Field Crops Research 143 (2013) 44–55

Contents lists available at SciVerse ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Use of agro-climatic zones to upscale simulated crop yield potential

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ARTICLE INFO

Article history:
Received 23 October 2012
Received in revised form
27 November 2012
Accepted 30 November 2012

Keywords:
Agroecological zone
Climate zone
Yield potential
Water-limited yield
Yield gap
Extrapolation domain
Global food security

ABSTRACT

Yield gap analysis, which evaluates magnitude and variability of difference between crop yield potential (Yp) or water limited yield potential (Yw) and actual farm yields, provides a measure of untapped food production capacity. Reliable location-specific estimates of yield gaps, either derived from research plots or simulation models, are available only for a limited number of locations and crops due to cost and time required for field studies or for obtaining data on long-term weather, crop rotations and management practices, and soil properties. Given these constraints, we compare global agro-climatic zonation schemes for suitability to up-scale location-specific estimates of Yp and Yw, which are the basis for estimating yield gaps at regional, national, and global scales. Six global climate zonation schemes were evaluated for climatic homogeneity within delineated climate zones (CZs) and coverage of crop area. An efficient CZ scheme should strike an effective balance between zone size and number of zones required to cover a large portion of harvested area of major food crops. Climate heterogeneity was very large in CZ schemes with less than 100 zones. Of the other four schemes, the Global Yield Gap Atlas Extrapolation Domain (GYGA-ED) approach, based on a matrix of three categorical variables (growing degree days, aridity index, temperature seasonality) to delineate CZs for harvested area of all major food crops, achieved reasonable balance between number of CZs to cover 80% of global crop area and climate homogeneity within zones. While CZ schemes derived from two climate-related categorical variables require a similar number of zones to cover 80% of crop area, within-zone heterogeneity is substantially greater than for the GYGA-ED for most weather variables that are sensitive drivers of crop production. Some CZ schemes are crop-specific, which limits utility for up-scaling location-specific evaluation of yield gaps in regions with crop rotations rather than single crop species.

1. Introduction

Growing demand for food in coming decades will require substantial increase in crop production (Godfray et al., 2010). Given disadvantages and limitations of massive expansion of existing cropland, such as loss of biodiversity and increasing GHG emissions, it is of critical importance to know where and how best to increase crop yield on existing cropland area (Foley et al., 2005; Tilman et al., 2002). Yield gap (Yg) analysis, an evaluation of the difference between crop yield potential and actual farmers' yields (Lobell et al., 2009), provides a quantitative estimate of possible increase in food production capacity for a given location, which is a critical component of strategic food security planning at regional, national and global scales. For irrigated cropping systems, yield potential (Yp) is defined as the yield of crop cultivar when grown without limitations from water, nutrients, pests and diseases; in rainfed cropping system, water-limited yield potential (Yw) is also determined by water supply amount and distribution during the cropping season (van Ittersum et al., 2013). At a given location, Yg is the difference between Yp or Yw and actual yield.

Both Yp and Yw are site-specific because they are determined by weather, management, length of growing season, and soil properties that affect root-zone water storage capacity (the latter for Yw only). Both can be estimated from research plots, in which

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http://dx.doi.org/10.1016/j.fcr.2012.11.023

the crop is grown without limitations, or by simulation using crop models (Lobell et al., 2009). In a recent comparison of these two options across a range of cropping systems and environments, van Ittersum et al. (2013) concluded that use of crop simulation with a long-term weather database provides a more robust estimate of Yp and Yw than research plots because simulation better accounts for the impact of variation in temperature, solar radiation, and rainfall over time. But use of crop models requires reliable location-specific data on sowing date, cultivar maturity, plant population, soils and weather and such data are not generally available for most locations (Ramirez-Villegas and Challinor, 2012). Obtaining these data at a large number of locations is time-consuming, costly, and often simply not feasible. Therefore, an upscaling method is needed to extend coverage of estimates of Yp and Yw based on location-specific information to an appropriate extrapolation domain using a protocol that minimizes the number of location-specific simulations. Ideally, extrapolation domains would be small enough to minimize variation in climate and crop management practices within the domain, and large enough to minimize data collection requirements to estimate Yg at regional and national scales. Likewise, relevance of a zonation scheme for simulation of Yp and Yw is determined by the quality, resolution, extent and choice of variables used to delineate boundaries.

Previous studies have distinguished geographical space by climate and soil classification schemes as a basis for extrapolating and applying agricultural information and research to broader spatial scales (Wood and Pardey, 1998; Padbury et al., 2002). A region can be divided into agro-climatic zones (CZs) based on homogeneity in weather variables that have greatest influence on crop growth and yield, while agro-ecological zones (AEZs) are defined as geographic regions having similar climate and soils for agriculture (FAO, 1978). Such zonation schemes have been used to identify yield variability and limiting factors for crop growth (Caldiz et al., 2002; Williams et al., 2008), to regionalize optimal crop management recommendations (Seppelt, 2000), compare yield trends (Gallup and Sachs, 2000), to determine suitable locations for new crop production technologies (Geerts et al., 2006; Araya et al., 2010), and to analyze impacts of climate change on agriculture (Fischer et al., 2005). Table 1 includes a description of previously published zonation schemes used to evaluate extrapolation domains for agricultural technologies and in yield gap analysis. Our review focuses on CZ schemes and the climatic components of AEZ schemes with the goal of identifying an appropriate CZ scheme for upscaling location-specific estimates of Yp or Yw to regional and national levels. To our knowledge, no such review has been previously published with this goal in mind. Specific objectives of this review are to: (1) evaluate zonation schemes based on the degree of variability in weather variables within zones, and (2) evaluate the usefulness and limitations of these zonation schemes for upscaling location-specific estimates of Yp and Yw to national levels.

2. Agro-climatic and agro-ecological zonation schemes

Zonation schemes essentially fall into two categories: matrix and cluster. In this section differences between matrix and cluster methodologies are explained, and six global matrix and cluster zonation schemes useful for extrapolation of estimates of Yp or Yw are described.

2.1. Matrix methodologies

Perhaps the best known and earliest example of a matrix zonation scheme is described by Köppen (1900). Köppen developed a climate classification system based on multiple variables related to temperature and precipitation, and used his system to identify the type of vegetation, including some crops, that could grow in each zone. In a matrix zonation, each variable used to delineate zones is divided into classes or class-ranges. Class cutoff values for each variable can be based on expert opinion or frequency distributions of the variable's range of values. Zones are formed by the matrix "cells" of intersecting classes. For example, a matrix zone cell might be a geographic area in which mean annual temperature is between 20 and 25 °C and mean annual precipitation is between 300 and 400 mm.

Matrix zonation schemes are advantageous in that the range of input parameters for all zones is known and specifically defined by the researchers. The size of the zones in a matrix zonation results from the number of input variables used and the degree of specificity in classes for each variable, i.e. more class variables and more sub-divisions within each variable result in a larger number of zones with smaller area. Thus, matrix methodology allows for high degree of control over the number the resulting zones as determined by intended use of the zonation scheme. Robust matrix schemes for uscaling Yp and Yw would use the most sensitive weather variables for simulation of crop yields under irrigated and rainfed conditions.

2.2. Cluster methodologies

Cluster methodologies [also referred to as statistical stratification (Hazeu et al., 2011)] relies on multivariate statistical analyses to separate cells into a researcher-specified number of distinct zones. Clustering essentially involves assigning grid-cell values derived from mathematical or statistical modeling of categorical variables. Grouping or "clustering" grid-cells based on these derived values is accomplished using a variety of techniques such as assigning a certain value or range of values as a class or cluster, minimizing the sum of the difference between grid-cells within clusters, or more sophisticated Iterative Self-Organizing Data Analysis (ISODATA). In the latter, the number of cluster centers is specified, randomly placed, and then clusters are divided or merged based on standard deviation of grid-cells assigned to each cluster (Tou and González, 1974). The process continues until reassignment of grid cells no longer improves cluster standard deviation. Due to the statistical nature of "clustering," subjectivity is avoided in selection of class ranges for each variable. Though class ranges may be more objective in clustering compared to matrix methodology, size of zones is partially dependent on number of zones specified by the researcher, which may introduce subjectivity. Unlike matrix zonation, the number of zones is not determined by the number of weather variables that determine the zonation. Therefore, a relatively large number of variables can be considered without necessarily reducing the size of the resulting zones.

One of the better known examples of a cluster zonation was created through climate-based modeling of natural vegetation on grid-cells, which were then grouped into regions based on dominant plant types (Prentice et al., 1992). Cluster methodologies also have been used to determine the applicability of farm management research in different regions (Seppelt, 2000), to study potential impacts of climate change on ecosystems and the environment (Metzger et al., 2008), and to identify potential new production areas for bio-energy crops (EEA, 2007).

2.3. Zonation schemes that can be used in estimation of yield potential

2.3.1. The Global Agro-Ecological Zone modeling framework

The Global Agro-Ecological Zone modeling framework (GAEZ) was developed to spatially analyze agricultural systems and

Table 1
Previously published global zonation schemes (AEZ).

AEZ scheme	Number of zones	Type of AEZ	Variables considered, methodology	Reference
FAO[a]	14	Matrix	Mean growing period temperature and length of growing period, determined by annual precipitation, potential evapotranspiration and the time required to evapotranspire 100 mm of water from the soil profile	FAO (1978)
CGIAR-TAC[b]	9	Matrix	Mean annual and growing period temperature, and length of growing period (determined the same as in the FAO zonation scheme)	Sivakumar and Valentin (1997)
Prentice	17	Cluster	Soil texture based water-storage capacity, monthly precipitation, sunshine hours, potential evapotranspiration, growing degree days, minimum temperature, mean temperature. These variables were used in a model which calculated most likely vegetation type for the environment of this gridcell and cells were grouped based on vegetation type.	Prentice et al. (1992)
Pappadakis	74	Matrix	Precipitation and temperature are used in calculations of a variety of seasonal statistics. Ranges of variables for each zone are based on crop requirements.	Papadakis (1966)
Köppen-Geiger	31	Matrix	Mean annual temperature, minimum and maximum temperature of warmest and coolest months, accumulated annual precipitation, precipitation of driest month, lowest and highest monthly precipitation for summer and winter half years, and a dryness threshold based on seasonality of precipitation	Kottek et al. (2006)
Holdridge	100	Matrix	Mean annual temperature, mean annual precipitation, elevation (evaporative demand and frost were also considered in determining climate ranges of zones).	Holdridge (1947)
GAEZ-LGP[c]	16	Matrix	Temperature, precipitation, potential evapotranspiration and soil characteristics are used to calculate length of growing season.	Fischer et al. (2012)
HCAEZ[d]	21	Matrix	Mean temperatures, elevation, and GAEZ-LGP are used to define thermal regimes and temperature seasonality.	Wood et al. (2010)
SAGE[e]	100	Matrix	Growing degree days (GDD; $\sum$Tmean–crop-specific base temperature) and soil moisture index (actual evapotranspiration divided by potential evapotranspiration).	Licker et al. (2010)
GLI[f]	25	Matrix	Harvested area of target crop, crop-specific GDD and soil moisture index (actual evapotranspiration divided by potential evapotranspiration).	Mueller et al. (2012)
GEnS[g]	115	Cluster	4 variables (GDD with base temperature of 0 °C, an aridity index, evapotranspiration seasonality, temperature seasonality) used in iso-cluster analysis to "cluster" grid-cells into zones of similarity.	Metzger et al. (in press)

[a] Food and Agricultural Organization.
[b] Consultative Group on International Agricultural Research – Technical Advisory Committee.
[c] Global Agro-Ecological Zone Length of Growing Period.
[d] HarvestChoice Agro-ecological Zone.
[e] Center for Sustainability and the Global Environment.
[f] Global Land Initiative.
[g] Global Environmental Stratification.

evaluate the impacts of agricultural policies at a global scale (Fischer, 2009). Delineation of AEZs within GAEZ are determined by monthly weather data with a resolution of 10′ (roughly 20 km × 20 km at the equator, or 400 km^2). The weather data were obtained from the Climate Research Unit (New et al., 2002) and the Global Precipitation Climatology Centre (Rudolf et al., 2005). Categorical variables used, or derived, from these data to define an AEZ include: (a) accumulated temperature sums for mean daily temperature above a base temperature [growing degree days (GDD)], (b) annual temperature profiles, based on mean annual temperature and within-year temperature trends, (c) delineation of continuous, discontinuous, sporadic and no permafrost zones, (d) quantification of soil water balance and actual evapotranspiration for a reference crop, (e) length of growing period (LGP), defined as the sum of days when mean daily temperature exceeds 5 °C and evapotranspiration for the reference crop exceeds half of potential evapotranspiration, (f) multiple cropping classification, which indicates whether annual single, double or triple cropping is possible in a given zone, based on the LGP and assuming a growth duration per crop of 120 days (Fischer et al., 2012). This GAEZ framework has been adapted to assess the potential production of all major bio-fuel crops (Fischer and Schrattenholzer, 2001), to analyze the potential impact of accelerated biofuel production on food security to 2050, and to evaluate the resulting social, environmental and economic impacts (Fischer et al., 2009). Additional assessments have used a GAEZ framework to evaluate scenarios of future land use and production of major crops at a global scale (Fischer et al., 2002, 2006). Of the various AEZ schemes used in the GAEZ framework, we selected the one based on LGP in which LGP is derived from temperature, precipitation, and soil water holding capacity as categorical variables. The GAEZ-LGP was selected because it utilizes the most agronomically relevant categorical variables and has the smallest, and presumably most climatically homogenous zones, within the GAEZ-family of AEZ schemes (Figs. 1a–5a).

2.3.2. *Center for Sustainability and Global Environment zonation scheme*

The Center for Sustainability and the Global Environment (SAGE) zonation scheme was generated using global, gridded data for two variables known to be important drivers for crop development and crop growth (Licker et al., 2010): growing degree-days (GDD) and a crop soil moisture index, the latter calculated as the ratio of actual to potential evapotranspiration following the approach of Prentice et al. (1992) and Ramankutty et al. (2002). Calculations utilized a 33-y monthly averaged weather database from the Climate Research Unit (New et al., 2002) with a 10′ resolution. Soil texture data used to estimate the soil moisture index were taken from the International Soil Reference and Information Center with a 5′ resolution (Batjes, 2006). By downscaling the weather data from a 10′ to a 5′ resolution, calculations were

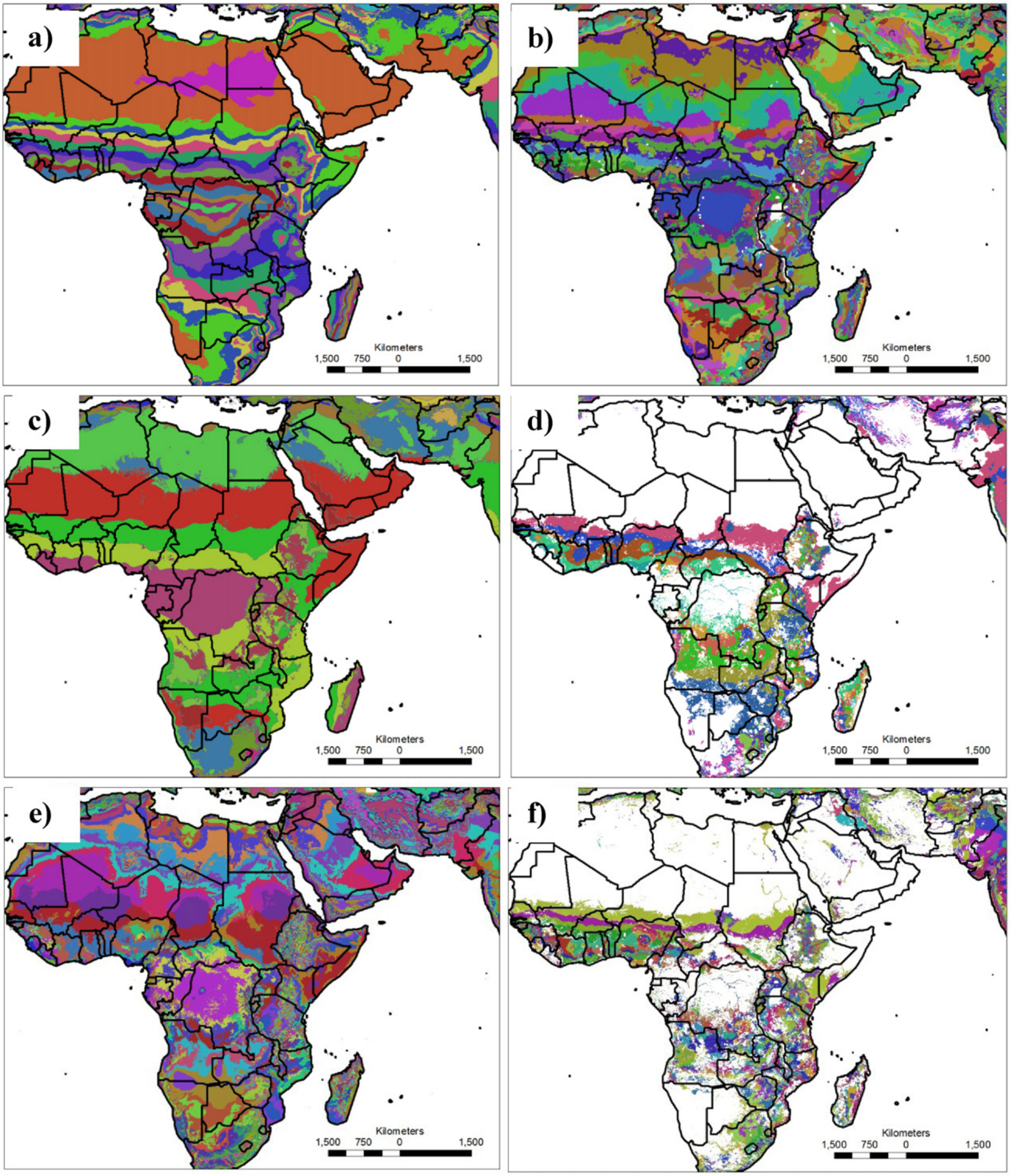

Fig. 1. Zonation of Africa for (a) Global Agro-Ecological Zone for length of growing season (GAEZ-LGP), (b) Center for Sustainability and the Global Environment (SAGE) zonation scheme (crop-specific, derived using GDD with base temperature of 8 °C as used for maize), (c) HarvestChoice Agroecological Zone (HCAEZ, d) Global Landscapes Initiative (crop-specific, derived using GDD with base temperature of 8 °C as used for maize), (e) Global Environmental Stratification (GEnS), (f) Global Yield Gap Atlas Extrapolation Domain (GYGA-ED).

carried out on a 5′ grid basis (approximately 10 km × 10 km, or 100 km^2 at the equator). The global ranges of the two categorical variables were each divided into ten classes, which were then used to develop a matrix of 100 unique combinations of growing degree-day and soil moisture conditions. Separate zonation schemes were developed for each of 18 crop species using crop-specific base temperatures for calculation of growing degree-days (e.g., 8 °C for maize, 5 °C for rice). The zonation scheme for maize is shown in Figs. 1b–5b.

This zonation scheme was developed to determine within-zone maximum yield achieved for a specific crop within each of the 100 zones. If the zonal-maximum yield was larger than observed yields for a particular region within the zone the authors considered this a Yg and identified the region as having an opportunity for increasing yields (Licker et al., 2010). The SAGE zonation was also employed by Johnston et al. (2011) to examine opportunities to expand global biofuel production through agricultural intensification in regions with similar growing conditions.

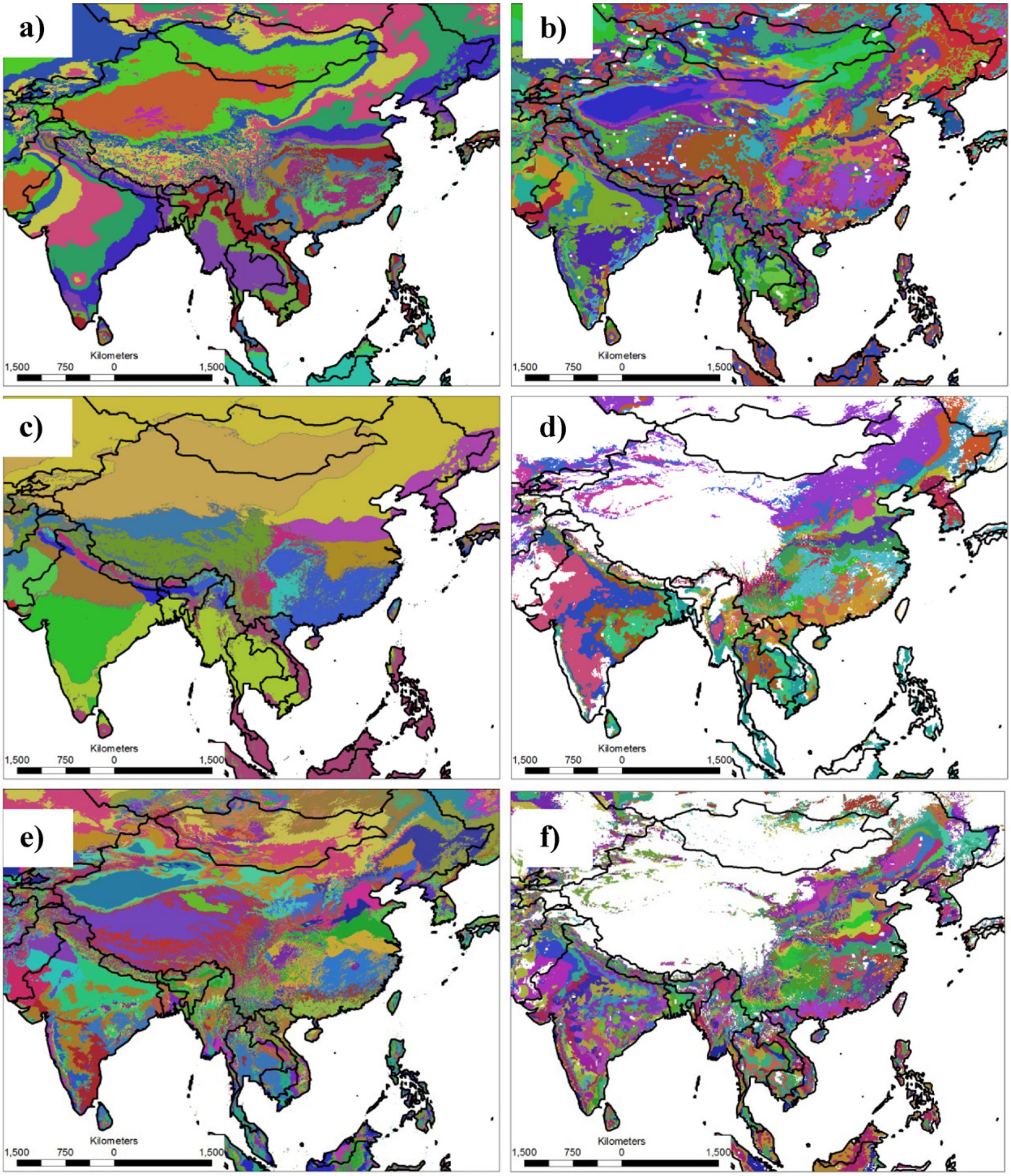

Fig. 2. Zonation of Asia for (a) Global Agro-Ecological Zone for length of growing season (GAEZ-LGP), (b) Center for Sustainability and the Global Environment (SAGE) zonation scheme (crop-specific, derived using GDD with base temperature of 8 °C as used for maize), (c) HarvestChoice Agroecological Zone (HCAEZ, d) Global Landscapes Initiative (crop-specific, derived using GDD with base temperature of 8 °C as used for maize), (e) Global Environmental Stratification (GEnS), (f) Global Yield Gap Atlas Extrapolation Domain (GYGA-ED).

2.3.3. Modifications of GAEZ and SAGE zonation schemes

Aspects of both the SAGE and GAEZ have been utilized or modified to develop improved AEZ schemes for yield gap analysis. The HarvestChoice[1] AEZ scheme (HCAEZ), developed for analysis in sub-Saharan Africa, is an example (Wood et al., 2000, 2010). It is a matrix with 21 zones based on GAEZ-LGP and thermal regime classes for the tropics, sub-tropics, temperate, and boreal zones distinguished by highland and lowland regions. Essentially, HCAEZ is a combination, or intersection, of several distinct and independent zonation schemes used in the GAEZ framework. Although it uses data of more recent orgin, the HCAEZ resembles an earlier

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[1] HarvestChoice is a large collaborative effort to provide knowledge products aimed at guiding investments to improve well-fare through more profitable agriculture in Sub-Saharan Africa led by scientists from the University of Minnesota and the International Food Policy Research Institute (IFPRI). Several zonation schemes have been used at HarvestChoice, based on the same underlying methodology.

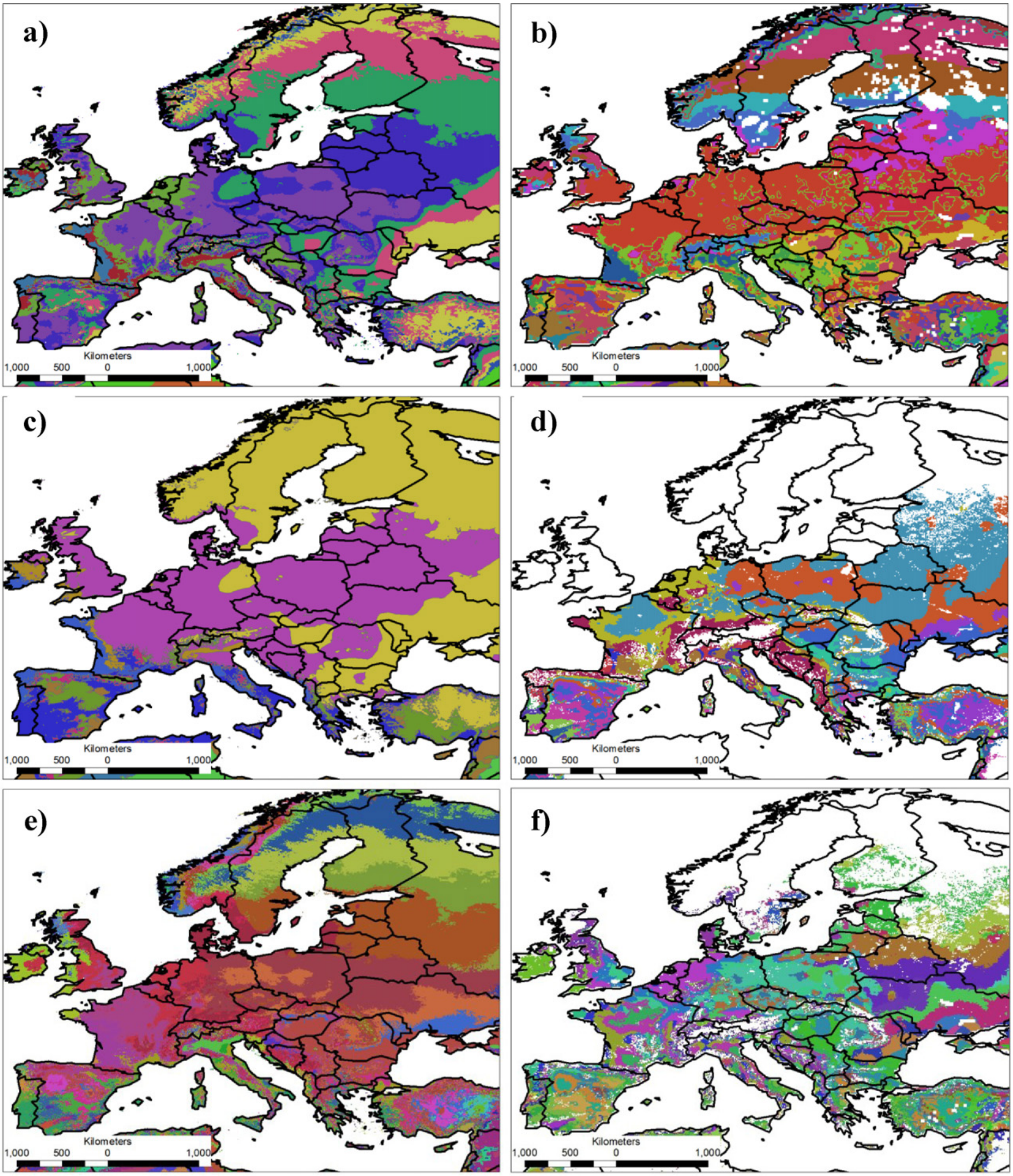

Fig. 3. Zonation of Europe for (a) Global Agro-Ecological Zone for length of growing season (GAEZ-LGP), (b) Center for Sustainability and the Global Environment (SAGE) zonation scheme (crop-specific, derived using GDD with base temperature of 8 °C as used for maize), (c) HarvestChoice Agroecological Zone (HCAEZ, d) Global Landscapes Initiative (crop-specific, derived using GDD with base temperature of 8 °C as used for maize), (e) Global Environmental Stratification (GEnS), (f) Global Yield Gap Atlas Extrapolation Domain (GYGA-ED).

AEZ scheme developed by the Technical Advisory Committee (TAC) of the Consultative Group on International Agricultural Research (CGIAR) (TAC/CGIAR, 1992; Sivakumar and Valentin, 1997).

The SAGE zonation scheme was modified by the Global Landscapes Initiative (GLI) group at the University of Minnesota, keeping the classification based on crop-specific GDD but replacing the crop soil moisture index by annual total precipitation. Another modification was that only terrestrial surface covered by harvested area for a specific crop was considered based on geospatial crop distribution maps of Monfreda et al. (2008). Climate zones were developed for each crop by dividing GDD and precipitation each into ten classes, the intersection of which formed a matrix of 100 individual CZs. Instead of using equal ranges for the classes, zones were determined using an algorithm such that 1% of the global harvested area of that specific crop was in each zone, a methodology known as the ‘equal-area approach’ (Figs. 1d–5d). This revision of the SAGE zonation scheme formed the basis of the yield gap estimates in Foley et al. (2011) and Mueller et al. (2012).

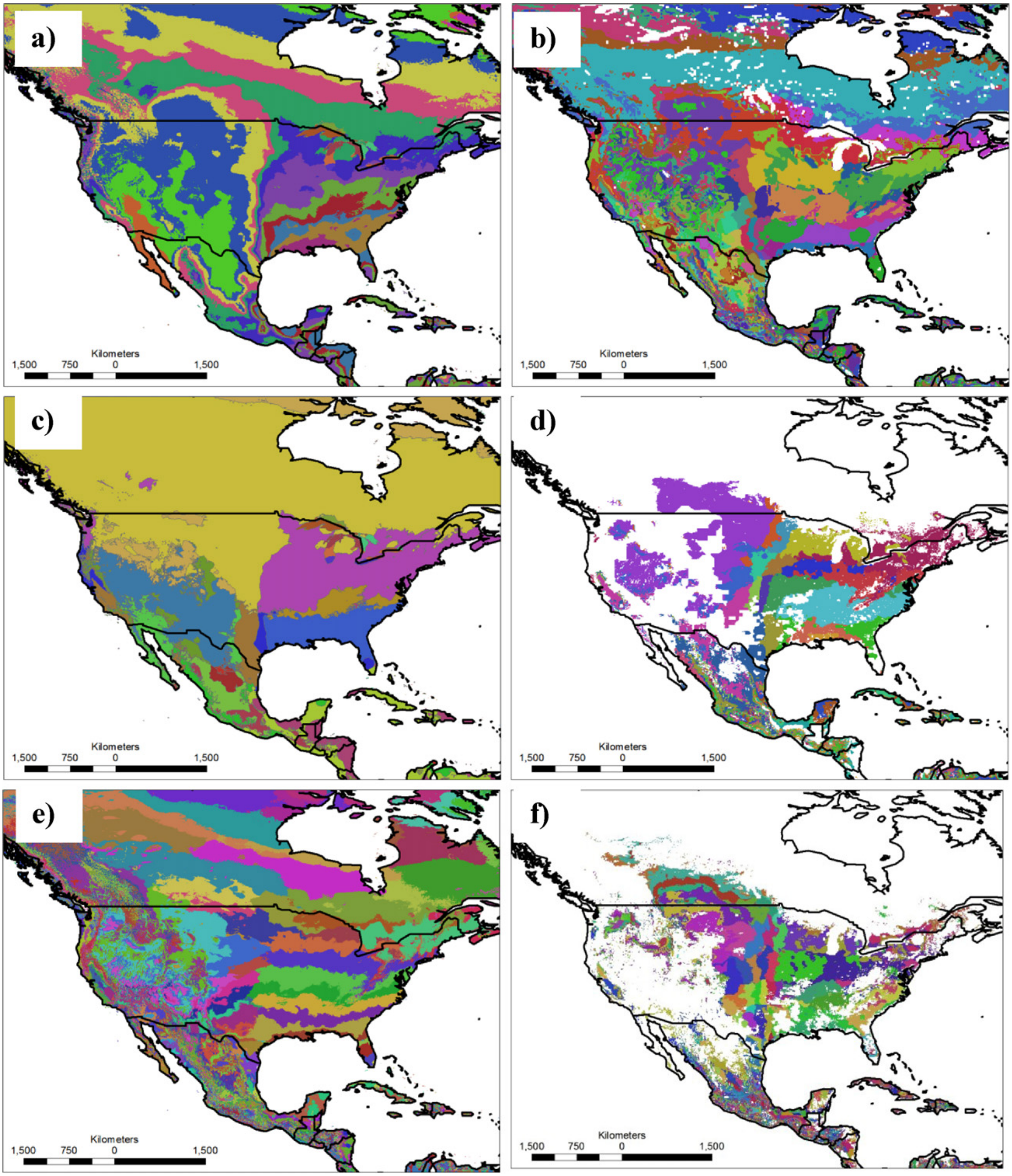

Fig. 4. Zonation of North America for (a) Global Agro-Ecological Zone for length of growing season (GAEZ-LGP), (b) Center for Sustainability and the Global Environment (SAGE) zonation scheme (crop-specific, derived using GDD with base temperature of 8 °C as used for maize), (c) HarvestChoice Agroecological Zone (HCAEZ, d) Global Landscapes Initiative (crop-specific, derived using GDD with base temperature of 8 °C as used for maize), (e) Global Environmental Stratification (GEnS), (f) Global Yield Gap Atlas Extrapolation Domain (GYGA-ED).

2.3.4. The Global Environmental Stratification methodology (GEnS)

The Global Environmental Stratification (GEnS) by Metzger et al. (in press) is the first cluster methodology aiming at establishing a global, climate-explicit zonation system. GEnS was developed within the Group on Earth Observations Biodiversity Observation Network (GEOBON, Scholes et al., 2008) and will be available to assist further research on global ecosystems. This cluster zonation uses monthly gridded climate data from the WorldClim database (Hijmans et al., 2005) and annual aridity and potential evapotranspiration seasonality derived from the CGIAR Consortium for Spatial Information (CGIAR-CSI, Trabucco et al., 2008; Zomer et al., 2008), with 30″ resolution (approximately 1 km^2 at the equator). GEnS was constructed in three stages. In the first stage, 42 categorical variables were screened to remove those that were auto-correlated. Among the variables with high auto-correlation,

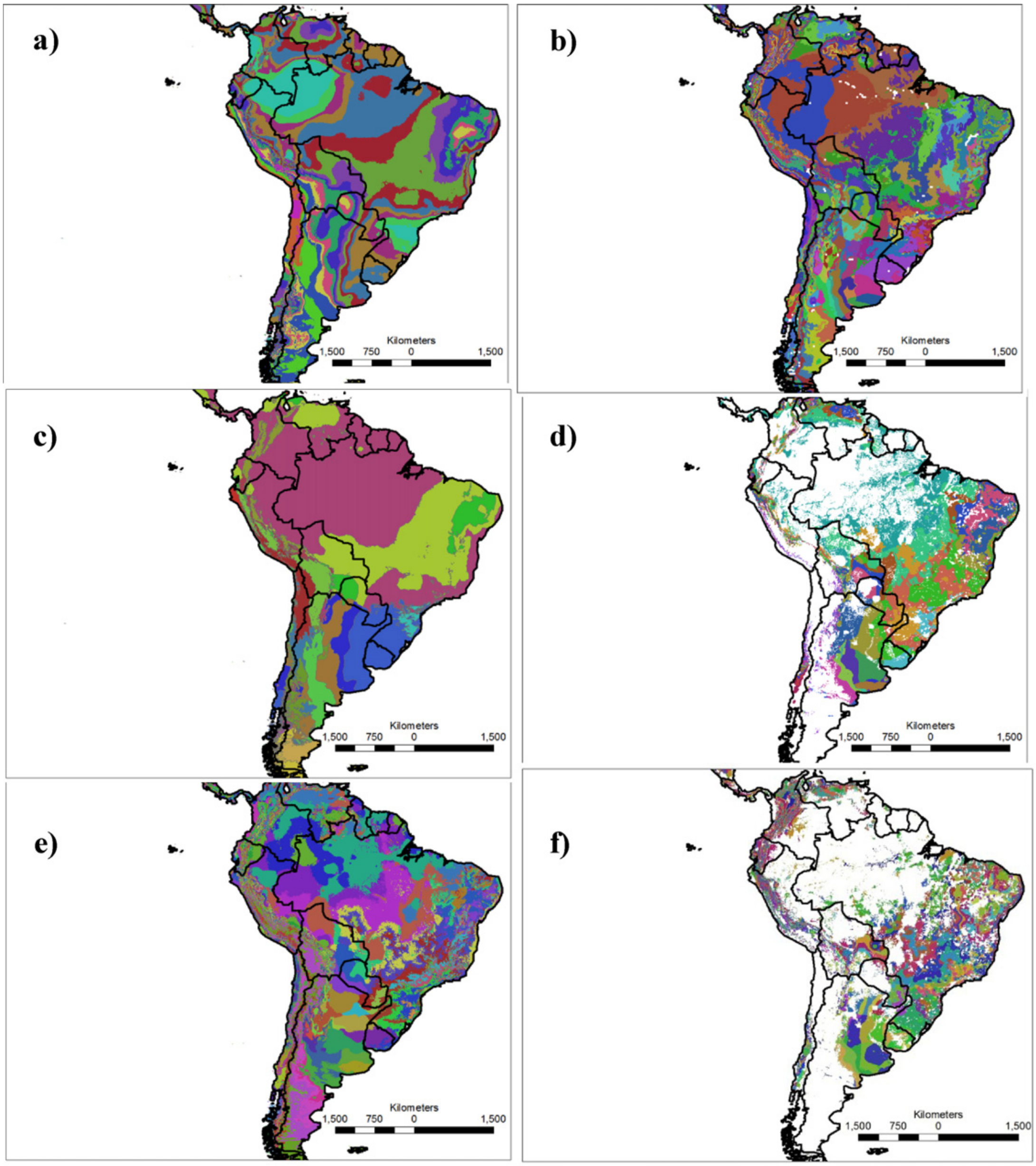

Fig. 5. Zonation of South America for (a) Global Agro-Ecological Zone for length of growing season (GAEZ-LGP), (b) Center for Sustainability and the Global Environment (SAGE) zonation scheme (crop-specific, derived using GDD with base temperature of 8 °C as used for maize), (c) HarvestChoice Agroecological Zone (HCAEZ, d) Global Landscapes Initiative (crop-specific, derived using GDD with base temperature of 8 °C as used for maize), (e) Global Environmental Stratification (GEnS), (f) Global Yield Gap Atlas Extrapolation Domain (GYGA-ED).

researchers selected the most sensitive parameters and eliminated the others to prevent over-weighting the zonation by co-linear variables. In the second step, statistical clustering analysis was performed on remaining variables: annual cumulative GDD using base temperature = 0 °C, temperature and potential evapotranspiration seasonalities (month to month variation), and an annual aridity index (calculated as the ratio of mean annual total precipitation to mean annual total potential evapotranspiration). The statistical clustering was carried out using principle component analysis and iterative self-organizing data analyses, resulting in 125 zones (Figs. 1e–5e). A climatic stratification of Europe (Metzger et al., 2005) has been used in modeling efforts to quantify crop production potential and yield gaps in Europe (Hazeu et al., 2009).

2.3.5. The Global Yield Gap Atlas Extrapolation Domain (GYGA-ED)

The goal of the Global Yield Gap Atlas (GYGA) project (www.yieldgap.org) is to estimate the yield gap for major food crops in all crop-producing countries based on locally observed data. Unlike past efforts to estimate Yg that rely on gridded weather data as described above, GYGA seeks to use a “bottom-up” approach with location-specific observed weather data. To extrapolate results from location-specific observed data, the GYGA approach utilizes a hybrid zonation scheme, called the GYGA Extrapolation Domain (GYGA-ED), which combines components of other zonation schemes as reviewed in this paper. The challenge of using a bottom-up approach is the time, expense and access to acquire observed weather data as well as associated location-specific information about crop rotations, soil properties and farm management, which are required for robust estimates of Yp and Yw (van Ittersum et al., 2013). Therefore, the GYGA approach strives for a zonation scheme that balances need to minimize the number of location-specific sites requiring weather, soils, and crop management data with the goal of minimizing climatic heterogeneity within the CZs.

GYGA-ED is constructed from three categorical variables also used by the GEnS: (1) GDD with base temperature of 0 °C and (2) temperature seasonality (quantified as the standard deviation of monthly average temperatures), and (3) an aridity index (annual total precipitation divided by annual total potential evapotranspiration). Grid cell size for the underpinning weather data was the same as for GLI based on the SAGE framework (5′ grid, or roughly 100 km^2 at the equator). Both GDD and temperature seasonality were calculated using climate data from WorldClim (Hijmans et al., 2005); the aridity index values were taken from CGIAR-CSI (Trabucco et al., 2008; Zomer et al., 2008). Following Mueller et al. (2012), only terrestrial surface covered by at least one of the major food crops (maize, rice, wheat, sorghum, millet, barley, soybean, cassava, potato, yam, sweet potato, banana and plantain, groundnut, common bean and other pulses, sugarbeets, sugarcane) was considered in this zonation scheme. To avoid inclusion of areas with negligible crop production, only grid cells with sum of the harvested area of major food crops > 0.5% of the grid cell area were accounted for, based on HarvestChoice SPAM crop distribution maps (You et al., 2006, 2009), which update geospatial crop distribution data of Monfreda et al. (2008). The resulting range in values for GDD and aridity index were divided into 10 intervals, each with 10% of grid cells with harvested area of the major food crops, and combined in a grid matrix with 3 ranges of temperature seasonality to give a total of 300 AEZ classes. Of these, only 265 occur in regions where major food crops are grown.

3. Comparison of the agro-climatic and agro-ecological zonation schemes

Zonation schemes vary widely in defining the size and boundaries of regions with similar climate (Figs. 1–5). For example, each of the schemes recognizes the significance of the Sahara desert, but they differ by as much as 2° or 3° (roughly 250–350 km) in location of the southern border in some areas. Differences among the zonation schemes are considered in the following sections according to relevance for assessing performance of crops and cropping systems within a zone, and in the degree of homogeneity of the underpinning weather variables.

3.1. Key variables used within the zonation schemes

All global zonation schemes analyzed in the present study are associated with temperature and water availability but they differ in selection of specific weather variables to delineate zones (Table 1). For example, to account for thermal conditions, GDD is calculated within the SAGE and GLI schemes using *crop-specific* base temperatures resulting in a different set of CZs for each crop while GEnS and GYGA-ED use a single, non-crop-specific base temperature (0 °C) to calculate GDD, which gives a single set of CZs for all crops. Creating a different zonation scheme for each crop, however, limits opportunities to analyze Yg for crop rotations and much of the world's cropland produces more than one major food crop. For example, crop-specific schemes make it difficult to reconcile performance of crops within a specific cropping system (e.g. double or triple rice or rice-wheat cropping systems in Asia). In addition to GDD, GEnS and GYGA-ED include a measure of temperature variation during the year based on temperature seasonality.

Different indexes have been used to quantify the degree of water limitation. Water supply in the GLI zonation is calculated as total annual rainfall. However, this approach does not account for the degree of water limitation to crop growth, which varies depending on the balance between crop water demand, hereafter called potential evapotranspiration, and water supply. In contrast, GAEZ-LGP, HCAEZ, and SAGE try to account for both water supply and demand using actual and potential evapotranspiration. Specifically, the number of days in which actual evapotranspiration is greater than 50% of potential evapotranspiration are used by GAEZ-LGP and HCAEZ to determine when crop growth is possible due to lack of water stress. SAGE considers the ratio of actual evapotranspiration to potential evapotranspiration as a soil moisture index. Estimation of actual evapotranspiration is derived from data on soil texture, bulk density, and depth of root zone (which defines plant-available water-holding capacity), temperature, precipitation, and leaf area. The soil components of this estimate are derived from spatially explicit global databases and require a number of assumptions in order to calculate hydraulic conductivity. Finally, GEnS and GYGA-ED consider an aridity index calculated as the ratio of annual total precipitation to annual total potential evapotranspiration. While not as sophisticated as the GAEZ-LGP or SAGE schemes, this aridity index is derived directly from variables in the weather database and does not require soil data and the associated uncertainties of assumptions used to estimate soil water holding capacity.

One of the most influential differences among zonation schemes is whether they define zones over total terrestrial area or only the fraction of that area in which crops are grown. For example, GEnS, GAEZ-LGP, HCAEZ and SAGE all consider total terrestrial area in constructing their zonation schemes. In contrast, GLI considers only harvested area of individual major food crop species to give separate zonation schemes for each crop while GYGA-ED considers one scheme based on harvested area of all major food crops. As a result the area over which zones are defined is therefore significantly reduced for those AEZ schemes that only consider harvested crop area (Figs. 1–5).

3.2. Climatic variability within the zones

Climate homogeneity for a given zonation scheme was evaluated by calculating frequency distributions of the range of grid-cell values found within each zone for mean annual temperature, cumulative annual water deficit (precipitation less evapotranspiration), temperature seasonality, and precipitation seasonality (month to month coefficient of variation in precipitation) based on WorldClim data at 5′ resolution (Hijmans et al., 2005). In addition to calculating ranges of these variables for each zone in a given zonation scheme, ranges of mean annual temperature and cumulative annual water deficit were calculated only for those cells in which wheat is grown based on spatial crop distribution of Portmann et al. (2010), in order to minimize bias for those zonation schemes that are not crop-specific. The geospatial distribution of Portmann et al. (2010) was chosen for use in this analysis over the SPAM or Monfreda et al. (2008) data because these two datasets were used in the derivation of one or more of the zonation schemes examined. However, it should be noted that climate data used for this analysis are the same as those used in the GEnS, GYGA-ED, and HCAEZ.

3.2.1. Temperature variability

Zone size was largest in GAEZ-LGP and HCAEZ (Table 2). Large zone area with schemes that consider complete terrestrial coverage results in a wide range of within-zone temperature as indicated by the cumulative frequency distribution of mean annual temperature (Fig. 6a). For example, 50% of the GAEZ and HCAEZ zones have a range of mean annual temperature > 29 °C and 24 °C,

Table 2
AEZ scheme coverage of global, China and USA rainfed wheat and maize based on data from Portmann et al. (2010). Values in parenthesis indicate (±SD) of the mean.

AEZ scheme	Number of zones	Average zone area (Mkm^2)	Rainfed maize area per zone (Mha)	Number of zones to cover 80% of rainfed maize harvested area		
				Global	China	USA
GAEZ-LGP[a]	16	20.2 (18.2)	7.5 (7.2)	7	6	4
HCAEZ[b]	21	15.3 (28.0)	5.8 (8.2)	6	3	2
SAGE[c]	100	2.7 (4.7)	1.2 (2.1)	28	11	5
GLI[d]	100	2.9 (2.0)	1.2 (0.7)	66	37	25
GEnS[e]	125	2.6 (2.5)	1.0 (1.7)	30	13	5
GYGA-ED[f]	265	0.3 (0.3)	0.4 (0.7)	49	21	9

[a] Global Agro-Ecological Zone Length of Growing Period.
[b] HarvestChoice Agro-ecological Zone.
[c] Center for Sustainability and the Global Environment.
[d] Global Land Initiative.
[e] Global Environmental Stratification.
[f] Global Yield Gap Atlas Extrapolation Domain.

respectively. In contrast, zonation schemes with smaller zone size have considerably less within-zone temperature variability. For example, the range of mean annual temperature for 50% of the GLI and GEnS zones is >4 °C. When only cropped terrestrial area is evaluated (whether for a specific crop or multiple crops), within-zone temperature variability decreases substantially. The clustering methodology of Metzger et al. (in press) also resulted in zones with small ranges in temperature variability despite considering total terrestrial area within zones. Apparently the large number of categorical variables considered in the GEnS clustering scheme results in relatively homogeneous temperature regime despite complete terrestrial coverage. When only wheat harvested area is considered in all zonation schemes, the frequency distribution narrows substantially (Fig. 6b).

3.2.2. *Water availability*

Similar to temperature variability within zones, schemes with the largest zone area (GAEZ-LGP and HCAEZ) have greatest range of cumulative water deficit (Fig. 6c). Likewise, crop-area zonation schemes, such as GYGA-ED and GLI have greatest homogeneity within zones. Considering only harvested wheat area within zonation schemes that have complete terrestrial coverage decreases the within-zone range of water deficit of the zonal schemes somewhat, but the range is still relatively large (Fig. 6d).

3.2.3. *Temperature and precipitation seasonality*

The GYGA-ED, which considers three ranges of temperature seasonality as categorical variables, and the GEnS scheme, for which temperature seasonality is an explicit input parameter, have smallest range in temperature seasonality within zones. While the HCAEZ, which also accounts for temperature seasonality, has less heterogeneity for this variable than zonation schemes that do not explicitly consider it, its large zone size results in a greater range than for GYGA-ED. The GAEZ-LGP has the largest within-zone range of temperature seasonality because its delineation is based more on water availability and many of its zones have relatively large north to south extension, capturing a wide range of temperature regimes. Range of precipitation seasonality was also smallest in the GYGA-ED scheme even though this parameter is not explicitly considered in its derivation.

3.3. *Balancing number of zones and within-zone climatic heterogeneity*

An appropriate zonation scheme for extrapolating point-based estimates of yield potential while limiting requirements for data collection is one which optimizes the trade-off between achieving climatic homogeneity within zones and minimizing the number of zones necessary to capture large portions of harvested area of target crop. While zonation schemes with few zones and large zone area, such as GAEZ-LGP and HCAEZ, require <10 zones to cover 80% of global rainfed maize harvested area (Table 2), they have large variability in weather variables that influence crop growth and yield (Fig. 6). Among schemes with at least 100 zones and smaller zone size, those schemes that use the clustering methodology (GEnS) or a three-parameter matrix (GYGA-ED) appear to have the best balance between number of zones for 80% coverage of harvested area (Table 2) and homogeneity in weather variables within zones (Fig. 6). While the crop-specific GLI zonation scheme has relatively homogeneous weather within its zones, it requires the largest number of zones to achieve 80% coverage of rainfed maize area, and it requires a separate zonation scheme for each crop species. In contrast, the SAGE scheme requires the smallest number of zones for 80% coverage of rainfed maize area but has high degree of variability in weather variables within its zones despite use of crop-specific base temperatures used to derive GDD.

4. Discussion

The GAEZ-LGP and HCAEZ schemes are simply too coarse for use in estimating and extrapolating yield gap analyses because climate heterogeneity within zones is too large. Both SAGE and GLI schemes are crop-specific and use a two-parameter zonation matrix. Of the two, the GLI approach gives much greater homogeneity of weather variables within zones, but it requires the largest number of zones to cover crop area. Both schemes require separate zonation schemes for each crop which would make it cumbersome to estimate Yp, Yw, and yield gaps in regions where more than one crop was grown in rotation. Both GYGA-ED and GEnS approaches are not crop specific and achieve relatively low within-zone heterogeneity in key weather variables. Whereas GEnS requires fewer zones to achieve 80% coverage of rainfed maize area and has slightly less heterogeneity in mean temperature, GYGA-ED has substantially less within-zone heterogeneity in cumulative water deficit and in seasonality of temperature and precipitation. Both methods appear to be well-suited for up-scaling yield gap analysis.

Several conclusions follow from this evaluation. Climate zones used as extrapolation domains for yield gap analysis of current production should focus on areas where crops are grown to minimize within-zone weather variability. While the cluster methodology also appears efficient at limiting the number of zones required to cover crop area and minimizing within-zone heterogeneity, they are less intuitive than matrix zonation schemes because of the sophisticated mathematics and large number of weather variables considered. However, for matrix-based zonation schemes it has not

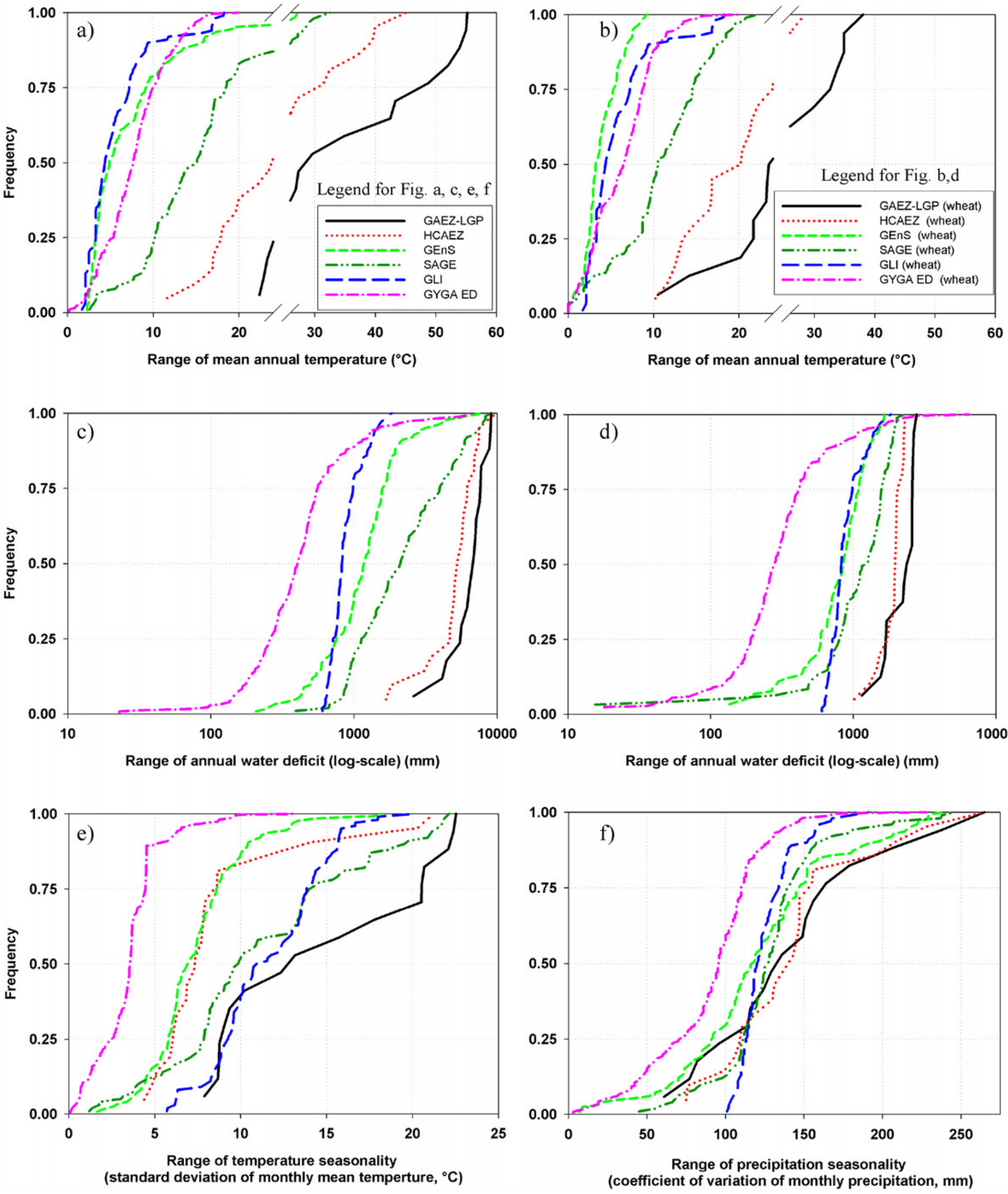

Fig. 6. Frequency distribution of within-zone range of mean annual temperature, annual water deficit (precipitation less evapotranspiration), temperature seasonality and month to month coefficient of variation in precipitation based on WorldClim data at 5′ resolution (Hijmans et al., 2005) for 6 climate zonation schemes. All terrestrial area covered by the zones are considered (panels a, c, e, f); mean annual temperatures and annual water deficit was also calculated considering only where zones overlap wheat harvested area (b and d). The latter evaluation eliminates bias of generic zonation schemes that evaluate all terrestrial area (GAEZ-LGP, GEnS, SAGE, HCAEZ) and all major crops (GYGA-ED).

been tested how to best determine the range-boundaries, whether by equal distributions (Licker et al., 2010), frequency distributions (GYGA-ED), or another set of criteria such as quantity of harvested area within zones (GLI). Beneficial future work would be validation and comparison of zonation schemes using weather data from different weather stations within a zone or by performing and comparing yield gap analysis for several sites within a zone.

All zonation schemes are limited by choice and quality of the underpinning data used to derive them. This includes availability and distribution of high-quality, location specific weather station data. Using any zonation scheme to estimate Yp, Yw and yield gaps at larger scales also requires data on soils and management variation within zones (van Ittersum et al., 2013), and quality of those data will also affect the accuracy and uncertainty in such large scale estimates (van Wart et al., 2013).

Acknowledgments

The authors would like to thank the Bill and Malinda Gates Foundation whose support of the Global Yield Gap Atlas project made this research possible. Secondly, we thank Dr. Marc J. Metzger from the University of Edinburgh for providing us with the data on GEnS.

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