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Mapping abiotic stresses for rice in Africa: Drought, cold, iron toxicity, salinity and sodicity

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ABSTRACT

Maps of abiotic stresses for rice can be useful for (1) prioritizing research and (2) identifying stress hotspots, for directing technologies and varieties to those areas where they are most needed. Large-scale maps of stresses are not available for Africa. This paper considers four abiotic stresses relevant for rice in Africa (drought, cold, iron toxicity and salinity/sodicity). Maps showing hotspots of the stresses, the countries most affected and total potentially affected area are presented. In terms of relative importance, the study identified drought as the most important stress (33% of rice area potentially affected), followed by iron toxicity (12%) and then cold (7%) and salinity/sodicity (2%). Hotspots for iron toxicity, cold and salinity are identified. For drought, local variation along the hydromorphic zone was a stronger determinant than larger-scale climatic variation, therefore mapping of drought based on climatic zones has only limited value. Uncertainties in the mappings are discussed.

1. Introduction

Maps of crop stresses can be used for research prioritization (Waddington et al., 2010). They can be used to focus research and development activities on the most important stresses. And they can be used to target dissemination of solutions for specific stresses. For example, for distributing varieties tolerant to iron toxicity specifically to those areas where iron toxicity is widely present. This paper focusses on four abiotic stresses in rice (*Oryza* spp.): drought, cold, iron toxicity and salinity. These four stresses were selected because (1) they are known to be important for rice (Balasubramanian et al., 2007; Diagne et al., 2013b) and (2) they are relevant in the context of a large breeding programme focused particularly on these four stresses, the Stress-Tolerant Rice for Africa and South Asia (STRASA) project (the fifth STRASA stress, flooding, is not mapped here).

There have been limited efforts to develop continent-wide maps of rice stresses in Africa. Diagne et al. (2013b) and Waddington et al. (2010) used surveys to identify major stresses. The most important constraints identified by the experts consulted by Waddington et al. (2010) were those of fertiliser supply/soil fertility, drought/water management and problems with weeds. Diagne et al. (2013b) report major constraints identified through farmer surveys for four rice-growing environments in Africa (irrigated, rainfed upland, rainfed lowland and "other"). Weeds, rodents and birds, and diseases were reported as the main constraints. The emphasis of Diagne et al. (2013b) and Waddington et al. (2010) is more on identifying the most important constraints than on mapping them.

Two other studies with continent-wide coverage are more "spatially explicit". Haefele et al. (2014) present global maps and area estimates of soil quality classes and constraints for rice. For rice in Africa, they identify low soil fertility as the main soil constraint (37.6% of all rice area in Africa, i.e. 3.94 Mha of a total rice area of 10.47 Mha), followed by drought (19.0%) and aluminium toxicity (18.8%); the latter is strongly linked to soil phosphate-fixation, causing phosphorus (P) deficiencies for rice and other crops. The drought analysis by Haefele et al. (2014) is based on soil water-holding capacity only, not on climatic data. Soils with low water-holding capacity were considered drought-prone. However, in humid climates or in areas with high groundwater levels, a low water-holding capacity need not be a problem. If there is no rain for a long time during the growing season then, no matter what the water-holding capacity, crops will experience drought. In this sense rice is more vulnerable than most other crops, because it has, with its shallow rooting system (20–40 cm), access to only a small volume of soil. An analysis of drought risk would benefit from taking into consideration rainfall and groundwater-table depth. The second "spatially explicit" continent-wide study was on major weeds in rice. According to Rodenburg et al. (2016), an estimated 1.34 Mha of rainfed rice is infested with at least one of the weeds *Striga asiatica*, *S. aspera* and *S. hermonthica* in rainfed uplands, and *Rhamphicarpa fistulosa* in rainfed lowlands. All four studies cited above discuss uncertainties associated

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with data and their use, which are large, and include uncertainties in the rice maps used.

Thus, for the four abiotic stresses of drought, cold, iron toxicity and salinity, few or no maps have been developed at the continental scale for rice in Africa. Only drought has been mapped to a limited extent by Haefele et al. (2014). Meanwhile, tolerant varieties for these abiotic stresses are in different stages of development.

Since salinity and sodicity are frequently found in the same places, in this paper a broader definition of salinity is adopted, including also sodic (also called alkaline) soils.

The objective of this paper was to map the four stresses, drought, cold, iron toxicity and salinity/sodicity. For each stress, the area potentially affected was estimated per country. The most affected countries are highlighted in tables and maps. More maps are provided online to allow readers to zoom in and identify hotspots for each stress.

2. Materials and methods

2.1. General approach

The general approach was to overlay a rice crop map with a "stressor" map to identify those areas with both rice and the "stressor". For each stress, uncertainties were identified via an extensive literature review and these uncertainties were then quantified using different input datasets. Owing to these uncertainties, we speak of "potentially affected" areas. For each stress, the area potentially affected is estimated.

2.2. Spatial datasets

2.2.1. Crop maps

Using three crop maps gives a sense of the uncertainty in estimating potentially affected areas because of uncertainty about where rice is grown. All three maps of rice harvested area (ha) have a 0.083° spatial resolution (approximately 9 × 9 km):

- SPAM2005 data for rice, downloaded from http://harvestchoice.org/data/rice_h (You et al., 2014a,b)
- MIRCA2000 data for rice, downloaded from http://www2.uni-frankfurt.de/45218023/MIRCA (Portmann et al., 2010)
- GAEZv3 data for rice, downloaded from www.gaez.iiasa.ac.at/ (Fischer et al., 2013).

Differences between these maps have been investigated by Anderson et al. (2015). All three make a distinction between rainfed and irrigated crops and provide separate maps for those. Rodenburg et al. (2016) note that these maps indicate a number of African countries with little or no data for rainfed rice while in reality we know there is a substantial rainfed rice area. This is also illustrated in two examples in the Appendix (§A.1), which clearly show that these maps are, for rice in Africa, too uncertain in terms of differentiating between where irrigated and rainfed rice are located. Consequently, I calculated the areas of rainfed lowland, rainfed upland, irrigated and mangrove rice by multiplying the mapped total rice area (SPAM2005, MIRCA2000, GAEZv3) by country fractions of rainfed lowland/upland and irrigated land calculated from country data reported by Diagne et al. (2013a). A drawback of this approach is that we remain less certain about the spatial distribution of these rice-growing environments within the countries, but it avoids the obvious gross allocation errors between irrigated and rainfed in the three crop maps.

2.2.2. Harmonised World Soil Database (HWSD)

Risk of iron toxicity and salinity was mapped using the Harmonised World Soil Database (HWSD). The HWSD is a course-scale map, 1:5,000,000 (FAO et al., 2012). It has 16,327 unique spatial mapping units (SMUs). Each SMU contains 1–10 (median 3) non-georeferenced soil units (Haefele et al., 2014). The online available raster version at 0.0083° resolution (approximately 0.9 × 0.9 km) was used. First, the share of iron/saline soil units was calculated for each SMU. This high-resolution iron/salinity map was aggregated (spatial average) to the same spatial resolution as the three crop maps and overlaid with the crop maps to identify potentially affected areas, i.e. those with both iron or salts and rice.

2.2.3. Climate zonation maps

The Köppen–Geiger climate zone map (Kottek et al., 2006) was used to spatially extrapolate site-based estimates of drought and cold stress. A key issue is whether climate zone maps are suitable for such extrapolation. Extrapolation becomes impossible with no simulation sites inside a climate zone. Extrapolation becomes highly uncertain with just one or few simulation sites inside. Extrapolation also becomes uncertain when within-zone (short scale) variation is larger than between-zone variation.

Van Wart et al. (2013) review 12 climate zone maps. Of these, six have fewer zones (9–25 zones) than the Köppen–Geiger (which has 31 zones) and five have more zones (74–265). A test (not shown) revealed that with 74 or more zones, there would be many zones with no or few simulation sites inside, which can therefore not be used for spatial extrapolation. Therefore, the five zonation maps with high numbers of zones were not considered suitable for the objective of presenting a map of drought or cold risk for the whole of Africa. Of the remaining seven maps with fewer zones (6–31), the Köppen–Geiger climate zonation has the largest number of zones (31), therefore the Köppen–Geiger climate zone map was considered most suitable for full spatial coverage at the highest viable spatial resolution.

2.3. ORYZA2000 model

Drought and cold stress were simulated with the model ORYZA2000v2n14. This version is based on ORYZA2000v2n13s14 as documented by van Oort et al. (2015a). This model includes recent updates on modelling heat, cold and phenology documented by van Oort et al. (2015a). A common set of sites, weather data, sowing dates and phenological parameters were used, which are documented in this section. More details on how drought and cold were simulated are provided in the following sections.

2.3.1. Site and season selection

Sites for drought and cold were selected with a protocol described by Van Wart et al. (2013). Sites were selected such that they together covered the major climatic zones and crop regions within a country. Countries were chosen such that these together represent the different agro-ecologies and major rice regions of the African continent, i.e. East, West and North Africa, irrigated and rainfed, and lowlands and highlands. In total, 19 countries were selected (West 11, North 1, East 7), with 53 irrigated sites and 52 rainfed sites.

2.3.2. Weather data

A site was defined as a weather-station point. For each point, the associated pixel of the AgMERRA weather dataset was identified. The AgMERRA dataset (Ruane et al., 2015) contains daily weather data from 1980 to 2010 at a 0.25° × 0.25° resolution (~28 × 28 km). Potential and water-limited yields (Bouman et al., 2001) were simulated for irrigated sites (1998–2002, five years) and rainfed rice (1996–2004, nine years). For irrigated sites, fewer simulations were needed to obtain robust long-term average stress indices because interannual variability in yields is less, due to smaller climatic risks.

2.3.3. Sowing dates and phenology

Sowing dates and crop duration were derived from the RiceAtlas (Laborte et al., 2017) and cross-checked with additional data when initial simulations showed unrealistically low simulated yields. Temperature sums for different developmental stages were calibrated