Mapping the Biophysical Limitations of Major Crops

by

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ABSTRACT

There are natural climate and soil conditions that are ideal for the growth of different crops. Cultivating in these naturally suitable conditions minimizes environmentally harmful human alterations and inputs to Earth systems such as fertilizers and irrigation. Using the framework outlined in Ramankutty *et al.* (2002), this research determines the relationships between different biophysical indicators (growing degree days, moisture index, soil carbon density, and soil pH) and the cultivation of seven major agricultural crops using statistical analysis of global data sets in a Geographic Information System (GIS). These relationships are then combined to determine the areas that are the most naturally suitable for cultivation of different crops, the potential for crop expansion into naturally suitable areas, and human alterations within biophysically limited cultivation areas. The analysis shows that out of the crops examined, barley, sorghum, millet, and rice have the most potential area for expansion. Despite significant methodological and data limitations, the analysis reasonably estimates and maps the naturally suitable biophysical limitations of the crops examined.

CHAPTER 1: INTRODUCTION

Agriculture is one of the most destructive human land uses on the planet, but also one of the most necessary for the survival of human populations (Foley *et al.,* 2005; Turner II *et al.,* 1990). Human inputs and alterations to the landscape through the application of fertilizers, irrigation, and conversion to agricultural land, can have harmful effects such as water pollution, soil erosion and degradation, biodiversity loss, and increased carbon dioxide concentrations in the atmosphere (Foley *et al.,* 2005). With a growing population that is projected to reach 9 billion by 2050 (United Nations, 2009), increasing food production through the expansion of agricultural land is one of the many necessary steps to feed the planet. Additionally, minimizing the adverse environmental effects of food production is becoming more and more crucial as we exceed the "safe operating space" of human-imposed changes to Earth systems (Rockstrom *et al.,* 2009).

By cultivating crops in locations that are naturally suitable for their growth, human inputs to the system can be reduced, which in turn reduces the environmental effects of production. This research aims to determine what these ideal natural biophysical conditions are for seven major crops, where these conditions exist on the planet, and potential areas for expansion of crop cultivation with minimal human alteration to the land. The analysis is modeled after the work of Ramankutty *et al.,* (2002), which calculated an index of suitability of land for natural cultivation. Chapter 2 provides an overview of the basic relationships between biophysical factors and crop growth, followed by a review of global crop models that have examined these relationships. The growing conditions (as found in the literature) of the seven major crops under consideration are presented as well. Chapter 3 explains the specific approach to the analysis, along with the indicators of biophysical conditions that are used. Chapter 4 presents the results of the analysis, which include global maps of suitable cultivable areas for all crops, an analysis of the room for agricultural expansion within the designated ideal areas for crop growth, as well as current crop growth within areas determined to be very biophysically limiting. Chapter 5 concludes the analysis, highlighting the locations most naturally suitable for crop cultivation, which of these areas has the greatest potential for agricultural expansion, and which areas are biophysically limiting to crop growth but still cultivate with increased human inputs. Major limitations, improvements to the analysis, and future research directions and applications are also discussed.

CHAPTER 2: LITERATURE REVIEW

Climatic influences on crops

Climate provides many of the vital necessities of plant life. Temperature, solar radiation levels, and day length all have an effect on crop growth. In order to photosynthesize and grow, vegetation needs adequate solar radiation inputs, which are directly linked to temperature (Grigg, 1984). The spread of vegetation towards the poles is strongly correlated with minimum temperatures that are regularly experienced in the area and the ability of a species to survive these low temperatures. At a certain threshold, depending on the crop, low temperatures can cause damage to the plant structure, decreasing its production potential and survival capacity (Woodward, 1987).

Towards the equator, where temperature and solar radiation levels are high, soil water availability (regulated climatically by the difference between precipitation and evapotranspiration) is a dominant limiting factor of crop growth. In arid regions, temperature and evaporation rates are high but precipitation rates are low and highly variable, limiting the water available to plants for growth. In humid tropical regions, less water may be lost to evaporation, however the variability of precipitation can still be quite high (Grigg, 1984).

Soil influences on crops

At its most basic, soil is simply the substance that plant roots grow in. Soils provide a host for many of the crucial factors in vegetative growth, including structural support, water, air, and nutrients (Brady, 1974). Across the globe and within the field, soils vary in their characteristics -- structure, texture, depth, acidity, and composition are different and are influenced by and interact with other environmental forces, primarily climate, vegetation, and parent material (Grigg, 1984). Because of these interdependencies, it can be difficult to attribute crop distribution solely to soil factors. For example, good soil texture can be an indicator of crop presence because it allows for ideal moisture availability in the soil. However, the amount of moisture present is ultimately depended on rainfall and evapotranspiration, i.e., functions of climate (Grigg, 1984).

While climate is seen as a major determinant of crop growth, and climate influences soil properties, soil can still be used as an important indicator of growing conditions. Crops typically have an ideal soil type or optimum soil conditions for their growth, and these conditions can differ from crop to crop. Some crops also have higher tolerances for less ideal conditions, and can therefore be grown where other crops would not survive (Grigg, 1984).

Terrain influences on crops

Elevation and slope also have an effect on crop growth. The effects of elevation on cultivation, however, are closely linked to climatic effects, as mean annual temperatures decrease with height. The growing season therefore ends earlier in the year and is shorter, and the plant receives less energy to grow. Additionally, in temperate zones, high elevations can experience more variable summer temperatures, which increase the risk of crop failure. High windspeeds are more frequent at high elevations, which can be so strong the grain is shaken from the plant. In many places higher rainfall that leads to more leaching occurs, leaving soils more acidic, which is not tolerated by the majority of crops (Grigg, 1984).

The angle and direction of the land has an influence on the type of farming that is done, as well as the crop types that may be grown. The steeper the slope, the faster water will move down it after a rain or snow event. If natural vegetation is gone, erosion is likely to take place. In Britain, for example, it was found that slopes greater than 11-13° are rarely cultivated (Grigg, 1984). In contrast, flat or low sloping lands can become waterlogged, which can reduce yields depending on the crop. This can be advantageous for the cultivation of some crops, such as lowland rice, which is grown in waterlogged conditions, so must be grown on flat land or terraced slopes. Additionally, the flooding of these areas can supply plant nutrients through the deposition of silt from upstream, which naturally maintains the soil fertility. In places that use mechanized production techniques, steep slopes limit the use of machinery, making it less advantageous to cultivate on sloping areas than on flat land. As such, mechanized cereal production has been proven to be associated with very low slopes in the United States, Russia, Canada, Australia, and Argentina (Grigg, 1984).

Human alterations to exceed physical limitations to crop growth

Humans can alter soils through inputs and management to make them more optimum for crop growth. Fertilizers, for example, can be added to soil that does not provide enough nutrients to the plant, filling that void. With these increased inputs, however, production cost can increase, and there is an economic limitation to the amount of inputs that can be profitably added to the soil (Grigg, 1984). Beyond these economic limits, there are the soil condition limits, where crops can physically just not grow.

Humans can also increase the amount of water available to crops, reducing the limitations imposed by dry conditions, through irrigation. Today, while irrigation occurs on only 15% of all cultivated lands, these lands account for almost half the total crop production in terms of value (Shiklomanov, 2000). Irrigation therefore contributes hugely to the amount of food we are able to produce today, however the extraction and use of water for irrigation can have severe environmental impacts, including species loss and soil salinization (Shiklomanov, 2000).

Terracing is another human alteration to the landscape that is done to expand cultivation onto steeper slopes. Levels of a sloped surface are essentially cut out and flattened, providing a uniform area for crop growth. This is a common technique in southern China, and rice paddies are frequently cultivated on terraces (Grigg, 1984).

Selective breeding of new cultivars of crops has also allowed for humans to overcome biophysical constraints to crop production. The development of more disease-resistant and higher temperature tolerant soybean cultivars made mechanized soybean production in the tropics (specifically Brazil) more feasible (Clay, 2004). Other soybean varieties that tolerate low levels of soil phosphorus have also been developed, which became a major factor in the expansion of soybean production throughout the Amazon (Clay, 2004).

History of global crop models

Several previous studies have performed global scale analyses of climate-crop interactions and cropland suitability. Cramer and Solomon (1993) determined rough global boundaries of potential agricultural areas based on climatic limitations. Cold, dry boundaries in higher latitudes were determined by a minimum number of growing degree days and a threshold value of the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET). Wet, warm limitations to agricultural growth, which occur in the tropics, were determined by minimum monthly temperature and an AET/PET threshold (Cramer and Solomon, 1993).

Leemans and Solomon (1993) used global datasets to calculate growing period lengths and the climatic requirements of ten major crops. Using temperature, precipitation, and soil moisture indicators, the authors constructed a map of growing period length, indicating the primary limiting climatic factor of growth where applicable (Leemans and Solomon, 1993).

While these studies were among the first of their kind, they were limited in their application to cropland suitability analyses, as major contributors to cropland suitability were not included. Biophysically, soil properties and characteristics and terrain are important factors of land for crop growth. None of these factors were included in these studies. Additionally, the final products were a Boolean grid of potential growing areas, and did not indicate if within these growing areas some locations were more naturally suitable than others on a continuum. Ramankutty *et al.* (2002) acknowledged these same limitations, and calculated the natural suitability of the land for growing crops using both climate and soil constraints. With the development of more accurate global datasets for both soil and climate characteristics, this was possible. The authors calculated an index of land suitability for cultivation, giving each pixel at the 0.5-degree resolution a value from zero to one. This analysis was done for cropland in general, and not for different crops (Ramankutty *et al.,* 2002).

A similar analysis – called Global Agro-Ecological Zones (or GAEZ) -- was done by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) in 2000. This study identified the climate, soil, and terrain conditions that limit the growth of different crops under different input and management scenarios and produced a suitability index of land for agriculture at the 5-minute resolution, both for irrigated and rainfed agriculture. GAEZ is continuously updated with the development of new available data, and an updated version using the new Harmonized World Soil Database (FAO *et al.,* 2009) is expected in the near future. The GAEZ methodology was originally known as Agro-Ecological Zones (AEZ) in 1978 when it focused on tropical areas, and did not include the boreal and temperate regions. Leemans and Solomon (1993) simplified and extended the AEZ methodology to the global scale when doing their analysis.

Growing conditions of major crops

Seven different crops are examined in this study: barley, maize, millet, rice, sorghum, soy, and wheat. Here a brief overview of each crop is presented, including their preferred growing conditions as found in the literature.

Barley

Barley is a temperate climate crop that is grown over a broad range of environmental conditions. It grows best where the seasons are cool and moderately dry, and will tolerate heat in dry climate or humidity in a cool climate. In a hot, humid climate, however, barley does not grow well, largely because of the increased presence of disease. Barley ripens earlier than other cereals, which suggests that it requires less heat units than other cereal crops to reach maturity, which allows it to be grown in high latitudes and high altitudes where the summer is too cool or too short for other cereal crops to grow. Because it matures early, barley ripens before soil moisture has depleted. As a result, barley can be grown on more droughty soils and in low rainfall areas, although it does respond well to more rainfall and irrigation. Barley grows best on well-drained, fertile loam or light clay soil. It is more tolerant than other cereals of alkaline conditions and less tolerant of acidic soils, allowing for an acceptable pH range of 6-8.5 for growth (Rasmusson, 1985).

Maize

Maize is widely produced around the world and is adapted to various growing environments with the help of improved varieties through breeding. The CIMMYT Maize Program classifies maize into four types based on these different growing environments. *Lowland tropical* maize is adapted to high mean temperatures and a short daylength during the growing season. Maize has lower yields here than in other environments, as weeds and disease can constrain production. *Subtropical* environments are cooler than the tropics during the growing season, and have longer days. Much of the maize grown here is subject to drought stress. *Temperate* environments have long daylengths allowing for optimum solar radiation for the crop, and yields can be high if moisture is not a limiting factor. *Highland* environments are where maize is grown approximately 1800-3600m above sea level. Here frost is a large constraint to crop growth, and maize grows slowly because of the cool environment (Smith, 2004). The wide range of climate and soil conditions within these four regions speak to the different varieties of maize with varying characteristics, and help illustrate the influence of production practices and human alterations to natural cultivation.

Millet

Millet is a warm weather crop that is a staple food of the semiarid tropics. With high water use efficiency and C_4 photosynthetic pathway, millet is tolerant of hot, dry conditions, and can be grown in agricultural drought conditions, where soil moisture and soil fertility is low. Millet is also tolerant of acidic soils, and the maximum response of millet to fertilizer occurs at a pH of 6.5 (Stoskopf, 1985).

Rice

Rice is the only major food crop that can be grown in standing water, and is commonly classified as either lowland or upland. Lowland rice is grown in almost continuously flooded conditions, such as flat alluvial plains. Upland rice does not require any confinement of water for growth (known as bunding), so is grown under a number of conditions such as hilly fields, in rainfed areas, or with flooding as well. Rice is typically seen as a tropical crop because it is culturally important to many tropical and subtropical regions of the world, however it can be grown in temperate regions, and since it is a C_3 crop, it is more sensitive to high temperatures. Two biotypes of rice are very common and help explain the wide distribution of rice cultivation on the planet and the variability in its growing conditions. One biotype, Indica, is adapted to the tropics, drought tolerant, and lacks cold tolerance, while another biotype, Japonica, is adapted to the temperate zone, is drought intolerant, and cold tolerant. Additionally, rice has photoperiod insensitivity, meaning the number of hours a day of sunlight rice receives does not have a dominant effect on its growth, aiding rice in its ability to flourish in different places (Stoskopf, 1985).

Sorghum

Sorghum is one of the main food grains of the world, and is adapted to hot, semiarid tropical and dry temperate regions of the world (Smith, 2000). Sorghum's main advantage over other cereal crops is its drought tolerance. As such, it is often planted in dry and marginal agricultural areas along with millet and as a substitute for maize, and is usually grown under rainfed conditions (Clay, 2004).

Light, temperature, and day length are considered the major controlling factors for growth, since sorghum is a C_4 crop, yet with the breeding of cultivars, lower-temperature-tolerant strands of sorghum are grown in parts of India, Kenya, Zaire, and Cameroon. Sorghum will tolerate a wide range of soil pH, from 5.0-8.5 (Smith, 2000). Although sorghum can be grown in high moisture stress conditions, in many areas where it is cultivated, moisture as opposed to soil fertility is limiting to growth, so fertilizer applications are not economical (Stoskopf, 1985).

Soybeans

Soybean is a grain legume crop, and the only crop examined here that is not a cereal. Soybean can be traced back to origins in East Asia, but since then has expanded and is now predominately grown in the United States and Brazil, China, India, and Argentina (Clay 2004). The breeding of different soybean strains resulted in the development of cultivars that overcame their "original" limitations to growing conditions (Sommerfield *et al.,* 1985). As such, soybeans can be grown in a range of conditions. In the tropics and subtropics, soybean cultivation commonly follows the harvest of rice, wheat, maize, or sorghum, so it could be deduced that the various soil and climate conditions preferred by these crops are also suitable for soybean production.

Wheat

Wheat is the most widely cultivated crop in the world, and more land is used to produce wheat than any other commodity (Clay, 2004). Wheat is a C_3 crop, so it is less tolerant of high temperatures, and is favored by cool temperatures. Fairly dry conditions are preferred by wheat, as high moisture levels can lead to the growth and spread of disease (Stoskopf, 1985). Different cultivars of wheat are tolerant of pH ranging from moderately acidic to slightly alkaline (5-8) (Brady, 1974).

CHAPTER 3: DATA AND METHODOLOGY

Overview of approach

Global datasets of different crops and climate and soil characteristics were used within Geographic Information System (GIS) software to determine the relationships between croplands and physical conditions. GIS was then used to construct a suitability ranking of land for the cultivation of specific crops. This research is based on the suitability of land for cultivation analysis done by Ramankutty *et al.* (2002). The fundamental difference is that this analysis examines the relationship between *individual* crops and climatic and soil characteristics, not all croplands.

Harvested crop area data

Datasets of the harvested area of seven crops were obtained from the global study of Monfreda *et al.* (2008) at 5-minute resolution in latitude by longitude. Each grid cell value represented the harvested area of a crop within a pixel as a proportion of the pixel's area. Monfreda *et al.* (2008) combined agricultural census statistics compiled for various administrative units (national, provincial/state, county/municipal/district, etc.), with a global dataset of croplands derived from a combination of remote sensing and census statistics, to create spatial datasets of the harvested area and yield of 175 different crops. In this analysis, absolute harvested area per pixel (km^2) was used to represent crop distribution.

The crops examined here are barley, maize, millet, rice, sorghum, soybean and wheat. Maize, wheat, rice, and soybean were chosen because they are some of the most highly produced crops today. Millet and barley were selected to examine how this approach works for strictly warm and cold weather crops, respectively. Sorghum was investigated as a warm weather crop as well, and its potential for increased substitution for maize in the future made it an interesting crop to examine. All were cereal grain crops with the exception of soybean, a leguminous crop.

Indicators

The indicators of climate and soil conditions used here and described below are similar to those used in Ramankutty *et al.* (2002). Since 2002, improvements have been made to many of these datasets, including higher spatial resolution.

Soil carbon density

Soil carbon density is a measure of the amount of carbon present in the soil, usually expressed in grams per square centimeter. Soil organic matter is composed mostly of carbon, making carbon density a good indicator of the amount of organic matter present in a soil (Clay, 2004).

Organic matter is a good indicator of soil fertility because its presence aids processes and activities that are crucial for plant health. Soil organic matter helps give the soil structure, keeping it loose and open so the soil can be properly aerated. The water holding capacity of soil with organic matter in it is increased, making more water available to plant roots for growth. Important macronutrients, such as phosphorous, sulfur, and nitrogen are all found in organic matter. The decomposed litter also serves as the main energy source for soil microorganisms, which break down the organic matter and make important nutrients available for plant uptake (Brady, 1974).

For this analysis, the IGBP-DIS (2000) global dataset of soil carbon density for the top 30 cm of soil was used at the 5-minute resolution in units of kilograms of carbon per square meter (kg C/m^2).

Soil pH

Soil pH is a measure of the hydrogen ion concentration in the soil, and therefore the acidity or alkalinity of the soil. The concentration of hydrogen ions affects the availability of nutrients for absorption by plant roots. For example, at a pH below 5, aluminum, iron, and manganese become so soluble in the soil that they are toxic to many plants. Low pH values are also associated with decreased presence of microbial activity in the soil, which is not advantageous for plant productivity. In general, a pH range of 6-7 (slightly acidic to neutral) allows for the most availability of the most nutrients that are advantageous for plant growth (Brady, 1974).

IGBP-DIS (2000) pH data for the top 30 cm of soil at the 5-minute resolution was used for this analysis.

Growing degree days (GDD)

GDD is a measure of the heat energy received by a crop over a period of time, and can be thought of as "heat units" (McMaster and Wilhelm, 1997). GDD has been shown to be a good indicator of the phenological development of a crop, especially compared to indicators such as time of year or number of days (McMaster and Wilhelm, 1997; Rotter and Van De Geijn, 1999). Annual GDD was used in this analysis as an estimate of growing season length.

GDD was determined using the mean monthly temperature dataset of New *et al.* (2002). This climatic data was interpolated from station measurements over 1961-1990 and is at 10-minute resolution. GDD was calculated using the same method as Ramankutty *et al*. (2002), where GDD is the annual sum of daily mean temperatures over a base temperature of 5°C :

$$GDD = \Sigma \max(0, T_{avg} - 5) \qquad (1)$$

Daily mean temperatures were linearly interpolated from the New *et al.* (2002) monthly averages. The grid was then interpolated to 5-minute resolution to match the spatial resolution of the other datasets used.

Moisture Index

The amount of moisture available to crops was estimated here as the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET), as originally used by Cramer and Solomon (1993). The AET and PET data used here is from the PEGASUS global crop model of Deryng *et al.* (in press), which is built around the same simple surface energy and water balance model of Ramankutty *et al.* (2002). Deryng *et al.* (in press) used the updated version of the New *et al.* (2002) climate data for their calculations. The ratio AET/PET was obtained from the model at 10-minute spatial resolution and interpolated to 5-minute resolution for this study.

Methodology

Each climate or soil characteristic dataset (GDD, soil moisture index, carbon density, and pH) was classified into broader groups of values, or “bins”. In a GIS the percent of total harvested crop area within each bin was calculated.

The bins were then ranked according to the percentage of total crop harvested area they contained. In descending order (bin with highest percentage of total harvested crop area to bin with lowest percentage of total harvested crop area), the cumulative totals of harvested crop area percentage were calculated. Bins that corresponded with the top 66% of total crop area were ranked highest, or 'ideal', with 66-98% ranked lower, or 'moderate', and the bottom two percent (98-100%) ranked the lowest, or 'very limiting'. In other words, the values of climate and soil characteristics represented by the highest-ranking bins are the conditions that are associated with where the largest amount of each crop is grown. Therefore, these conditions were interpreted as the ideal conditions for the crop in question's growth.

For each crop, the result was four grids, one for each of the four climate and soil indicators, with indicator values ranked in the grids as 'ideal', 'moderate', or 'very limiting' to that crop's growth. These four grids were then overlayed and reclassified, so areas with an ideal rank present for all four climate and soil indicators were classified as having 'no limiting factors' to the cultivation of the crop in question. Areas with three indicators ranked as ideal and one indicator ranked as moderate were classified as having '1 moderately limiting factor'. This continued, so areas with two indicators ranked as ideal and two indicators ranked as moderate were classified as having '2 moderately limiting factors', and so on. When one or more of the indicators in an area was ranked as very limiting, the area was classified as having '1 or more very limiting factors'. The end result was a global classification of land by the presence of preferred biophysical conditions to crop growth.

The regions of the world depicted by this analysis as having ideal growing conditions (i.e., no limiting factors) were then overlayed with a dataset of total cropland area (expressed as a proportion of pixel area). This was done to examine if areas that are ideal for a specific crop's growth coincide with areas that do not already have a high proportion of cropland, in order to pinpoint areas that may have additional land available for crop expansion. Lastly, the regions with very limited growing conditions for each crop were overlayed with the current harvested area for each crop. In doing so, areas which cultivate relatively more of a crop within very limiting conditions were identified, indicating regions where crops are grown with high human inputs that alter the non-ideal natural conditions for growth.

CHAPTER 4: RESULTS AND DISCUSSION

Different crops and their soil and climate relationships

Figures 4.1 and 4.2 show the percent of each crop's total harvested area within each climate and soil variable bin. The rankings assigned to each bin for each crop, including the percentage breakdown of each crop within the bins, and the percentage of harvested crop area in each rank are listed in **Appendix A and B, respectively**. **Table 4.1** summarizes the climate and soil conditions for each crop that were ranked 'ideal'.

GDD

Overall, many of the results are consistent with the growing condition limitations described in the literature. High percentages of most of the C_4 crops (millet, sorghum, maize), which are more efficient photosynthetically under high temperatures than C_3 crops, occur at locations with high GDD values. An exception to this is maize, which is present in a wider range of GDD values. This is probably due to the development of different cultivars of maize that can tolerate cooler conditions, and its resulting expansion globally. Although it is a C_3 crop, the highest percentage of rice is grown at high GDD values. This is perhaps explained by lowland rice cultivation in the tropics, and the importance of rice production for the livelihoods of subtropical and tropical region people. A high percentage of rice is also grown at lower GDD values, which is perhaps representative of temperate cultivation. Very high percentages of barley are present at lower GDD values, as expected because barley is a cold-weather crop. Soybean is present over a wide range of GDD values, similar to maize, but has three "peaks" of high percentages that are classified as ideal, which may be due to the high concentration of soy production in three areas of the planet. The first peak (GDD 1,600-3,200) is most likely explained by soybean cultivation in the Midwestern United States, the second peak (GDD 4,000-4,800) by growth in Argentina and Brazil, and the third peak (GDD 7,200-8,000) by cultivation in India.

Moisture index

The highest percentages of millet and sorghum occur at relatively low moisture index values. This is expected, as these crops have high water use efficiencies and as a result are usually grown in drier areas. Rice, in contrast, is mostly grown in regions with a very high moisture index, which may be explained by its common cultivation in flooded areas where AET would be close in value to PET. A high percentage of soybeans are also grown at a high moisture index. Wheat is almost perfectly normally distributed over the range of moisture indices, which perhaps is expected, as it is the most widely grown crop on the planet. Maize is also grown in a wide range of moisture index values, but is more skewed towards higher moisture areas.

Soil Carbon Density

Ramankutty *et al.* (2002) derived from the soil carbon density-cropland relationship that the optimum range of soil carbon in the soil for all croplands on average is 4-8 kg C/m^2. This can be used as rough reference for what typically soil carbon density is for croplands. Millet and sorghum are the only crops with high percentages of cultivation at soil carbon density values outside of this range. Their ideal values are 2-5 kg C/m^2, which could be explained by the low productivity of vegetation in the drought-prone areas these crops are grown in, so there is little organic matter to be decomposed. All of the other crops have the same ideal carbon density values of 4-7 kg C/m^2. The distribution of rice within these values, however, is perhaps unexpected. Because much of rice is grown in lowland, waterlogged conditions, which have high soil carbon densities, it is interesting that there is more rice grown at soil carbon densities of 4-5 kg C/m^2 than at higher values.

pH

With the exception of rice, all the examined crops have the same ideal pH values of 6.0-7.9. The highest percentage of rice grows in areas with a pH of 6, however high percentages of rice are also grown at pH of 5 and 7, and even the lowest ranked pH, 8, has approximately 5% of total rice grown in it. This wide range of pH can be explained by the ability and tendency of rice to grow in submerged soils, as when acidic soils are submerged they become less acidic, and alkaline soils become less alkaline (Stoskopf, 1985). While the distribution of crops within the pH bins varies somewhat when compared to each other, when the bins are ranked this variation is lost, and the pH of 6.0-7.9 is classified as ideal for all crops examined except for rice.

Combined biophysical limitations to crop growth

The top panels of **Figures 4.3-4.9** are the resulting maps of the biophysical limitations to each crop's growth as determined by combining the ranked soil and climate characteristic maps.

The biophysical conditions for barley cultivation (**top panel, Figure 4.3)** are dominantly ideal (have no limiting factors to growth) in northern latitudes, more so than for any of the other crops examined. These areas with ideal barley conditions include areas of current barley cultivation in the Canadian prairies and Europe, as well as areas that do not currently grow much barley, such as across Asia to Mongolia, the central United States, and northeast Russia. The analysis does not capture much area that grows barley in South America (parts of Bolivia, Peru, and Argentina) as ideal for cultivation. This could be explained by the fact that most of the barley grown is concentrated in Europe and Canada, skewing the ideal conditions to be similar to these areas, or perhaps barley is grown in South America under non-ideal conditions.

Sorghum's ideal biophysical conditions **(top panel, Figure 4.4)** are concentrated in the tropics, in the Sudan region of Africa, India, northern Australia, and eastern Brazil. These ideal condition locations are identical to those for millet cultivation **(top panel, Figure 4.5)**. No sorghum or millet is currently grown in Australia where the biophysical conditions are ideal according to this analysis. The area of the United States that grows sorghum, although it does not cultivate much sorghum, is classified as having 2-3 moderately limiting factors present. pH is the only indicator present at its ideal value for sorghum growth when there are three moderately limiting factors. Soil carbon density and pH are ideal for growth when there are two moderately limiting factors present. This perhaps suggests that in the United States climate (GDD and moisture index) is more limiting than soil (pH and carbon density) for the cultivation of sorghum.

While the areas with no limiting factors for millet and sorghum cultivation are the same, the areas with moderately limiting factors are different for each crop. There are 2-3 moderately limiting factors to millet cultivation present in the Ukraine and nearby parts of Russia, where sorghum cultivation is ranked as very limiting due to low GDD values. The very limiting classification of sorghum cultivation therefore restricts sorghum in northern areas where millet cultivation is only moderately limited by soil and climate. Similar conditions occur but in reverse in China, where millet cultivation is very limited and sorghum cultivation is only moderately limited by biophysical factors.

The areas with no limiting biophysical factors to rice cultivation (**top panel, Figure 4.6**) occur in many places where rice is not currently grown today. While the analysis categorizes most of the Indo-Gangetic plain and parts of southeast Asia that cultivate high concentrations of rice as ideal, areas that cultivate less rice or none at all are also ranked as having no limiting biophysical factors. These areas include tropical rainforest zones of Africa, particularly Gabon, Cameroon, and the Democratic Republic of Congo, and central Brazil, Colombia, and Guyana. GDD is a moderately limiting factor in almost all of the non-ideal areas in the south-central United States and China, which are roughly at the same latitude and therefore have similar GDD.

The analysis also suggests that areas with ideal biophysical conditions for soybean cultivation (**top panel, Figure 4.7**) extend into the Ukraine and Russia, France, and Italy, but do not occur in the parts of Brazil, Argentina, and Paraguay where high soybean yields occur today. This could possibly be explained by the fact that the distribution of total soybean harvested area within GDD bins (**Figure 4.1**) is relatively uniform for soybeans, or at least a relatively large percentage of soybeans are harvested within many different GDD ranges. The GDD range that was categorized as ideal, however, encompasses soybean growth within the United States, and GDD ranges that occur in South America were not chosen as being ideal. Therefore, the conditions chosen as ideal are skewed by the high production of soybeans in the United States, even though it is known that soybeans are cultivated in large amounts in Brazil, and similar GDD values to the ideal ones occur along the areas of Europe and Asia, contributing to their classification as land with no limiting biophysical factors.

Wheat (**top panel, Figure 4.8)** has a larger area of no limiting biophysical factors to cultivation then any of the crops analyzed. Most of these areas include places that already cultivate large portions of the world's wheat, such as the central United States and northward in the Canadian prairies, and eastern China. The northern-most portion of the Indo-Gangetic plane, however, is ranked as moderately limiting, despite the large amount of wheat cultivation that occurs there today. The analysis classifies parts of Mexico and parts of the Russian steppe and Kazakhstan as ideal for wheat cultivation when relatively small amounts of wheat are grown there today.

Areas of no limiting biophysical factors to maize cultivation (**top panel, Figure 4.9**) encompass the Midwestern United States and eastern China where large concentrations of maize are grown. Interestingly, Central America, which is where maize is thought to have originated, is ranked as having moderately limiting factors to maize cultivation (Staller *et. al,* 2006). With the development of new cultivars of maize, and its increased tolerance to different conditions, maize can be grown in many areas, and perhaps the high percentages of maize grown in the United States and China have biased the analysis of ideal conditions for growth. Concentrations of ideal conditions are present in parts of Brazil/Bolivia and Argentina, yet the areas of these countries that actually grow maize are ranked as having 3-4 moderately limiting factors (with GDD being the ideal characteristic).

Potential areas for future crop expansion

The biophysical limitations to the cultivation of different crops indicates potential areas for agricultural expansion, given the indicators used and their associated limitations. However, while the analysis suggests ideal areas for cultivation for all of the crops apart from where they are currently grown, these areas may already be growing other crops and do not have the capacity for further expansion. The middle panels of **Figures 4.3-4.9** examine this problem by displaying the total area of all croplands within the ideal cultivation area of each of the major crops analyzed.

Barley, sorghum, millet, and rice have more areas with ideal conditions where there is also little total cropland than wheat, corn, and soybeans do (**middle panels, Figures 4.3-4.9)** This could perhaps be explained by the fact that barley sorghum, millet, and rice are tolerant of more extreme conditions than other crops. The ideal condition areas for barley that have the greatest potential for expansion according to this analysis are concentrated in northern China, east Mongolia, and northeast Kazakhstan. Sorghum and millet have identical ideal areas for cultivation, with the greatest potential for expansion occurring in eastern Brazil, the Sudanian Savanna in Africa, and northern Australia. Areas with greatest potential for expansion of rice include parts of Brazil, Colombia, Guyana, the Democratic Republic of Congo, Gabon, south Cameroon, south Chad, select areas of western Africa, and Southeast Asia.

Soybeans have fewer areas with expansion potential; the largest concentration occurs along the border of southwestern Brazil, Bolivia, and Paraguay. Other areas are scattered across Europe and China, and a small portion of eastern Texas. The potential areas for wheat expansion include the center of South America, as well as the central United States, Western Sierra Madre, northeast Kazakhstan, and parts of northern China. Similarly, potential areas for maize expansion are a cluster in the center of South America, the Western Sierra Madre, and northern China, as well as the Yucatan peninsula.

Current crop cultivation within biophysically limited regions

There are more natural limitations to the cultivation of crops than the ones discussed here, such as slope and terrain, as well as the distribution of sunlight and water within a year (seasonality). That said, perhaps the areas classified as very limiting to cultivation in this analysis narrow down the ‘unsuitable’ lands for cultivation more accurately, and examining these areas can provide us with a general picture of where it would not be possible to cultivate without significant human alteration to the landscape.

The bottom panels of **Figures 4.3-4.9** show the harvested area of each crop within regions classified as having one or more very limiting factors for the cultivation of that crop. The majority of the very limiting regions contain no harvested area of their respective crop, but there are some areas that do contain high proportions of harvested area. Where this is the case may be indicative of human alterations to the natural conditions to make them more suitable for cultivation. It is also possible that these areas indicate weaknesses in the analysis, and that those areas are fairly suitable for cultivation, but are just not accurately captured by the model.

Some of the regions that have high crop areas where soil and climate factors are very limiting also have a large percentage of area equipped for irrigation (Siebert *et al.,* 2007). This suggests that these areas are able to be cultivated because irrigation water is supplied. The Nile River delta in Egypt, which has a large percentage of area equipped for irrigation, is included in the very limiting areas for all of the crops, and higher amounts of rice, wheat, maize, soybean, and barley are grown there. The same is true for the Indo-Gangetic Plain and rice, wheat, barley, and millet cultivation, as well as for eastern China and rice, soybean, wheat, sorghum, and millet growth. Other areas, such as the central United States and southern California, have large percentages of area equipped for irrigation, but are not included as very limiting regions for wheat, rice, maize, barley, and soybean. These areas are heavily irrigated, causing stress on the water resources of the surrounding regions, yet they are not classified as very limiting. Perhaps this is because the conditions that exist there are naturally suitable for cultivation, however humans still irrigate in order to maximize yields.

Limitations

The global scale of this analysis presents certain limitations. Data accuracy at the global scale is a primary one. It is assumed that the value of each 5-minute pixel is the condition across the entire cell, when in reality it is most likely an average, and conditions vary across the cell. This is especially true with the soil datasets, as there can be huge variation in soils within a field, let alone a 5-minute pixel. Moreover, the 5-minute resolution for most of these data sets is just a pseudo-resolution to enable global analysis and use within models, the real accuracy is at a coarser scale, therefore pixel-specific results should be treated with caution.

The method used here to determine crop cultivation conditions has some circularity. The values of GDD, the moisture index, soil carbon density, and soil pH that are classified as ideal, moderate, and very limiting are based on where the crop is grown today. Areas are ranked by how naturally suitable they are for cultivation, but this is based on not completely natural cultivation patterns. Therefore, perhaps a better interpretation of the biophysical limitation maps **(top panels, Figures 4.3-4.9)** is that the ideal rankings indicate locations that will not need additional human alterations or inputs than already present in the location that most of the crop is grown at.

The variables that are analyzed here to determine cultivation conditions, while they encompass important aspects of crop growth, are not the only determining factors of where a crop is grown or what a crop needs to survive. For example, low slope is an important factor for lowland rice cultivation, and may have more of an influence on where lowland rice is cultivated than the other variables examined. Additionally, it is important to keep in mind that there are other factors outside of the biophysical ones that have a large influence on where crops are grown, such as cultural preference and economic demand, and these are not included in this analysis.

CHAPTER 5: CONCLUSION

Summary of main findings

This research shows that the naturally suitable biophysical conditions for crop growth are reasonably estimated and mapped using simple spatial analysis with growing degree days, moisture index of AET/PET, soil carbon density, and soil pH as climate and soil indicators of growing conditions. Some locations possess the natural ideal growing conditions for multiple crops, suggesting that they are advantageous for the minimal-input growth of most crops, according to this analysis. The general Midwest and Central United States area and parts of the Canadian prairies, for instance, are ideal for maize, barley, soybean, and wheat cultivation. Those four crops are also ideally suited for growth in other locations, most notably across Europe, western Russia, and northeast China. Most of India, the Sudanian Savanna, and northern Australia are found suitable for both millet and sorghum cultivation. Rice exhibits a closer pattern of ideal growth locations to millet and sorghum than to the other crops, as its ideal conditions concentrate in tropical areas, including much of South America, parts of Africa, and Southeast Asia.

Out of these areas with ideal growing conditions for multiple crops, the areas that possess the most room for cultivation (i.e., with the least amount of cropland currently) are western Russia for maize, barley, soybean, and wheat, and the Sudanian Savanna, northern Australia, and eastern Brazil for millet and sorghum. Central South America and tropical Africa show the most potential for rice cultivation. Overall, barley, sorghum, millet, and rice are crops that have the most potential area for expansion, suggesting that agricultural production can expand in the future with the least human inputs by cultivation of these crops.

Much of the existing cultivation in areas that are very biophysically limiting to crop growth occurs where irrigation systems are in place. This provides evidence of human alteration of the land that circumvents natural growth limitations. The Nile River delta, Indo-Gangetic Plane, and eastern China all have large irrigated areas that grow the majority of the crops examined here, even though this analysis shows those regions are naturally very biophysically limiting to crop growth.

Notable caveats to the results

For some crops (soybeans, wheat, and maize) the difference between the bins of an indicator that were classified as 'ideal' and as 'moderate' were likely not statistically significant. The resulting biophysical limitation maps of those crops therefore present with less confidence than maps where crops have more statistically significant distinctions between harvested area within indicator bins (such as barley, millet, and sorghum).

This analysis demonstrates, therefore, that barley, millet, and sorghum are more biophysically limited than rice, soybeans, wheat, and maize, since their graphs of percent harvested area within the indicator bins (**Figures 4.1-4.2)** are less uniformly distributed. However, those crops (barley, millet, and sorghum) may naturally grow in more places than those labeled as ideal, they just may not be culturally or economically preferred. This is the case with millet and maize, as millet is more drought tolerant and there is a higher demand for maize, so millet is only cultivated where maize cannot be grown (Stoskopf, 1985). Hence the ideal growth conditions for millet appear to be these drier, less fertile areas, when in reality millet is capable of natural cultivation in the same conditions as maize. Thus, the resulting figures of biophysical growth limitations are probably more concise for crops like barley, millet, and sorghum, with the caveat that economic and cultural preference may limit growth in the ideal areas.

Future analysis

Including more biophysical factors, such as slope, to determine areas suitable for cultivation could improve this research. Further, some biophysical indicators are more influential on different crops than on others, and tailoring a biophysical limitations map to consider only the most relevant factors for a particular crop may make the analysis more precise. Additionally, calculating a more sophisticated relationship between the crop and soil and climate indicators, and then using that relationship to create a true zero to one index (as in Ramankutty *et al.,* 2002), would result in more accurate biophysical limitation maps for individual crops.

This work has potential for use as a guideline for policy makers, aid agencies, planners, or anyone attempting large-scale cultivation while minimizing inputs. It is most useful, however, at the preliminary level; there are many other complex factors that determine if growing a crop is a good environmental, cultural, or economic choice. Despite that, the analysis and the maps shown here provide initial suggestions of potentially suitable crops for areas across the planet.

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TABLES

Table 4.1: The different values of the climate and soil indicators that are ranked as ideal for each crop. The number of bins included in the ideal range is given in parentheses.

Ideal Conditions (number of bins)				
Crop	**GDD, day °C**	**Moisture Index**	**Carbon Density, kg/m^2**	**pH**
Barley	8,000-3,200 (3)	.30-.69 (4)	4-7 (2)	6.0-7.9 (2)
Maize	1,600-4,000; 7,200-8,000 (4)	.50-.79 (3)	4-7 (2)	6.0-7.9 (2)
Millet	7,200-8,800 (2)	.20-.49 (3)	2-5 (2)	6.0-7.9 (2)
Rice	6,400-8,800 (3)	.40-.49; .70-.89 (3)	4-7 (2)	5.0-6.9 (2)
Sorghum	7,200-8,800 (2)	.20-.49 (3)	2-5 (2)	6.0-7.9 (2)
Soybean	1,600-3,200; 4,000-4,800; 7,200-8,000 (4)	.60-.79 (2)	4-7 (2)	6.0-7.9 (2)
Wheat	1,600-4,000; 7,200-8,000 (4)	.30-.69 (4)	4-7 (2)	6.0-7.9 (2)

FIGURES

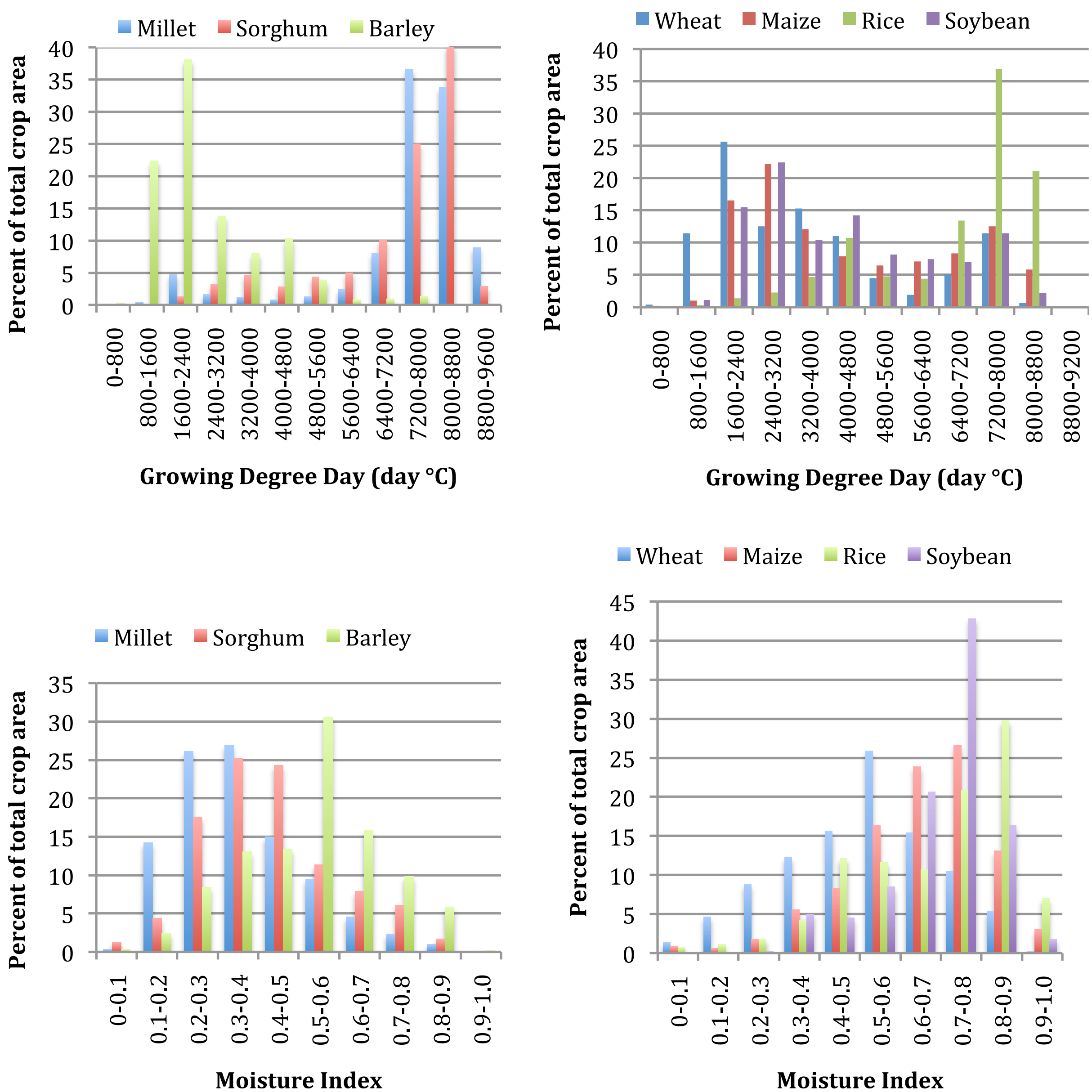

Figure 4.1: Percentage of total harvested crop area present at different values of the climate indicators.

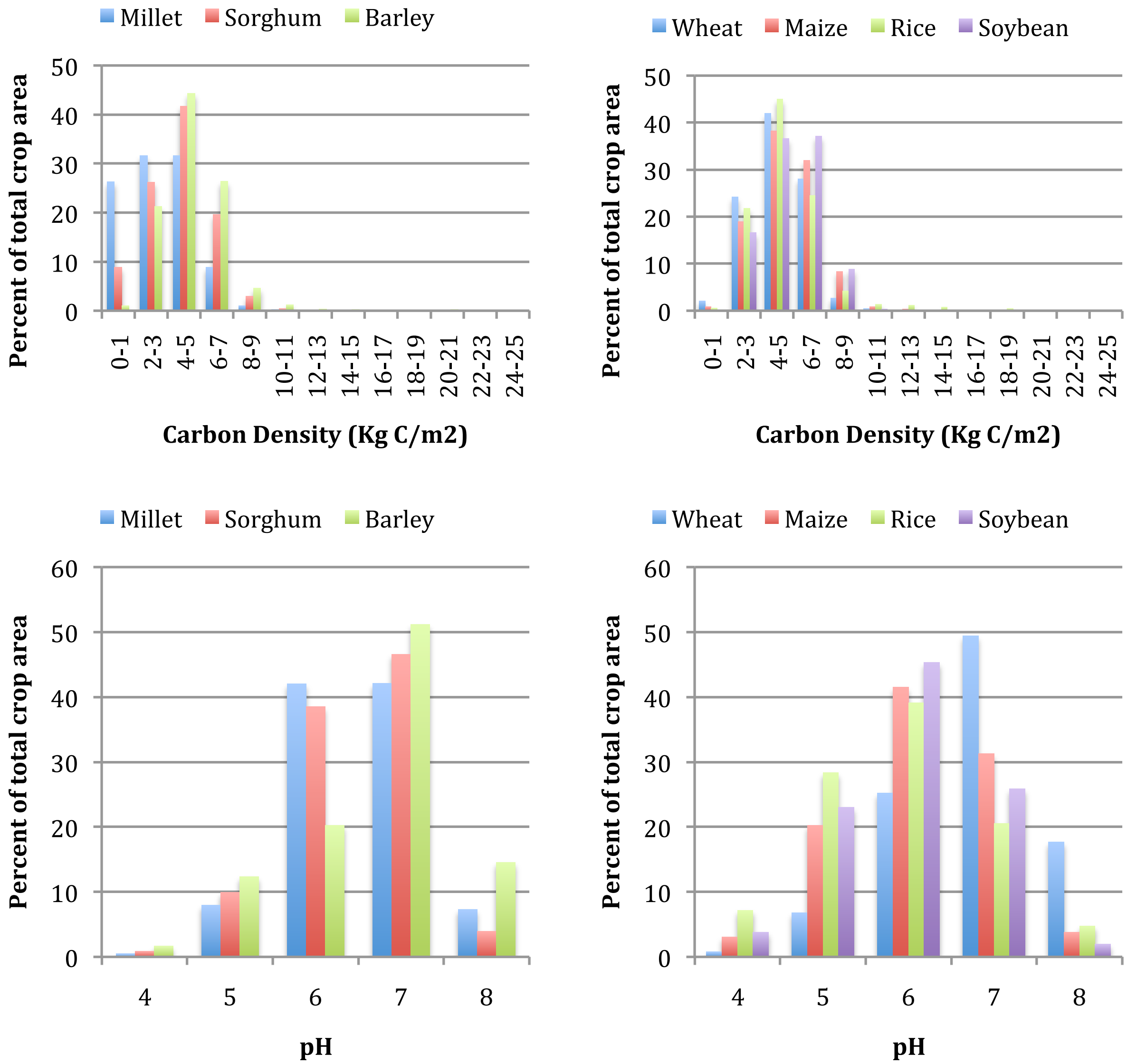

Figure 4.2: Percentage of total harvested crop area present at different values of the soil indicators.

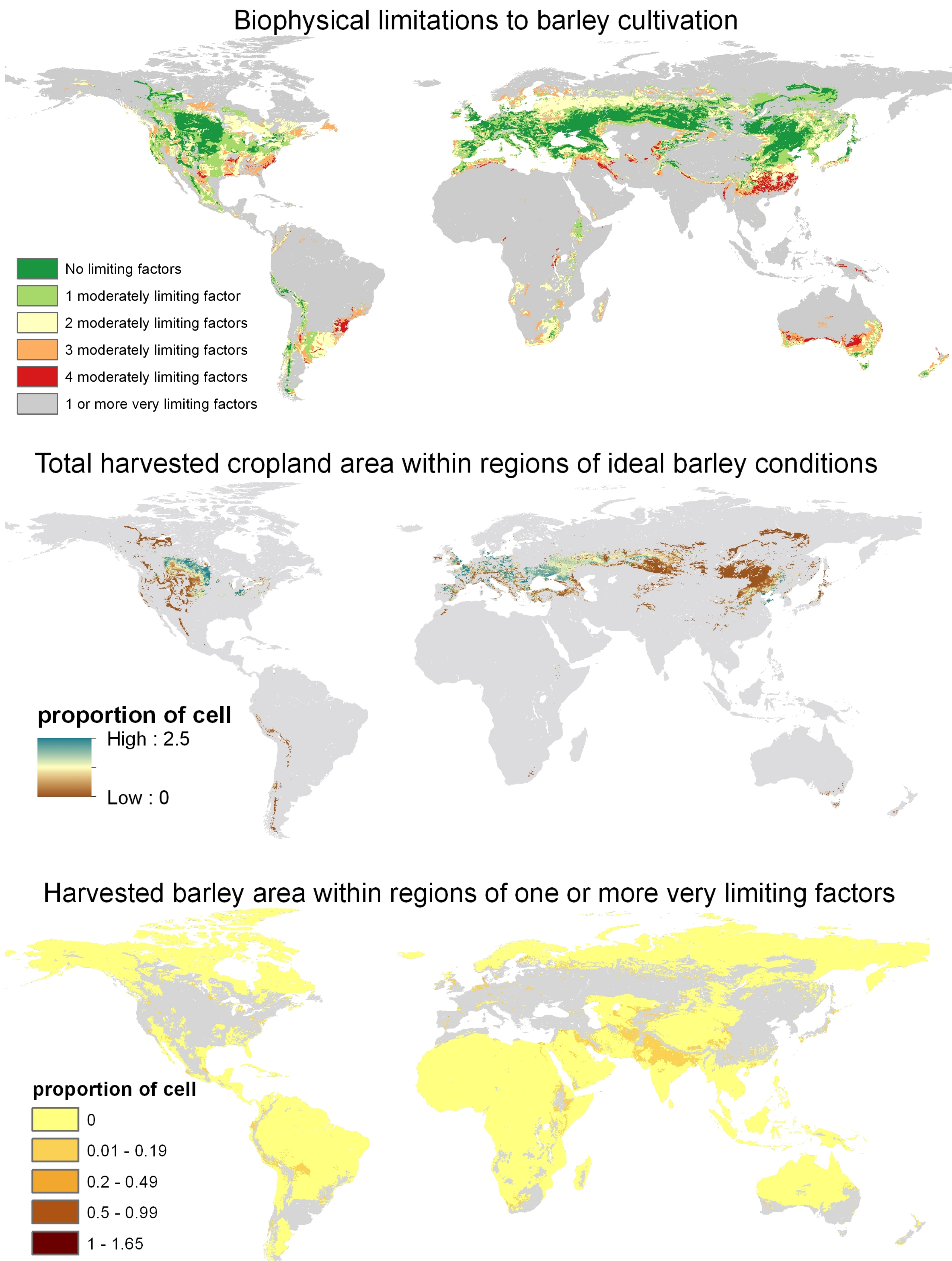

Figure 4.3: The calculated biophysical limitations to cultivation of barley (top panel), harvested area of all croplands within ideal cultivation regions of barley (middle panel), and harvested area of barley within regions of one or more very limiting factors (bottom panel).

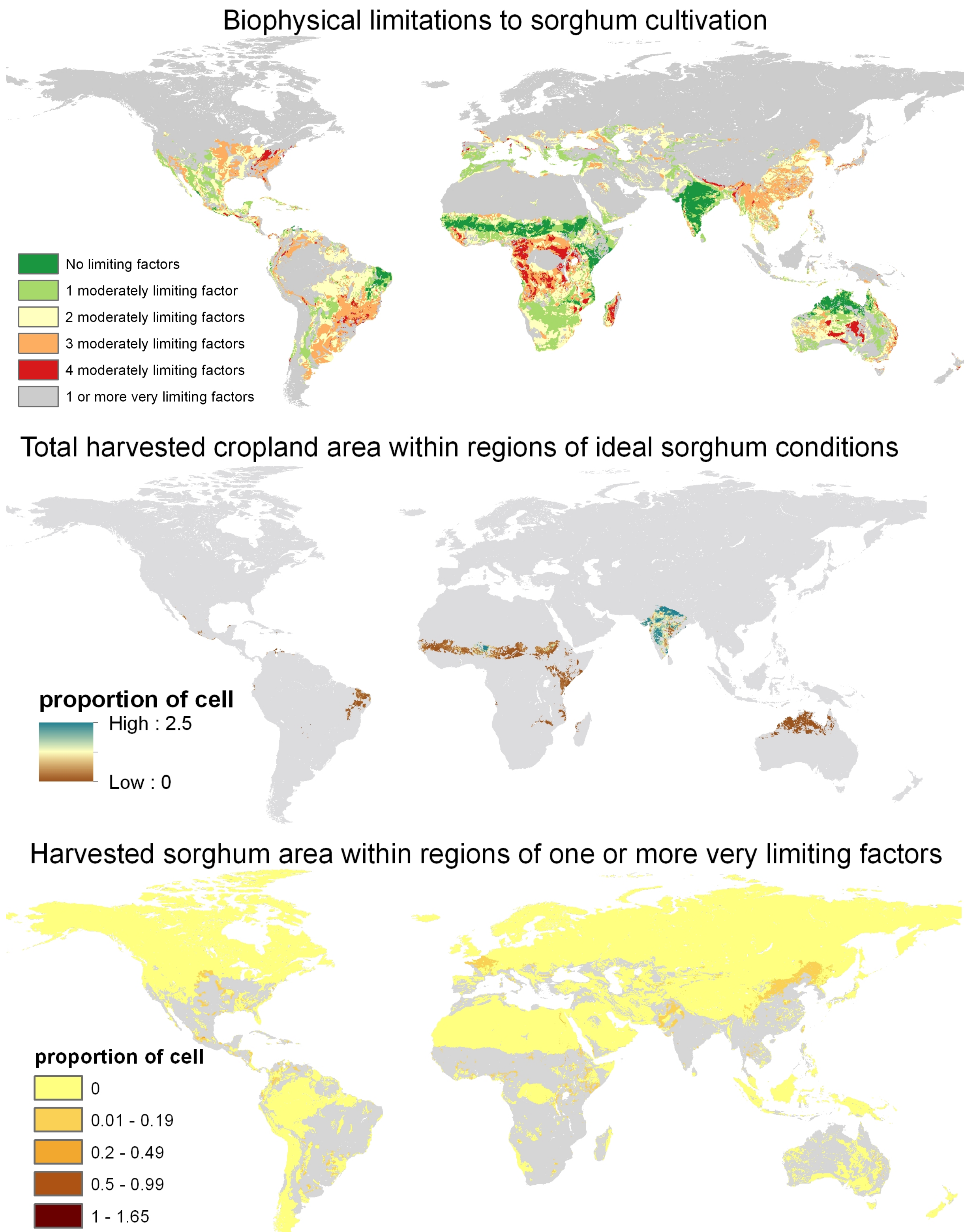

Figure 4.4: The calculated biophysical limitations to cultivation of sorghum (top panel), harvested area of all croplands within ideal cultivation regions of sorghum (middle panel), and harvested area of sorghum within regions of one or more very limiting factors (bottom panel).

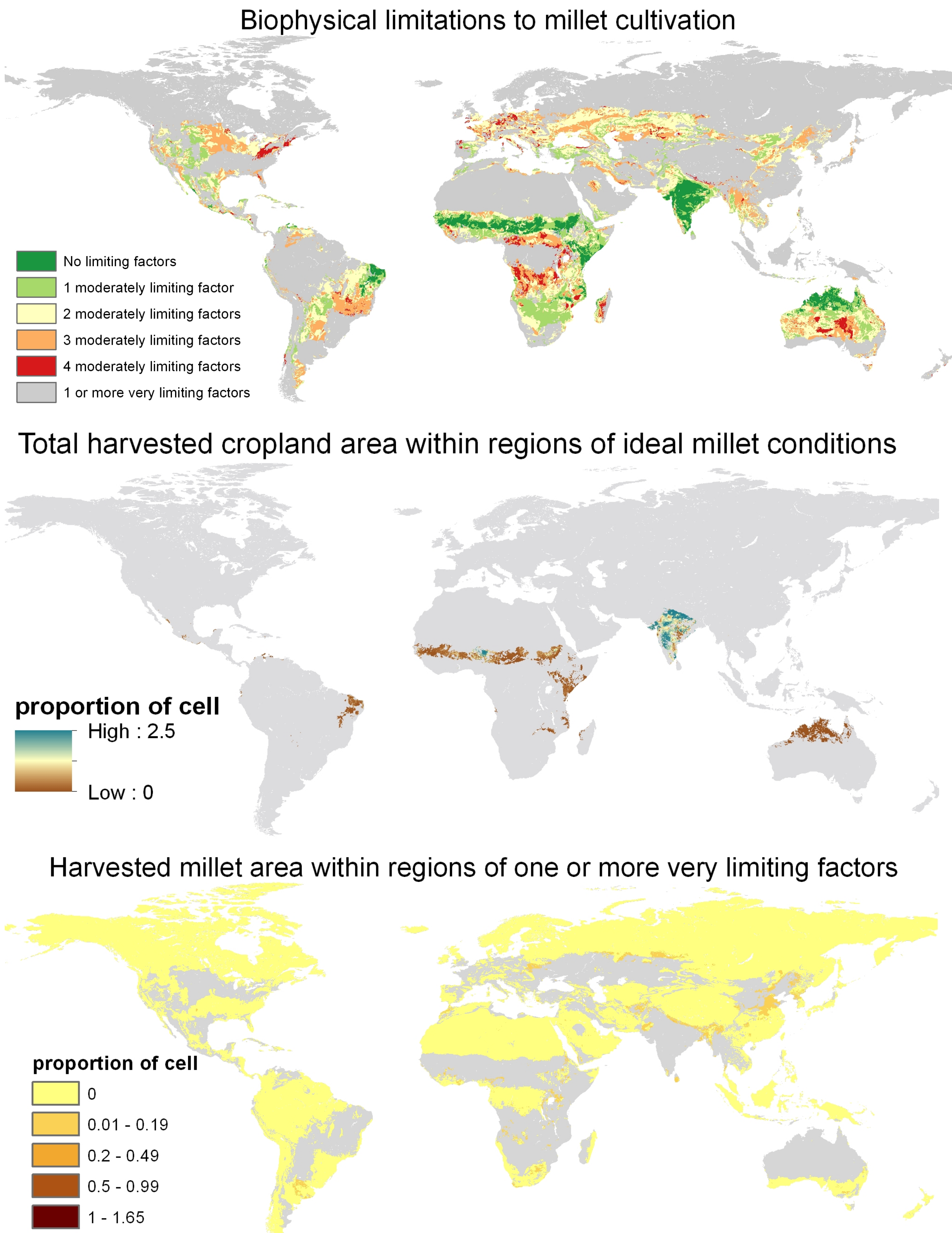

Figure 4.5: The calculated biophysical limitations to cultivation of millet (top panel), harvested area of all croplands within ideal cultivation regions of millet (middle panel), and harvested area of millet within regions of one or more very limiting factors (bottom panel).

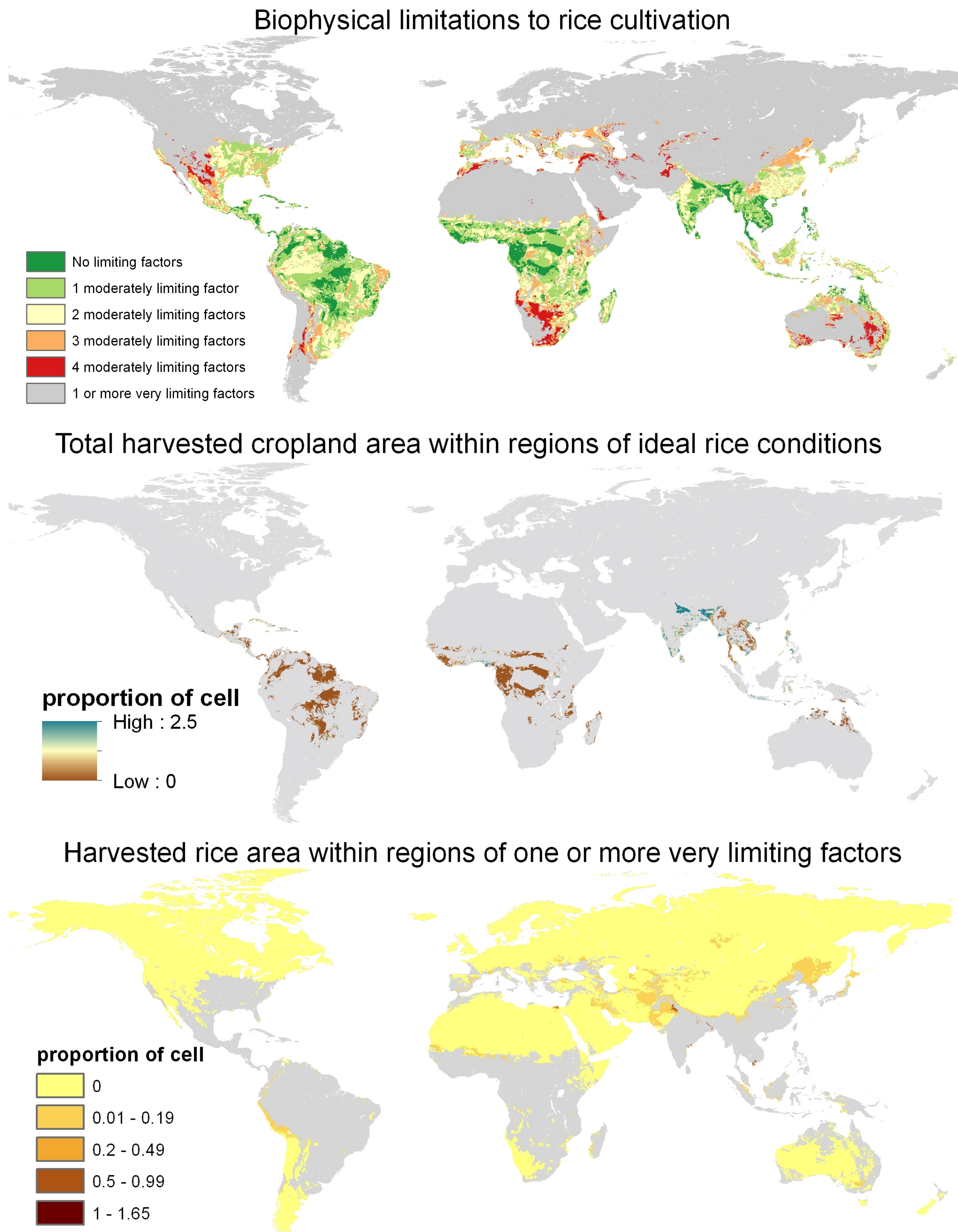

Figure 4.6: The calculated biophysical limitations to cultivation of rice (top panel), harvested area of all croplands within ideal cultivation regions of rice (middle panel), and harvested area of rice within regions of one or more very limiting factors (bottom panel).

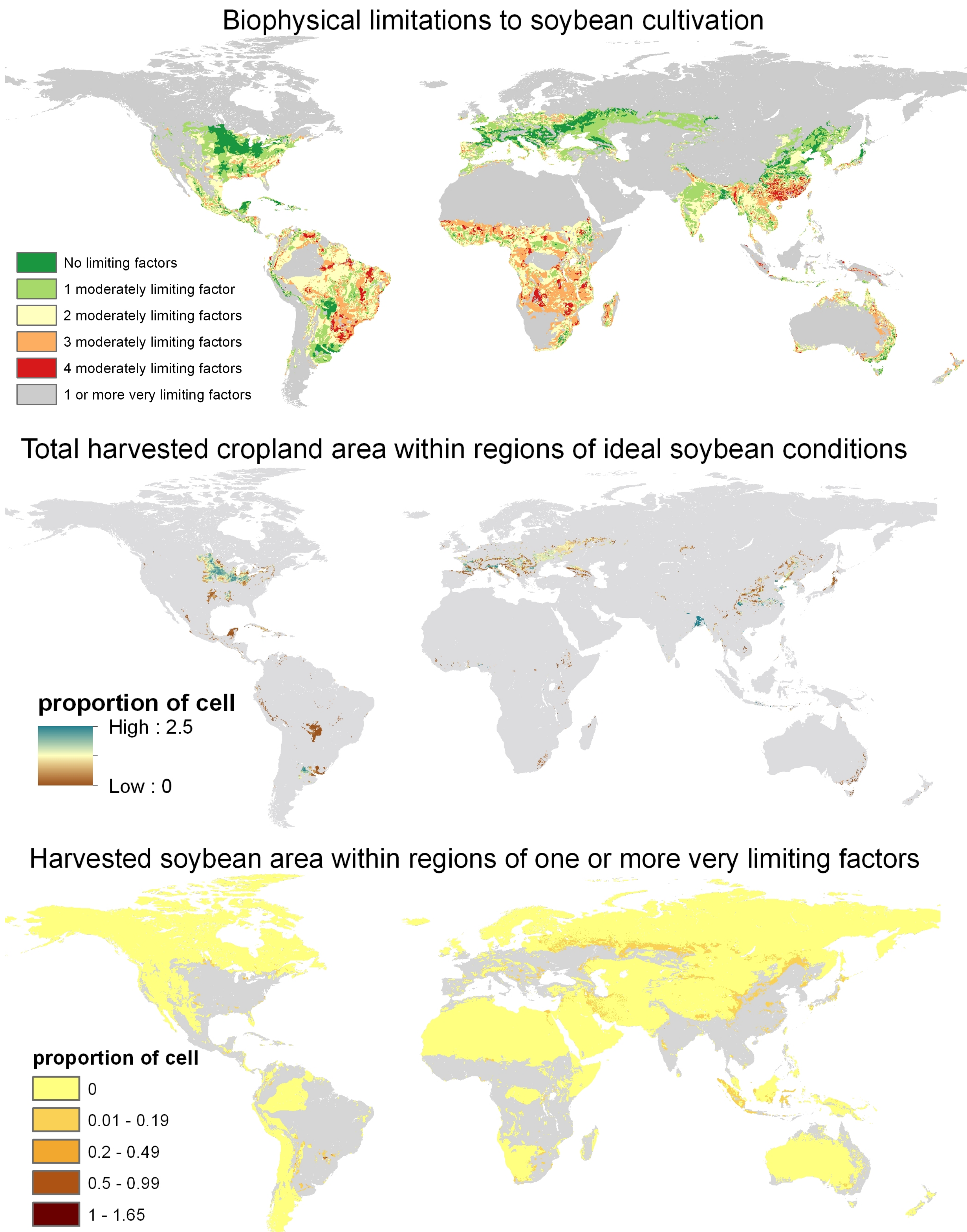

Figure 4.7: The calculated biophysical limitations to cultivation of soybean (top panel), harvested area of all croplands within ideal cultivation regions of soybean (middle panel), and harvested area of soybean within regions of one or more very limiting factors (bottom panel).

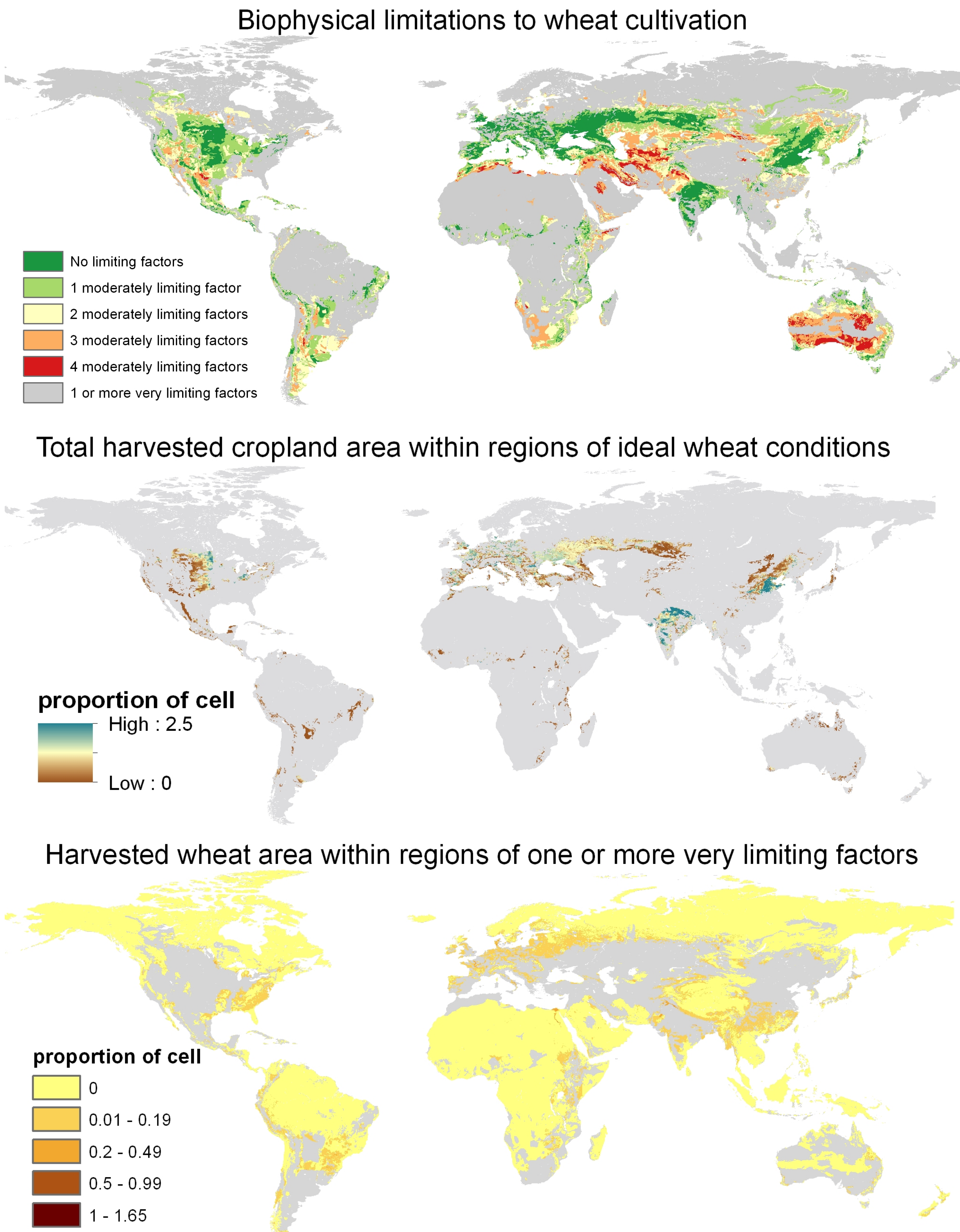

Figure 4.8: The calculated biophysical limitations to cultivation of wheat (top panel), harvested area of all croplands within ideal cultivation regions of wheat (middle panel), and harvested area of wheat within regions of one or more very limiting factors (bottom panel).

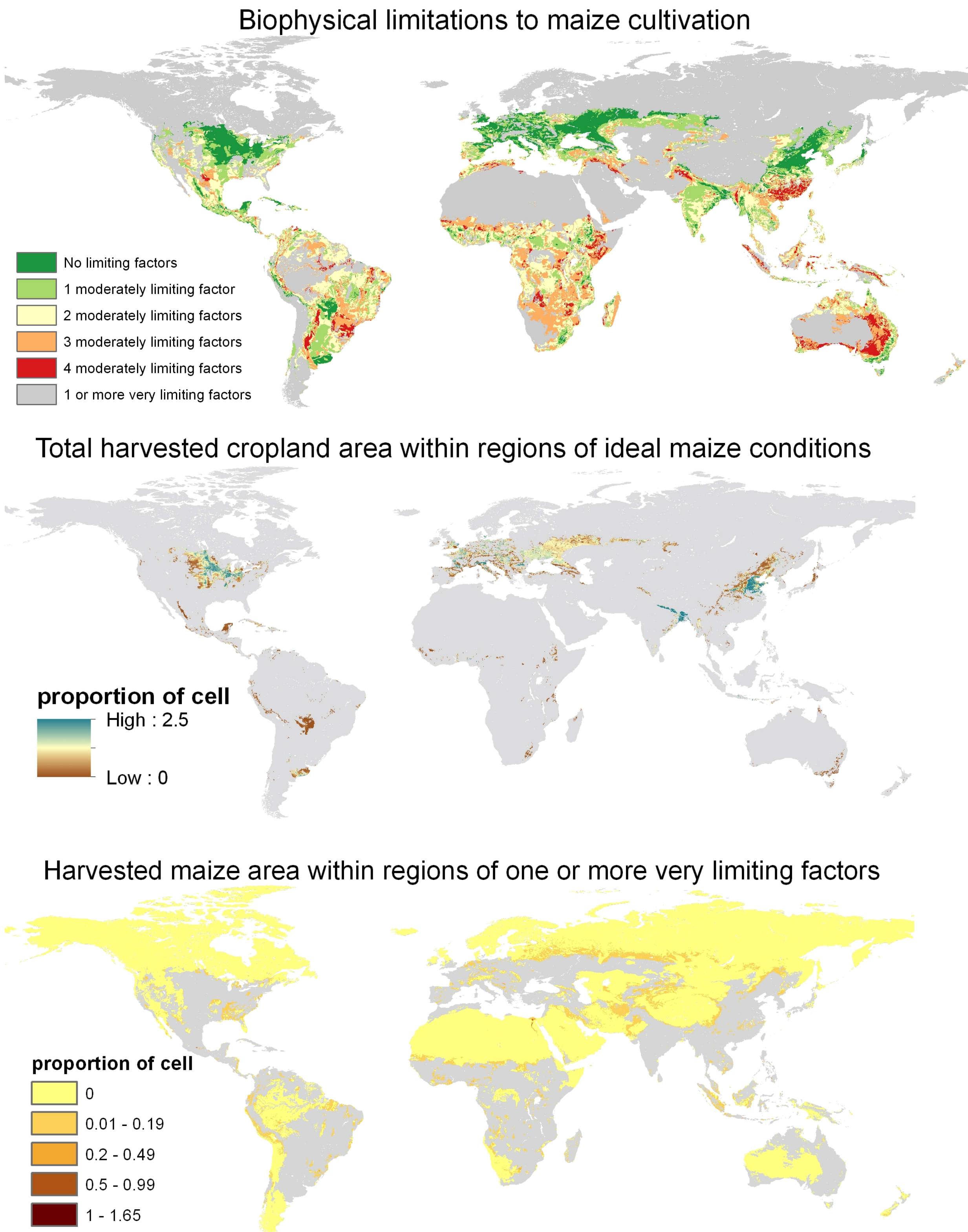

Figure 4.9: The calculated biophysical limitations to cultivation of maize (top panel), harvested area of all croplands within ideal cultivation regions of maize (middle panel), and harvested area of maize within regions of one or more very limiting factors (bottom panel).

APPENDIX A: DISTRIBUTION OF CROP HARVESTED AREAS WITHIN INDICATOR BINS AND ASSIGNED BIN RANKS

Each of the four tables below show the breakdown of the percentage of each crop's total harvested area within the soil and climate characteristics. The ranks that were assigned to these percentages are indicated as well, where VL (red) = Very Limiting, M (yellow) = Moderate, and I (green)= Ideal

Percentage of the total harvested area of each crop within GDD bins (day °C) and bin rank for each crop

	Millet		Barley		Sorghum		Rice		Soybean		Wheat		Maize	
GDD Bin	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank
0-800	0.04	VL	0.35	VL	0.01	VL	0.08	VL	0.09	VL	0.40	VL	0.2	VL
800-1600	0.46	VL	22.41	I	0.13	VL	0.30	VL	1.15	VL	11.42	M	1.0	VL
1600-2400	4.70	M	38.14	I	1.30	VL	1.36	VL	15.46	I	25.62	I	16.5	I
2400-3200	1.63	M	13.77	I	3.25	M	2.31	M	22.44	I	12.56	I	22.2	I
3200-4000	1.23	VL	8.03	M	4.62	M	4.64	M	10.37	M	15.29	I	12.1	I
4000-4800	0.80	VL	10.27	M	2.83	M	10.73	M	14.23	I	11.04	M	7.9	M
4800-5600	1.27	M	3.84	M	4.40	M	4.74	M	8.16	M	4.52	M	6.4	M
5600-6400	2.38	M	0.79	VL	4.99	M	4.42	M	7.44	M	1.89	VL	7.0	M
6400-7200	8.10	M	0.93	VL	10.10	M	13.38	I	7.03	M	5.12	M	8.3	M
7200-8000	36.68	I	1.37	VL	25.06	I	36.83	I	11.42	I	11.44	I	12.5	I
8000-8800	33.83	I	0.07	VL	40.38	I	21.11	I	2.21	M	0.67	VL	5.8	M
8800-9600	8.88	M	0.02	VL	2.91	M	0.10	VL	0.00	VL	0.02	VL	0.0	VL

Percentage of the total harvested area of each crop within moisture index bins and bin rank for each crop

	Millet		Barley		Sorghum		Rice		Soybean		Wheat		Maize	
Moisture Index Bin	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank
0-0.1	0.36	VL	0.35	VL	1.30	VL	0.74	VL	0.02	VL	1.37	VL	0.8	VL
0.1-0.2	14.22	M	2.47	VL	4.42	M	1.11	VL	0.05	VL	4.65	M	0.6	VL
0.2-0.3	26.14	I	8.45	M	17.56	I	1.81	M	0.26	VL	8.81	M	1.7	M
0.3-0.4	26.92	I	13.07	I	25.23	I	4.21	M	5.01	M	12.25	I	5.6	M
0.4-0.5	14.97	I	13.43	I	24.31	I	12.13	I	4.54	M	15.64	I	8.4	M
0.5-0.6	9.47	M	30.58	I	11.35	M	11.68	M	8.50	M	25.91	I	16.3	I
0.6-0.7	4.56	M	15.81	I	7.90	M	10.69	M	20.63	I	15.41	I	23.9	I
0.7-0.8	2.33	M	9.81	M	6.07	M	20.86	I	42.82	I	10.43	M	26.6	I
0.8-0.9	1.02	VL	5.86	M	1.73	M	29.76	I	16.39	M	5.31	M	13.1	M
0.9-1.0	0.02	VL	0.16	VL	0.15	VL	7.01	M	1.76	VL	0.22	VL	3.0	M

Percentage of the total harvested area of each crop within soil carbon density bins (kg C/m^2) and bin rank for each crop														
	Millet		**Barley**		**Sorghum**		**Rice**		**Soybean**		**Wheat**		**Maize**	
CD Bin	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank
0-1	26.32	M	1.02	VL	8.85	M	0.53	VL	0.05	VL	2.10	M	0.9	VL
2-3	31.66	I	21.25	M	26.26	I	21.82	M	16.62	M	24.20	M	18.9	M
4-5	31.70	I	44.32	I	41.76	I	45.02	I	36.66	I	41.96	I	38.3	I
6-7	8.88	M	26.41	I	19.67	M	24.52	I	37.20	I	28.04	I	32.0	I
8-9	1.06	VL	4.60	M	2.93	VL	4.22	M	8.83	M	2.71	M	8.4	M
10-11	0.27	VL	1.22	M	0.43	VL	1.42	M	0.40	VL	0.46	VL	0.9	VL
12-13	0.09	VL	0.39	VL	0.09	VL	1.21	M	0.12	VL	0.14	VL	0.4	VL
14-15	0.00	VL	0.29	VL	0.01	VL	0.77	VL	0.02	VL	0.19	VL	0.1	VL
16-17	0.00	VL	0.10	VL	0.00	VL	0.01	VL	0.01	VL	0.04	VL	0.0	VL
18-19	0.00	VL	0.05	VL	0.00	VL	0.47	VL	0.01	VL	0.02	VL	0.0	VL
20-21	0.01	VL	0.22	VL	0.00	VL	0.01	VL	0.00	VL	0.07	VL	0.0	VL
22-23	0.00	VL	0.04	VL	0.00	VL	0.00	VL	0.00	VL	0.02	VL	0.0	VL
24-25	0.00	VL	0.08	VL	0.00	VL	0.01	VL	0.09	VL	0.06	VL	0.0	VL

Percentage of the total harvested area of each crop within soil pH bins and bin rank for each crop														
	Millet		**Barley**		**Sorghum**		**Rice**		**Soybean**		**Wheat**		**Maize**	
Soil pH Bin	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank	%	Rank
4	0.48	VL	1.66	VL	0.91	VL	7.17	M	3.83	M	0.79	VL	3.1	VL
5	8.00	M	12.36	M	9.94	M	28.39	I	23.04	M	6.80	VL	20.3	M
6	42.08	I	20.23	I	38.55	I	39.09	I	45.32	I	25.24	I	41.6	I
7	42.12	I	51.20	I	46.61	I	20.57	M	25.86	I	49.45	I	31.3	I
8	7.32	M	14.55	M	3.98	VL	4.77	VL	1.95	VL	17.72	M	3.8	M

APPENDIX B: PERCENTAGE OF HARVESTED CROP AREA IN EACH RANK

The following table shows the amount of harvested crop area in each rank of the soil and climate indicators, expressed as a percentage.

Percentage of harvested crop area within each rank of each climate and soil indicator				
Crop	**Characteristic**	**Percent Ranked as Ideal**	**Percent Ranked as Moderate**	**Percent Ranked as Very Limiting**
Barley	GDD	Top 74	74-96	96-100
	Soil Moisture Index	Top 73	73-97	97-100
	Carbon Density	Top 70^	70-97.8	97.8-100
	pH	Top 71	71-98	98-100
Maize	GDD	Top 63	63-98.7	98.7-100
	Soil Moisture Index	Top 66.7	66.7-98.5	98.5-100
	Carbon Density	Top 70	70-97.6	97.6-100
	pH	Top 72.8	72.8-97	97-100
Millet	GDD	Top 70	70-97.5	97.5-100
	Soil Moisture Index	Top 68	68-98.6	98.6-100
	Carbon Density	Top 63	63-98.5	98.5-100
	pH	Top 84	84-99.5	99.5-100
Rice	GDD	Top 71	71-98	98-100
	Soil Moisture Index	Top 62	62-98	98-100
	Carbon Density	Top 69.5	69.5-98	98-100
	pH	Top 67.5	67.5-95	95-100
Sorghum	GDD	Top 65	65-98.5	98.5-100
	Soil Moisture Index	Top 67	67-98.5	98.5-100
	Carbon Density	Top 68	68-96.5	96.5-100
	pH	Top 85	85-95	95-100
Soybean	GDD	Top 63.5	63.5-98.8	98.8-100
	Soil Moisture Index	Top 63	63-98	98-100
	Carbon Density	Top 73	73-99	99-100
	pH	Top 71	71-98	98-100
Wheat	GDD	Top 65	65-97	97-100
	Soil Moisture Index	Top 69	69-98.4	98.4-100
	Carbon Density	Top 70	70-99	99-100
	pH	Top 74	74-92	92-100