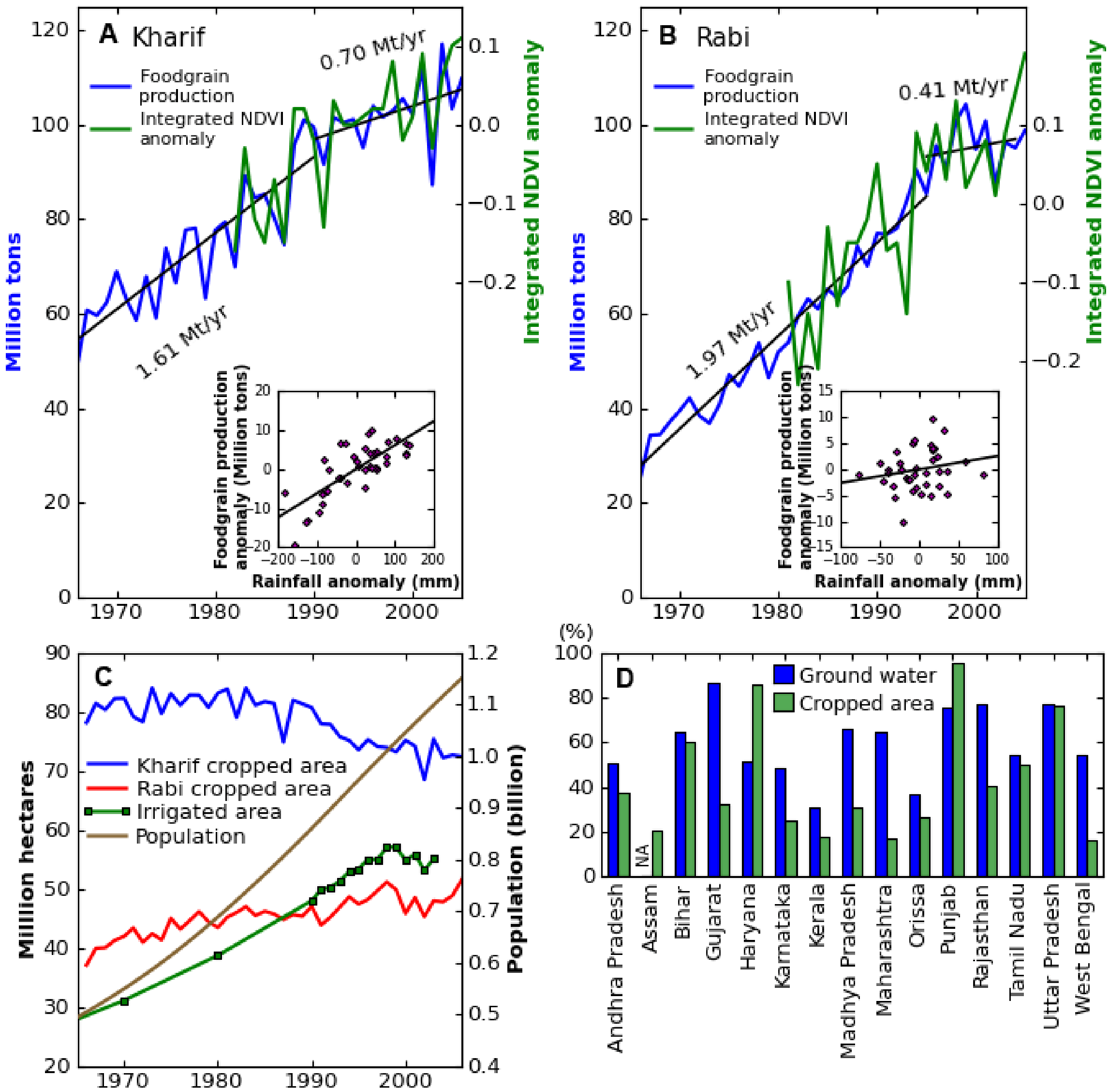
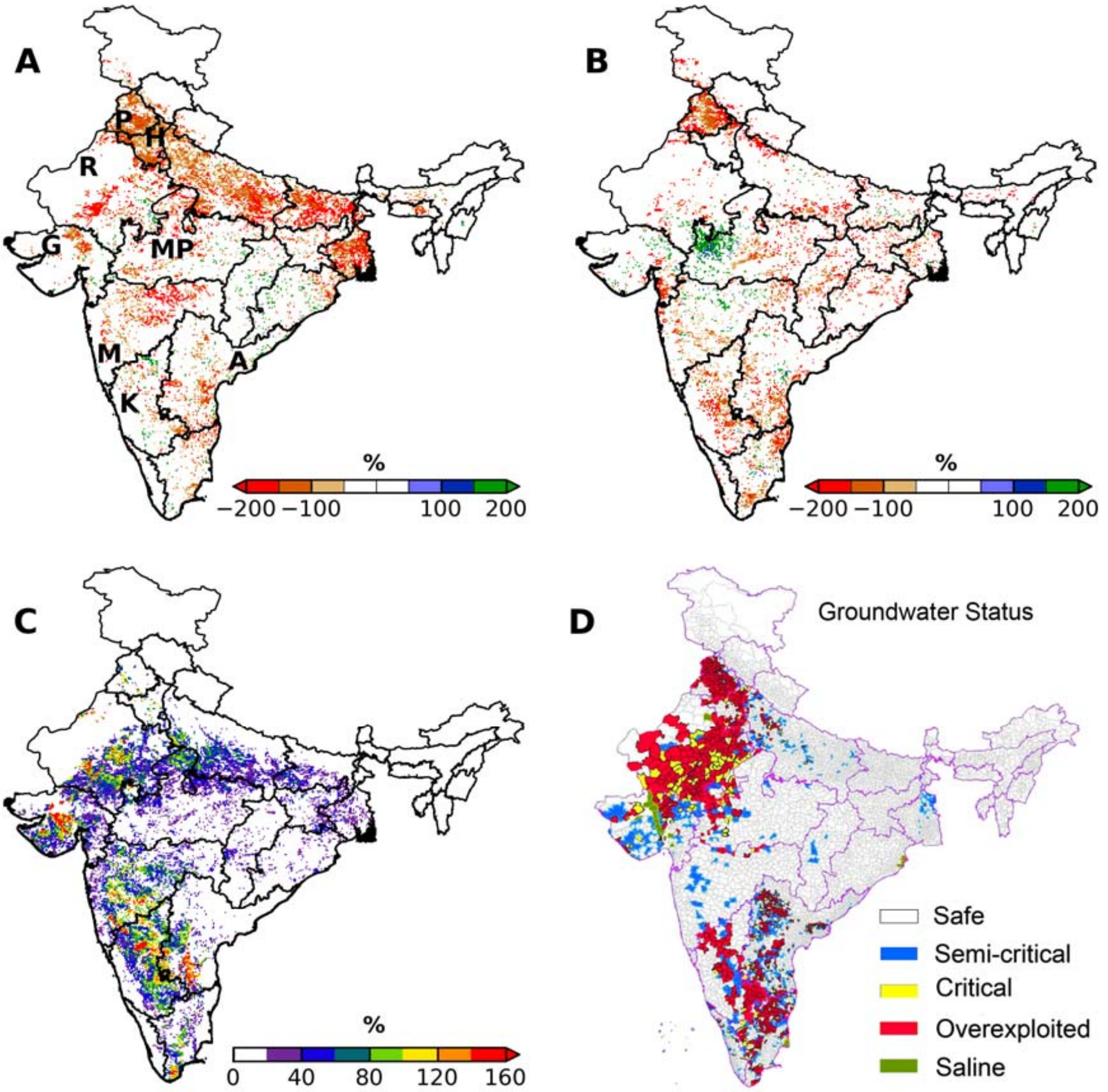


Figure 6. Geographical distribution of the change in growth rate (%) of (A) rabi and (B) kharif iNDVI for the decade (1996/97 to 2005/06) compared to the decade (1982/83 to 1991/92). Land use and crop statistics [31] report recent decreases in wheat area over the portions with sharpest declines in rabi iNDVI growth rate in the states of Punjab (P), Haryana (H) and Rajasthan (R), and decreases in irrigated area in the states of Maharashtra (M), Karnataka (K), and Andhra Pradesh (A). Increasing rates of iNDVI are observed during the kharif season in Madhya Pradesh (MP) in proximity of the Gandhi Sagar Dam. (C) amount of water needed to support the observed greening during the rabi season in the period 1982/83 to 2005/06, expressed as % mean annual rainfall (see *Data and Methods*). The states of Punjab and Haryana do not show change in water requirements because here the greening preceded the satellite record of vegetation greenness. (D) Status of groundwater exploitation by geographic block in India as of March 2004 [32].



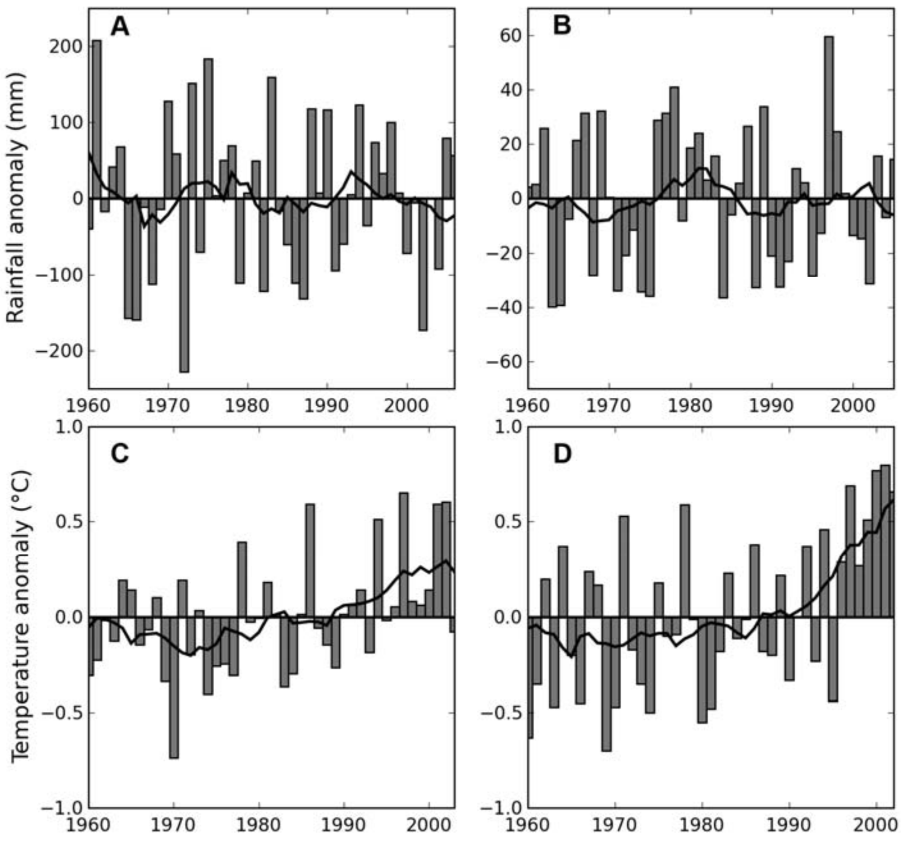
The advantage of satellite data, compared to coarse scale grain production statistics, is that they show the geographical patterns of changes, as in Figure 3. In most of the WLT countries, detailed food grain production time series are hard to assemble at the sub-national scale. In India, state-wise data of food grain production are consistently accessible only since 1995/96 [33], during which period none of the major food producing states has recorded a consistent increase in production. We use the time series of iNDVI to infer the sub-national food grain production for the time period 1982/83 to 2005/06, suggesting that the patterns of declining growth rate are present both in the rabi and kharif season across all the major water-limited food producing states of India (Figure 6A and 6B). Recent declining growth rates are seen in the main food grain producing states in the Indo-Gangetic Plain and in the central portion of the country (Rajasthan, Maharashtra, and Karnataka to Andhra Pradesh). A t-Student test for change in slope indicates that 30% of the declines during the rabi season are statistically significant ($p < 0.10$), while only 2% of the increases are statistically significant. During the kharif season, 18% of declines are statistically significant, and 3.5% of the increases are significant (Figure 6A). Statistically significant declines are also evident over 18% ($p < 0.10$) of the cropland area during the kharif season (Figure 6B), prominently in Punjab and in the southern portions of the peninsula. Recent district-wise land use and crop statistics [31] for the areas affected by the sharpest declines indicate distinct contractions in irrigated areas and shifts in cropping patterns for the more water demanding crops, *i.e.*, declines in rabi wheat (for example, in Punjab, Haryana and parts of Rajasthan) and kharif rice areas (Tamil Nadu). On the other hand, a significant increase in kharif production can be observed over Madhya Pradesh in the Chambal valley, perhaps due to a recent expansion in irrigation with surface waters. Efforts to map yearly changes in crops distributions will allow to better understanding to what extent large shifts in cropping patterns rather than changes in yield are responsible for the declines in iNDVI growth rates.

3.3. Climatic and Land Use Drivers of Declining Growth Rates

Agricultural production is governed by a large number of economic, technological and environmental factors and determining the precise contribution of each factor is generally extremely difficult and beyond the scope of this study. For example, globalization and international trade leading to increases in food grain imports could have influenced the changes in production in some countries of the WLT. In India, FAOSTAT data [7] show that while pulses imports have increased over the studied period, the import of cereals has declined drastically. The net result is no change in imports, but could explain some of the seasonal patterns. While these factors will require a separate study, here we analyze the possible role of climatic and land use drivers in the deceleration in food grain production in India, considering this country a leading example of the challenges faced by agriculture in the WLT region.

In India, the main increases in food grain production during the past four decades have been realized during the rabi season. The rabi season crops have gone from contributing a third of the food grain production in the mid 1960s to today's capacity to produce as much as the kharif season on one third less cropped area (Figure 5C). Food grain production suffers major declines in occasion of widespread droughts during the kharif season, the occurrence of which can be tracked by the major dips in the time series of both production and iNDVI anomalies of Figure 5A and 5B in 1987, 1990, and 2001–2002 The impact of rainfall on food grain production is prominent during the Kharif season, when the two variables show a Pearson correlation coefficient (r) of 0.76 (inset, Figure 5A). While the rainfall during the rabi season is too little to influence rabi food grain production ($r = 0.11$) (inset, Figure 5B), this also has a modest correlation with the kharif rainfall of the previous season ($r = 0.52$), suggesting that aquifer recharge is a relevant component of rabi production. However, the long term trend in rainfall over India does not reveal significant changes that could justify the strong increases in rabi food grain production up to the mid 1990s (Figure 7A,B). While a recent succession of droughts has certainly impacted food grain production, a similar period of below normal precipitation was present during the 1980s (Figure 7A). On the other hand, the rabi production boost is consistent with the expansion of irrigated area in India (Figure 5C), which has accelerated from the mid seventies through the late 1990s to take advantage of the higher yield potential offered by the availability of improved seeds and fertilizers. Currently, at least one third of the cropped area is irrigated in most Indian states, with 50-80% of the irrigated surface relying on groundwater [31,34] (Figure 5D), made possible through a massive expansion of private wells [35]. This facilitated cultivation of higher yielding non-rainfed crops during the rabi season and stabilized planting dates during the kharif season when monsoon rains are delayed.

Figure 7. 1960–2005 all-India rainfall and temperature anomalies for kharif (A, C) and rabi seasons (B, D) [25]. Kharif season has mean annual rainfall of 911 mm and mean annual temperature of 27.09 °C. Rabi season has mean annual rainfall of 161 mm and mean annual temperature of 22.48 °C. The black line represents the 11-year moving average.



Although groundwater irrigation has been one of the primary drivers of increased food grain production in rapidly developing countries such as India as well as in the other countries of the WLT, there is increasing evidence that its use has been unsustainable [36]. Countries with high groundwater use such as India, Pakistan, United States, Iran and Mexico are located in regions with low aquifer recharge rates [37], and may have reached a limit in the groundwater-based expansion of food grain production. Although estimates of regional groundwater extraction are not easily available for India, a number of sources document a widespread decline in water tables [32,38]. Our conservative estimates of the amount of water required to sustain the rabi season production rate in India (Figure 6C) indicates that large portions of the peninsula (49% of the mapped cropland area) would require from 30% to 150% increase in local annual rainfall to sustain the greening measured by the trend in iNDVI for the period 1982–2002 in the absence of irrigation. Given the massive expansion in wells documented in India over the past decades [39], this water requirement has been likely largely satisfied with groundwater irrigation. Our calculations of increase in crop water demand are greatest over the northwest and central-southern peninsula and coincide to a good approximation with areas mapped as suffering from groundwater overexploitation and at risk of salinization [32] (Figure 6D). Thus, we may expect the number of overexploited aquifers to further increase, eventually pushing farmers to revert to less productive rainfed crops if measures to increase water productivity are not implemented in the few coming years. Moreover, depleting reserves of groundwater effectively eliminates one option of mitigating climatic change impacts on agriculture in these countries [40,41]. There are several opportunities for improving water productivity, especially through better use of green water sources (infiltrated rain) during years of normal rainfall. However, it has also been estimated that limits in the total water availability for future agricultural production in a number of WLT countries of Africa, the Middle East and South Asia will severely hinder future self-sufficiency in food grain production even if all sources of water both from rivers and aquifers, as well as from naturally infiltrated rain, will be well managed [42].

Another climatic factor that may be substantially contributing to the declining relative rates of food grain production is accelerated warming since the mid 1990s (Figures 7C,D). Over the past decade, average temperatures have increased by 0.25 °C during the kharif and by 0.6 °C during the rabi season. It is not clear whether the recent stalling of food grain production in the rabi season is related to the rabi increase in temperature. If the agricultural deceleration in this season is due to a stalling in the expansion of irrigation, then the warming could be, in part, due to a reduction in evaporative cooling effect of irrigated areas, suggesting that in the absence of further irrigation expansion this season will continue warming. Studies suggest that the recent warming has potentially reduced crop yields by 6% percent in the rabi season [43,44], also contributing to the flattening of food grain production. Based on the relationship between temperature and PET, we estimate that the recent rabi season warming could have increased evaporative demand by about 5%, exerting additional pressure on water resources. Projected warming over the WLT is likely to further depress crop yields and exacerbate water scarcity, constraining attempts to increase food grain production [5,45]. El Niño-Southern Oscillation (ENSO) also impacts WLT climate and crop production [46]. However, the recent weakening of the relationship between Indian monsoon and ENSO [47] precludes the role of ENSO in the flattening of recent food grain production trends, but this may change in the future.

A third major environmental driver involved in the decline in relative growth rate of food grain production is the slow down in cropland area expansion. Spare arable land for boosting agricultural production is limited in most WLT countries. For example, in India land available for kharif cultivation, after peaking at 84.1 million hectares in 1983, has been declining since the early 1990s and is down to 72.4 million hectares by 2006 (Figure 5B). The area under cultivation during the rabi season, after expanding from 37 million hectares just before the Green Revolution, has not grown much since the late 1990s, when it stabilized around 50 million hectares. Further expansion of rabi crops and cropping intensification during the kharif season may likely be constrained by the current limits in the exploitation of existing water resources. Additionally, as urban population continues to increase, more land is converted from agricultural to housing and other urban uses [48,49] and so does competition for water from household and industrial consumers.

There are a number of other environmental factors that could also be involved in the deceleration of food grain production and that have not been analyzed here. For example, overcoming nutrient limitations is essential for increasing food grain production in the WLT [3] and recent constraints in fertilizer availability and management could also be playing a significant role in the recent deceleration of food grain production that need to be further analyzed. Reductions in rice yields in India have been also linked to declines in solar radiations due to increasing atmospheric pollution [50,51], but it is not clear how spatially extensive this effect is. The future availability of longer time series of satellite observations may help better understand the impacts of air pollution on crop production.

4. Conclusion

In this study we provided a satellite-based, independent assessment of the declines in growth rates of food grain production in the countries of the WLT reported by crop statistics. We also analyzed some of the major environmental drivers involved in this decline, focusing on the case of food grain production of India, which shows the largest declines in the WLT.

Agriculture in the WLT is strongly constrained by the availability of water, but long term changes in trends of precipitation cannot be consistently linked to the declining rates in food grain production, suggesting that other environmental factors, both known and unknown, play a major role. In India, time series of iNDVI along with land use and climate data suggest that there is a strong link between the deceleration of food grain production and the unsustainable use of water for irrigation. High population growth rates and rapidly developing economies demand ever increasing rates of food production. In India alone, a 50–100% increase in yields of major crops is required to achieve food security by the middle of the 21st century under the current population projections [52]. This will be a challenge for India and other WLT countries currently experiencing declining rates of production. The increasing competition for water foreshadows a growing food security concern that could be worsened by continued warming, the possibility of future increases in drought frequency, competing use of water from non-agricultural sectors, and loss of croplands to salinization, urbanization, and other uses.

Observed increasing average temperatures and declines in cropland area are also found to temporally match the declines in relative growth rates of food grain production in India. Other important environmental factors such as limits imposed by nutrient deficiencies and pollution-induced decreases in solar radiation could also be involved in the decline. A similar country-wide spatially explicit comparison between data on fertilizer use and aerosols concentrations and patterns of declines of growth in vegetation greenness should be done to elucidate the roles of these factors on the stagnation of agricultural production in India.

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