Haefele, S.M.; Nelson, A.; Hijmans, R.J.
Soil quality and constraints in global rice production Geoderma, 2014; 235-236:250-259

10.1016/j.geoderma.2014.07.019

Soil quality and constraints in global rice production

S.M. Haefele [1], A. Nelson [2], and R.J. Hijmans [3],

[1] ACPFG, University of Adelaide, Adelaide, Australia; stephan.haefele@acpfg.com.au, Tel.: +61 8 8313 7499, Fax: +61 8 8313 7102;
[2] International Rice Research Institute, Los Baños, Philippines
[3] Department of Environmental Science and Policy, University of California, Davis, CA, USA

Abstract

We assessed soil quality in global rice production areas with the Fertility Capability Soil Classification (FCC) system adjusted to match the harmonized world soil database, established by the Food and Agriculture Organization and the International Institute for Applied Systems Analysis. We computed the distribution of 20 soil constraints, and used these to categorize soils as ‘good’, ‘poor’, ‘very poor’, or ‘problem soil’ for rice production. These data were then combined with data of global rice distribution to determine soil quality in the main rice production systems around the world. Most rice is grown in Asia (143.4 million ha), followed by Africa (10.5 million ha) and the Americas (7.2 million ha). Globally, one-third of the total rice area is grown on very poor soils, which includes 25.6 million ha of irrigated rice land, 18.5 million ha in rainfed lowlands, and 7.5 million ha of upland rice. At least 8.3 million ha of rice is grown on problem soils, including saline, alkaline/sodic, acid-sulfate, and organic soils. Asia has the largest percentage of rice on good soils (47%) whereas rice production on good soils is much less common in the Americas (28%) and accounts for only 18% in Africa. The most common soil chemical problems in rice fields are very low inherent nutrient status (35.8 million ha), very low pH (27.1 million ha), and high P fixation (8.1 million ha); widespread soil physical problems especially severe in rainfed environments are very shallow soils and low water-holding capacity. The results of the analysis can be used to better target crop improvement research, plant breeding, and the dissemination of stress-specific tolerant varieties and soil management technologies.

Key words: global rice production areas; soil quality; P fixation; problem soils;

Introduction

Soil quality has long been synonymous with agricultural productivity. Before mechanization and widespread fertilizer use, inherent chemical, physical, and biological soil properties were the major determinant of soil fertility, and farmers had a limited number of options to improve soil quality and crop production. And, although today there is a wider range of technologies reducing the importance of inherent soil quality and soil fertility for agricultural productivity, they cannot overcome all constraints, they may not always be economical, or they may not be within the reach of farmers for other reasons. Intensive soil amelioration often is economical only for high-value crops, and many farmers, especially in developing countries, do not have the resources to invest much in fertilizer, soil amendments, or machinery to overcome soil constraints. Others may not be willing to make such investments if they don't own the land or their production environment is risky, for example, in drought- or flood-prone environments. Thus, "natural" soil quality remains a major factor of productivity in most agricultural production systems because it provides favorable growing conditions and determines the indigenous nutrient supply to the crop. In addition, soil characteristics affect the retention and plant availability of fertilizers and the benefit of other soil amendments, thereby controlling the possible yield increase and return for a given investment. Soil characteristics also influence the amount of crop-available water in water-limited environments, and certain conditions in the rhizosphere, such as salinity, acidity, alkalinity, and toxicity may affect crop growth negatively.

Rice cultivation extends from the humid tropics to temperate regions of northeastern China and southeastern Australia, and from sea level to altitudes of more than 2500 m in Nepal and Bhutan. Although most rice is grown in Asia, substantial areas are also planted with rice in Africa and the Americas, whereas relatively small rice production areas are situated in Oceania and Europe. As a consequence of this broad geographic distribution, rice is grown in many different climates, and on a wide range of soils with huge differences in soil quality. There have been some earlier efforts to characterize rice soils in flooded rice production systems in Asia (e.g., Kawaguchi & Kyuma, 1977; Moormann & van Breemen, 1978; IRRI, 1978, 1985). However, most studies of rice soils concentrated on specific characteristics or processes in flooded rice soils (e.g., Ponnamperuma, 1972; Banta & Mendoza, 1984; Ladha et al., 1992; Wassmann et al., 2000; Kirk, 2004; Koegel Knabner et al., 2010), and recent studies on the spatial characterization and distribution of rice soils are rare. Consequently, comparable quantitative data on rice soil quality across regions and rice production systems are not available and important soil quality-related questions can usually be answered only in a qualitative way by local experts. A better spatial characterization of soil quality and constraints could serve several purposes. Spatial information on environmental constraints to crop production can be used to evaluate, target, and focus agricultural research (e.g., Hijmans et al., 2003) and assist technology dissemination (Singh & Singh, 2010). Knowledge of spatial distribution and the importance of abiotic stresses related to soil characteristics, climate, or hydrology could help to better target rice varieties with specific traits such as submergence tolerance (Xu et al., 2006), salinity tolerance (Thomson et al., 2010), P-deficiency tolerance (Gamuyao et al., 2012), and drought tolerance (Verulkar et al., 2010). Similarly, such information could be used to improve research and the dissemination of management options for specific soil-related problems. And, a better understanding of what the most important problems in a specific region are could help to focus limited research or development resources on widespread problems.

Any analysis of soils under rice production and their characteristics has to consider the major rice production systems (IRRI, 1984). Most rice is grown in aquatic conditions in bunded fields that retain a shallow water layer for most of the season. These fields may be irrigated and/or rainfed, and are referred to as the “lowland rice production system”. Lowland rice production also occurs in mountainous areas as terracing allows for the construction of fields that are bunded and flooded. “Upland rice”, in contrast, is grown under aerobic soil conditions, without bunds around the field and no standing water like most other crops. Upland rice is commonly grown on plateau uplands (mainly in India) or on sloping land (mainly in Southeast Asia). Most of these fields are rainfed, but, in some regions, notably in parts of Brazil, upland rice is irrigated. Additional, but less common, production systems are the “deepwater rice” systems in which fields may be naturally flooded with as much as 5 meters of water, and “tidal wetland” rice systems in coastal regions.

The present study is based on previous work by Garrity et al. (1986) and Haefele & Hijmans (2007) that combined data on rice distribution and soil fertility constraints for the characterization of rainfed lowland ecosystems in Asia. Both these studies used now outdated soil data and considered only soil constraints in rainfed lowland rice production in Asia, partly because rainfed lowlands are generally assumed to have the most abiotic stress problems and partly because continuous flooding typical for most irrigated systems brings about a multitude of chemical, physical, and microbiological changes that render flooded soils very different from well-drained soils (Ponnamperuma, 1972). However, not all irrigated environments have good soils and some problem soils are even preferably cultivated with irrigated rice. Also, many negative soil characteristics for crop production like low nutrient reserves, very low cation exchange capacity (CEC), or high Fe/Al oxide content, are not much affected by flooding. The objective of the present analysis was therefore to use the most recently developed spatial databases for a quantitative characterization of soil quality for rice production systems worldwide.

Materials and methods

We analyzed soil fertility-related characteristics of rice environments by combining global spatial databases of soil characteristics and of rice production systems. The rice distribution data came from an updated and expanded version of the database for sub-national administrative regions of South and Southeast Asia of Huke & Huke (1997). For each country, the area of each rice production system (irrigated lowland, rainfed lowland, upland, and other [i.e., deepwater or mangrove]) was compiled at the best available level of spatial detail, with an emphasis on collecting more spatially detailed data in the larger and more important rice-growing regions of the world. For example, the distribution of rice production systems was compiled for 1749 counties in China and for 434 districts in India. In total, the database contained 9218 spatial units with rice production, or one unit per 17,400 ha of the global rice area across 112 countries. When necessary, we adjusted the sub-national data pro rata to match the rice area for 2010-2012 according to FAOSTAT (2013). The data for each rice production system were transferred from the administrative area polygon data structure to a raster data structure with a 30 arc-seconds (~0.9 km^2 at the equator) spatial resolution. For each administrative area, the area of rice production was distributed across the raster cells that were deemed most likely to support that rice production system. Cells that were assumed to have rice were those that had agriculture according to a satellite image-derived raster database of global land cover (GLOBCOVER version 2.3; Arino et al., 2008), for flooded systems in South and Southeast Asia complemented by satellite derived data on the extent of paddy rice cultivation by Xiangming et al. (2006). For some regions, these datasets had much less area with crops than the rice area reported for the administrative regions. This happened in regions with double (or triple) cropping of rice, but frequently it appeared to be caused by underreporting of agricultural land use. When necessary, we therefore allocated rice area to additional cells within an administrative area, excluding areas with no soil (e.g., rocks or water), with cities, or with very steep slopes.

We used soil data from the Harmonized World Soil Database (HWSD, version 1.2; FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). It has 16327 unique map units, and rice was produced in 6162 of them. Each map unit describes a soil unit or associations of soil units. When a map unit is not homogeneous, it is composed of a dominant soil unit and component soil units. The latter are either associated soils (maximum three, each covering at least 20% of the area) or soil inclusions (maximum four, covering together less than 20% of the area). The median number of soil units per map unit is 3, and 90% of the map units have 5 or fewer soil units (the maximum was 10 soil units in a single map unit). The median share (relative area) of a soil unit in a map unit is 24%. Each soil unit has an FAO soil name and many additional soil properties for the topsoil and subsoil, such as texture, soil depth, gravel, organic carbon content, pH, CEC, calcium carbonate (lime) content, exchangeable sodium percentage, and electrical conductivity of the soil (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012).

To generalize these data into groups of soil fertility constraints, we classified all the soil units within each map unit based on the Fertility Capability Soil Classification (FCC) system (Sanchez & Buol, 1985; Sanchez et al., 2003). The FCC groups soils according to their physical and chemical properties causing problems in crop production. It consists of two categorical levels, describing topsoil and subsoil texture (the first category) and soil conditions affecting plant growth (the second category). The second category consists of several modifiers indicating whether a soil has, for example, a low pH, limited CEC, or salinity problems. The fraction of the area covered by each FCC modifier was computed for each raster cell based on the fraction of the area covered of a soil type in a particular soil unit. We then multiplied the raster cell values representing the area of each rice production system with these FCC fractions to compute the distribution of soil fertility constraints by rice production system. We aggregated and tabulated these data to country and regional levels and reported the results, at a conservative level of precision, to the nearest 1000 ha.

We distinguished four groups of soils with different levels of soil fertility and severity of soil constraints, because groups of these modifiers go together in soils anyway and because the larger groups are easier to report, use, and visualize (but the underlying data can also be retrieved for each separate modifier). The three main groups (good, poor, and very poor) provide a clear and easy to use, high level soil fertility classification. The 4th group (problem soils) are soils with specific soil chemical constraints which can be addressed with management and/or tolerant rice germplasm.

1. **Problem soils:** all topsoils designated with the FCC modifier *s* (saline soils), *c* (acid-sulfate soils), *O* (organic soils), *n* (sodic soils), or *b* (alkaline soils). Crop growth on these soils is likely to be limited by salinity (*s*); very low pH; P deficiency; Fe/S/Al toxicity (*c*); nutrient deficiencies of N, Zn, K, P, Cu, and Mo (*O*); or high pH causing P, Fe, and Zn deficiency (*n, b*). These are the most frequently cited “problem soils” in rice-based systems (Sanchez & Buol, 1985; Sanchez et al., 2003).

2. **Very poor soils, considerable soil constraints:** all topsoils designated by one or more of the FCC modifiers *k* (< 10% weatherable minerals in silt and sand fraction or exchangeable K < 0.20 cmol per kg soil), *e* (effective CEC < 4 cmol per kg soil), *a* (> 60% Al saturation), or *i* (% free Fe_2O_3 divided by % clay > 0.15 and more than 35% clay or hues of 7.5 YR or redder and granular structure). Crop growth on these soils is potentially limited by combinations of low nutrient reserves (*k*), low CEC (*e*), Al toxicity (*a*), and/or high P fixation. We added the characteristics “very shallow (< 30 cm)” and “limited water-holding capacity (< 50 mm m^{-1})” to this group. Generally, these are highly weathered soils with very limited indigenous nutrient supplies, low nutrient retention capacity, frequent and often severe P deficiency, acidic to very acidic soil reaction (pH < 5.5), and Fe/Al toxicity. They also might be shallow and prone to drought spells.
3. **Poor soils, no major soil constraints:** According to Haefele and Hijmans (2007), these were all soils with no other FCC modifier than *h* (10-60% Al saturation of the effective CEC or pH between 5 and 6). Sanchez et al. (2003) added the *h* modifier to the soils without constraints but introduced the a^- modifier (weathered soils with limited indigenous nutrient supplies, low nutrient retention capacity/CEC, and moderately acid), which we considered characteristics of very poor soils. New characteristics added to this group were indicators of limited soil fertility such as low organic C content in the topsoil, shallow soils (*R*), gravelly soils (*r*), and slightly alkaline (*n*-) soils. Thus, this group includes various soils with only minor constraints and/or limited soil fertility.
4. **Fertile (good) soils, no or minor soil constraints:** These are all soils not designated with any of the FCC modifiers *h, k, e, a, i, s, c, O, n,* or *b*; therefore, none of the constraints indicated by these modifiers would occur. Soils included can be designated with the FCC modifiers *x* (volcanic materials) or *v* (vertic soil properties), and we also added calcareous soils (modifier *b*) and waterlogged soils (g, g+) to this group. In addition, this group contains soils not characterized by any of the FCC condition modifiers. Soils in this group are much less weathered, have considerably higher natural soil fertility than poor and very poor soils, and soil constraints are minor or absent.

As the definitions in the FCC do not exactly match the data available in the HWSD, we developed an adjusted system that matches the spirit and concepts of the FCC with the HWSD, and focused on constraints to rice production (Table 1). We used R v3.0.1 (R Development Core Team, 2012) and the raster package (Hijmans, 2013) to tabulate the area of each rice production system for each soil mapping unit, and then to estimate the distribution of soil fertility constraints by rice production system.

Results

World rice area has been rising over the past decade: from a recent low point of 148 million ha in 2002 to 164 million ha in 2011 (FAOSTAT, 2013). The global rice area in the years analyzed (the average for 2010-2012) was about 162 million ha annually (Table 2). About 30 million ha are planted at least twice a year to rice; hence, the land area with at least one rice crop is about 132 million ha per year. In the results below, the area of “rice soils” refers to “annual area planted with rice”, not “physical area on which rice is planted”. Thus, in tallying soil characteristics, if a field is planted with rice twice a year, it is counted twice, and the rice soil area always sums up to 162 million ha.

Most rice is grown in Asia (about 143.4 million ha), and substantial but much smaller areas are planted with rice in Africa (10.5 million ha) and the Americas (7.2 million ha) (Table 2, Figure 1). Among these major rice-growing continents, irrigated rice is most important in Asia (60%) and the Americas (54%, not including irrigated upland rice), and least important in Africa (21%). In Asia, most rainfed rice is found in South and Southeast Asia. Rainfed rice is the dominant rice production system in Africa (79%), with large shares of lowland rice (44% of the total annual area) and upland rice (28% of the total annual area). In contrast, most rainfed rice in the Americas is upland rice (46% of the total annual area). Deepwater/mangroves rice systems (other in Figure 1) in Asia (3.5 million ha) are located mostly in South and Southeast Asia, either in coastal deltas (Southeast Asia) or inland (South Asia). In Africa, there are about 0.7 million ha of deepwater/mangrove rice systems in coastal regions of West Africa and in the inland Niger delta. Only small rice areas are found in Europe and Oceania (about 0.7 and 0.04 million hectares, respectively), and almost all is irrigated. Most of the European rice is concentrated in Italy, Russia, and Spain whereas most of the rice in Oceania is grown in Australia. A second rice crop in the dry season is mostly important in Asia, but additional areas where this is important occur in Africa, for example, Madagascar, Nigeria, and some irrigated areas in the Sahel region. A more recent development in Latin America is that rice production has been shifting from low-yielding upland rice to high-yielding and much better managed irrigated rice (Dawe et al., 2010; Jennings, 2007).

Of all the continents, Asia has the largest percentage of good rice soils (47%) and of rice soils without major constraints (good and poor soils, 65%) (Table 3; Figure 2). Good rice soils are less common in the Americas (28%) and account for less than a fifth of the total area in Africa (18%). Consequently, the share of soils with major constraints (combining very poor soils and problem soils) is much higher in Africa (64%) and the Americas (55%). Saline problem soils represent a large fraction of the rice soils in Oceania, whereas rice soils are often very sandy/poor in southern Europe.

Beyond these general trends, there is considerable variation within continents. Asia has the largest percentage of rice soils without major soil constraints (Table 3), but these relatively good soils are not evenly distributed (Figure 2). Regions where rice is grown on relatively good soils are South Asia (good and poor soils = 81%) and East Asia (good and poor soils = 61%). However, many less favorable rice soils are common in Southeast Asia, where very poor soils and problem soils dominate (52%). Within Africa, rice soils without major soil constraints are common in northern Africa (78%) whereas very poor and problem rice soils are widespread in West, Central, and East Africa (64%, 76%, and 67%, respectively) (Figure 2). In South America, much rice is grown on very poor soils with major constraints (62%), whereas, in North America, Central America, and the Caribbean, it is grown on better soils (good and poor soils = 76%, 74%, and 70%, respectively).

In addition to these differences between and within continents, considerable soil quality differences are found between the different rice production systems (Table 4). In Asia and the Americas, irrigated rice systems tend to have better soils than other rice systems. This is not the case in Africa, because a large percentage of irrigated rice is grown on problem soils (mostly saline soils, especially in Egypt), and because much of the irrigated rice area in Africa is in Madagascar, which has generally very poor soils. The soil quality difference between irrigated and rainfed environments is largest in the Americas, where almost all the rainfed rice is upland rice, but the difference is also considerable in Asia and Africa. In rainfed production systems, very poor soils and problem soils together constitute 39% in Asia, 66% in Africa, and 72% in the Americas.

In all three major rice-growing continents, there is a trend of a decreasing fraction of good soils and problem soils when going up in the landscape (deepwater/mangrove environments – irrigated lowlands – rainfed lowlands − uplands), and an increase in very poor soils in the same direction (Tables 4 and 5). This trend is strongest in Southeast Asia, the Asian sub-region with the worst soils. There, the percentage of good rice soils increases from 18% in the rainfed uplands to 34% in deepwater environments, while the percentage of very poor soils decreases from 64% to 27% (Table 5). Problem soils increase from 3% to 18% going down the toposequence. Similar trends for upland and lowland rice were found for the Americas and sub-regions in Africa (data not shown).

In Asia, problem soils cultivated with rice are not common (5% of the total rice area there) but they are locally important, especially in Pakistan and northern India (alkaline and sodic soils); in some coastal lowlands of India, Bangladesh, Myanmar, Thailand, and Vietnam (saline and acid-sulfate soils); and in coastal regions of Borneo, Sumatra, and New Guinea (acid-sulfate and organic soils) (Figure 2). Problem soils in the Americas (6% of the total rice area) are mostly saline or organic and occur in coastal areas and at a few inland sites (Figure 2). In Africa, they are common in Egypt, in some Sahelian irrigation schemes, and in coastal regions, but they occupy “only” 3% of the total rice area. Within the problem soils assessed here, salt-related problems are the most common in rice cultivation (Table 6). Worldwide, soil salinity is a constraint for rice on about 2.7 million ha, and alkalinity/sodicity affects 3.5 million ha. Because salinity, alkalinity, and sodicity often overlap (e.g., many alkaline/sodic soils can also be saline), the sum of the areas with individual soil problems is considerably higher than the total area of problem soils. About

3.0 million ha of rice are cultivated on acid-sulfate soils, and around 1.5 million ha are grown on organic soils. With respect to total area, Asia is the most affected by problem soils but the relative abundance of rice on problem soils is highest in the Americas (see Tables 3 and 6).

The distribution of individual soil constraints for the main rice-growing areas and the major production systems is shown in Table 7. Saline and alkaline/sodic characteristics are important soil problems across regions and systems, whereas acid-sulfate soils are mostly important in Asia, and organic soils in Asia and the Americas. Saline/alkaline/sodic soils are closely associated with deepwater, mangrove, and irrigated environments, whereas acid-sulfate soils are most common in rainfed lowlands and deepwater/mangrove environments. All four problem soil constraints are rare in upland rice (Table 7). In the Americas, alkaline/sodic soils are the main problem in irrigated rice whereas organic soils are the main problem soil type in rainfed rice. In the group of very poor soils, poor nutrient status and very low pH are the most common problems (36 and 27 million ha, respectively). Limited water-holding capacity is an important problem mainly in Asia and Africa, where it also often coincides with rainfed environments. High P fixation caused by high Fe/Al oxide concentration in highly weathered soils occurs on 8 million ha of tropical soils in Asia, Africa, and the Americas. Poor soils are most often limited by moderate acidity/limited Al toxicity, low soil organic matter content, and soil physical impediments (gravelly). Within the good soils, high carbonate content can cause P and Zn deficiencies, considerable P fixation occurs on 9.6 million ha of vertic and andic soils, and gleyic conditions can indicate drainage/submergence problems but are otherwise no constraint for rice. Soils without any constraints are most common in Asia (24%) and least common in Africa (12%).

Discussion

The total world rice area of 162 million ha in this study is within the normal range of the past decade, going from a recent low in 2002 (148 million ha) to the maximum rice area reached in 2011 (164 million ha), and the main part of this fluctuation occurs in Asia and Africa (FAOSTAT, 2013). Within Asia and in comparison with the mid-1990s (Huke & Huke, 1997), irrigated rice land increased from about 55% of the total area to 60% now, rainfed lowland rice decreased from 35% to about 32%, upland rice decreased from 7% to 6%, and deepwater/other production systems decreased from 3% to 2%. However, the actual area of upland and deepwater/other rice hardly changed − it just did not increase. Thus, the main area trends in Asia are a considerable flexibility of the total rice area and an increasing share of irrigated rice. The total rice area in Africa increased considerably from 7.0 million ha in 1995 to 10.5 million ha now. In the Americas, the total area remained stable in the last 17 years according to FAOSTAT (2013), but a considerable shift from rainfed upland rice to irrigated lowland rice was reported for South America (Dawe et al., 2010).

Before discussing the soil quality results, some methodological limitations should be mentioned. Our analysis of rice soil quality and constraints is obviously dependent on the resolution and quality of the underlying data sources. Global agricultural and environmental data that is based on data compiled from national sources (whether crop area, soils, climate, or other variables) varies considerably in resolution and uncertainty by country, and probably also within country. For example, the resolution and quality of the soil and rice data for China seems very high but, at the other extreme, in some parts of Africa the data is much more uncertain. Another issues is that we identified 9218 spatial units with rice production but “only” 6162 soil mapping units with rice production. This would suggest that the rice data were more detailed which is not necessarily true because the same soil types can occur over large areas and be mapped with high precision (i.e. high resolution, few spatial units). But an important uncertainty in the soil data is that the spatial distribution of the dominant soil unit and associated component soil units within a mapping unit is unknown. In case of the rice area units, we downscaled the rice data using land cover data such that the spatial resolution was much higher than the original administrative boundaries data. More accurate results from this type of characterization studies will be possible when databases with a higher spatial resolution become available. Improved rice distribution maps using remotely sensed land cover data for mapping rice production systems are already being developed (e.g., Xiao et al, 2006; Gumma et al., 2011). A more detailed characterization could also be achieved by integrating geomorphology and hydrology into the characterization as both factors have been shown to modify soil characteristics and constraints (Homma et al., 2003; Oberthür & Kam, 2000). And, improved spatial resolution of soil databases could be obtained by digitizing and reconciling national-level soil maps and making better use of legacy soil profile data (Tempel et al., 2013).

The major soil fertility groups we distinguished were based on the earlier study by Haefele & Hijmans (2007), which addressed only rainfed lowland environments. Similar fertility groups for paddy soils in tropical Asia were also found by Kawaguchi & Kyuma (1977). They analyzed 410 topsoil samples from paddy soils in nine Asian countries and distinguished three main factors determining soil fertility: inherent potentiality (determined primarily by the nature and amount of clay, and base status), organic matter and nitrogen status (related to total organic carbon and nitrogen, and extractable NH_3-N), and available phosphorus status (total P, available P indicators). High scores in the “inherent potentiality factor” would in most cases qualify for the “good soils” group, and low scores in the “available phosphorus factor” would generally lead to the “very poor soil” category. Sanchez et al. (2003) also proposed a new FCC modifier “*m*”, denoting an organic carbon deficit, probably similar to the “organic matter and nitrogen status factor” determined by Kawaguchi & Kyuma (1977). Consequently, we included “organic carbon concentration” as an indicator of soil fertility in this analysis, as such data were available in the new HWSD database. Sanchez et al. (2003) also proposed to combine the former *“h”* modifier (acid but limited Al toxicity) with the “no major chemical constraints” group, but we kept the new indicator *a-* as a characteristic of poor soils because it denotes considerably weathered soils with lower indigenous nutrient supplies, limited nutrient retention capacity, and potential Al toxicity.

Although a characterization of world rice soils has not been conducted before, our results for rainfed lowlands in Asia (Table 4) can be compared with those of Garrity et al. (1986). These authors found that 44% of the shallow lowlands (in shallow rainfed lowlands, submergence of the rice crop is usually limited to less than 10 consecutive days; IRRI, 1984) were fertile without major constraints and that the FCC modifiers for very poor soils *(a, e*, and *l*, representing low CEC and low CEC plus high P fixation) accounted for 45% of the total area. Problem soils covered 11% of the rice area in this ecosystem. In comparison, our results for all rainfed lowland environments indicate that “only” 5.5% can be characterized as problem soils (Table 4). Fertile soils without major constraints according to Garrity et al. (1986) would combine good and poor soils (= 60%) in this study. Thus, we found a considerably higher percentage of soils without major constraints and fewer problem soils, although we added soils typified by *the k* modifier only (< 10% weatherable minerals in silt and sand fraction or exchangeable K < 0.20 cmol per kg soil) to the very poor soils whereas Garrity et al. (1986) added them to the fertile soils (about 10% of shallow rainfed lowlands, data not shown). Thus, our study detects considerably fewer rainfed lowlands with very poor soils (35%) in Asia than the study of Garrity and co-authors (45%). Possible reasons for these differences are that we analyzed soil quality across shallow *and* intermediate rainfed lowlands (submergence in intermediate rainfed lowlands is more frequent and can last more than 10 days; IRRI, 1984), we used the newest and improved soil database (HWSD), and our rice area maps had a higher resolution. Also, there was obviously a significant change in rainfed rice area: Garrity et al. (1986) reported about 28 million hectares of shallow rainfed lowlands whereas Huke & Huke (1997) already found 34 million hectares. Large-scale reclamation of problem soils in, for example, the Indo-Gangetic plains (Yadav et al., 2010) should not have affected the results because such developments are not integrated into the available soil maps. However, these differences indicate that some uncertainty exists and that higher resolution data are needed to verify the results of our study.

Apart from this comparison, few quantitative data on soil quality in rice soils using the FCC system have been published. The dominance of very poor soils in mainland Southeast Asia has also been reported by Garrity et al. (1986), who estimated that about two-thirds of the rainfed area in northeast Thailand, Laos, and Cambodia falls into that category. Similarly, Kawaguchi & Kyuma (1977) found that most of their soils tested with very low “inherent potentiality” came from northeast Thailand, and most of the soils with very low “available phosphorus status” came from northeast Thailand and Cambodia. They also reported that most soils with a high fertility status with respect to both parameters were from India or the Philippines. In an analysis of upland rice, Gupta & O'Toole (1986) classified 58% of South and Southeast Asian upland rice soils as infertile but added that South Asia had more upland rice on fertile soils than Southeast Asia. This clear dominance of very poor soils in upland rice is confirmed by our analysis (Table 5, Figure 2) for Southeast Asia (64%) but not for South Asia (21%). It is noteworthy that, although very poor soils are dominant in mainland Southeast Asia, several countries there have policies to not support or even discourage the use of inorganic fertilizer in rice, which clearly restricts productivity growth. In contrast, other countries, including China and India, that have better soils heavily subsidize inorganic fertilizer use. In Africa, Balasubramanian et al. (2007) highlighted the dominance of very poor soils in upland systems, and of generally better soils in lowland environments. Windmeijer & Andriesse (1993) described a similar distribution of soil fertility in many inland valleys with lower fertility on the slopes and higher fertility in the valley bottom. The important effect of production system rather than locality for African rice soils is confirmed in our analysis (Tables 3 and 4). That the position in the landscape, toposequence, and/or rice system has a similar effect worldwide is also illustrated by the data presented in Tables 4 and 5. The trend there is that the occurrence of very poor rice soils is decreasing in the sequence from uplands to rainfed lowlands to irrigated lowlands and deepwater/mangrove areas. Good soils obviously show the opposite trend. This is caused by the transport of nutrients and particles from higher to lower parts of the landscape (colluvium, alluvium, leaching), and its effect on the fertility of rice soils was described earlier (e.g., Oberthür & Kam, 2000; van Asten et al., 2003; Haefele & Konboon, 2009). In contrast, problem soils are much more frequent in the lower parts of the landscape, to a large extent because saline and acid-sulfate soils are typical lowland/coastal soils (Driessen and Dudal, 1991). The fact that these trends were detectable despite the limited spatial resolution of the input data, as discussed above, augments the confidence in the method used and the results achieved.

The most widespread problem soils for rice are soils affected by salinity, which in its wider definition includes alkalinity and sodicity (Table 6). Apart from salinity and alkalinity, these soils are frequently also constrained by P and Zn deficiency (Neue et al., 1998). The rainfed lowland rice area in Asia with salinity problems was estimated by Akbar et al. (1986) at about 1.3 million ha, and Garrity et al. (1986) in the same year confirmed these 1.3 million ha of saline rice soils but added 1.3 million ha of alkaline rice soils. Our study indicates 2.5 million ha of saline rice soils and 3.0 million ha of alkaline/sodic rice soils in Asia today, which is a large increase even if these two categories overlap considerably. However, we could not confirm rough estimates of 9–12 million ha of rice soils with salinity problems in all Asian rice environments by, for example, Bouman et al. (2007), and the basis of such estimates is unclear. In Africa, rice on saline soils accounts for about 250,000 ha according to our estimates (total problem soils minus acid-sulfate and organic soils), which is again far below the 650,000 ha estimated by Manneh et al. (2007). We did not find any published values to compare with our estimate for soil salinity in rice soils of the Americas (about 240,000 ha).

Additional soil constrains previously reported to be widespread in Asian rice are acid-sulfate soils (≈ 2 million ha) and Fe toxicity (≈ 7 million ha) (Garrity et al., 1986, Akbar et al., 1986; van Bremen & Pons, 1978). According to our analysis, the area of acid-sulfate soils cultivated with rice in Asia is larger (about 2.9 million ha), possibly because of different estimation methods and an increased cultivation of acid-sulfate soils. Outside Asia, the rice area on acid-sulfate soils is relatively small. According to WARDA (1983), about 214,000 ha of cleared mangrove swamps were then cultivated with rice, and much of that was assumed to have potential acid-sulfate soils (Sylla et al., 1983). We do not know whether our much lower estimate (51,000 ha) is caused by a reduction in rice area in that ecosystem or because acid-sulfate soils are less common than previously assumed. Also, their extent may be underestimated in our study due to the insufficient resolution of the available data, because these areas usually occur in narrow coastal strips.

Iron toxicity is well recognized as the most widely distributed nutritional disorder in lowland-rice production (Fairhurst et al., 2007). It is a complex phenomenon, often occurring together with soil acidity, Al toxicity, P deficiency, and generally low nutrient availability (Neue et al., 1998). Garrity et al. (1986) estimated that, in northeast Thailand, Laos, and Cambodia, about two-thirds of the rainfed area is characterized by soil acidity, widespread Fe toxicity, low cation exchange capacity, and low soil N, P, and K reserves. Sanchez & Buol (1985) also reported that acidity is widespread in wetland soils. Our analysis did not allow us to specifically identify soils with Fe toxicity but it is likely to occur on soils characterized by the FCC indicator *a* (Al-toxic, very acidic), which covers 23.5 million ha of rice soils worldwide (Table 7, excluding aerobic upland environments, where Fe toxicity is rare). This estimate seems very high but balanced nutrition as used in most irrigated fields reduces the Fe susceptibility of rice, and constraints to rice growth might occur only in early growth stages in mildly Fe-toxic conditions (Fairhurst et al., 2007). Our analysis also indicates that Fe toxicity is very common in Africa (19% across all environments). Although this confirms the importance of this problem in Africa, our estimate is considerably lower than estimates from a preliminary survey by WARDA (2001), which suggested that as much as 60% of the lowland rice area in West and Central Africa may suffer from iron toxicity. In lowland rice in the Americas, the area of very poor soils with potential Fe toxicity is substantial (about 0.5 million ha, data not shown). Very poor soils are even more common in rainfed upland rice in Latin America (68%; there is no upland rice in North America) but Fe toxicity is usually not a problem under aerobic soil conditions typical for that system.

Although not the subject of this study, it should be mentioned that abiotic stresses not related to soil quality are probably equally important constraints for productivity and intensification of rice-based lowlands. In rainfed lowlands, drought stress is considered the most important limitation to production and is estimated to frequently affect 19 to 23 million hectares (Garrity et al., 1986). In our analysis, drought-prone soils due to a low available water capacity add up to 14.4 million ha, mostly located in Asia and Africa, and in rainfed environments (Table 7). Another important abiotic stress in lowlands is submergence, regular occurring in deepwater/mangrove systems (other in Figure 1) but also in irrigated and rainfed lowlands. Huke & Huke (1997) estimated that about 11 million ha of lowland rice area were prone to temporary submergence from flooding, whereas Mackill et al. (1996) estimated the submergence-prone rice area at about 16 million ha. In sub-Saharan Africa, as much as one-third of the rainfed lowland area is thought to be affected by submergence, which would correspond to about 1 million ha of submergence-prone rice area. In the Americas, most rice is irrigated or grown in uplands, and submergence is not a significant constraint (Table 4). Mapping approaches to quantify and localize drought as well as submergence areas grown to rice are underway and will complete our analysis of soil constraints in rice cultivation.

Conclusions

To our knowledge, this study is the first attempt to quantitatively characterize soil quality in rice soils worldwide. This was achieved by classifying a global spatial database of soils according to the Fertility Capability Soil Classification (FCC) system, and by intersecting these data with rice area distribution data. Although the accuracy of the results is limited by the spatial resolution of the available data, it appears that this method does allow for a reasonable interpretation of soil constraints at the regional level. This was illustrated by the correspondence of our results with the few published studies using very different methods, and the observed trends between rice systems and within the toposequence, which agreed with important soil formation and quality-determining processes. The study clearly showed that rainfed lowland rice in Southeast Asia and upland rice all over the world are strongly associated with very poor soils with various soil constraints, but it also revealed that irrigated environments have their fair share of poor and very poor soils. The spatial analysis within environments showed that soil quality is not equally distributed and that some regions are clearly disadvantaged. Problem soils are most common in the lowest part of the toposequence, and the study provides quantitative data on their distribution and importance. The results presented and the detailed database underlying the analysis will help to better focus research, and allow tailoring germplasm selection and management practices for the dominant abiotic stresses in any given rice environment. Especially if our analysis is complemented by an analysis of the incidence of drought and flooding, the knowledge of abiotic stresses in rice will be markedly increased and allow applications from regional planning to field-specific technology dissemination. Our approach could also be applied to better understand the spatial distribution of soil constraints for the world’s other major staple crops.

References

Akbar, M., Gunawardena, I.E., Ponnamperuma, F.N., 1986. Breeding for soil stresses. In: International Rice Research Institute, Progress in rainfed lowland rice. IRRI, Los Baños, Philippines, p. 263-272.

Arino, O., Bicheron, P., Achard, F., Latham, J., Witt, R., Weber, J.L., 2008. GLOBCOVER The most detailed portrait of Earth. Esa Bulletin-European Space Agency 136: 24-31.

Balasubramanian, V., Sie, M., Hijmans, R.J., Otsuka, K., 2007. Increasing rice production in Sub-Saharan Africa: Challenges and opportunities. *Advances in Agronomy,* 94:55-133.

Banta, S., Mendoza, C.V., 1984. Organic matter and rice. International Rice Research Institute (IRRI), Los Baños, Philippines, 631 p.

Bouman, B.A.M., Barker, R., Humphreys, E., Tuong, T.P., Atlin, G.N., Bennett, J., Dawe, D., Dittert, K., Dobermann, A., Facon, T., Fujimoto, N., Gupta, R.K., Haefele, S.M., Hosen, Y., Ismail, A.M., Johnson, D., Johnson, S., Khan, S., Lin, S., Masih, I., Matsuno, Y., Pandey, S., Peng, S., Thiyagarajan, T.M., Wassman, R., 2007. Rice: feeding the billions. In: Molden, D. (ed.), Water for food, water for life. A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan, and Colombo: International Water Management Institute, p. 515-549.

Dawe, D., Pandey, S., Nelson, A., 2010. Emerging trends and spatial patterns of rice production. In: Pandey, S. (ed.), Rice in the global economy: strategic research and policy issues for food security. Los Banos, Philippines, International Rice Research Institute, p. 15-35.

Driessen, P.M., Dudal, R., 1991. The major soils of the world. Lecture notes on their geography, formation, properties and use. Wageningen University, The Netherlands and Katholieke Universiteit Leuven, Belgium. 310 pp.

Fairhurst, T.H., Witt, C., Buresh, R.J., Dobermann, A., 2007. A practical guide to nutrient management (2nd edition). International Rice Research Institute, International Plant Nutrition Institute, and the International Potash Institute, 89 p.

FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. Harmonized World Soil Database (version 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

FAOSTAT 2013. Database available at http://faostat.fao.org/site/339/default.aspx.

Garrity, D.P., Oldeman, L.R., Morris, R.A., 1986. Rainfed lowland rice ecosystems: characterization and distribution. In: Progress in rainfed lowland rice. International Rice Research Institute (IRRI) Los Baños, Philippines, p. 3-23.

Gamuyao, R., Chin, J.H., Pariasca-Tanaka, J., Pesaresi, P., Catausan, S., Dalid, C., Slamet-Loedin, I., Tecson-Mendoza, E.M., Wissuwa, M., Heuer, S., 2012. The protein kinase Pstol1 from traditional rice confers tolerance of phosphorus deficiency. *Nature*, 488:535-539.

Gumma, M.K., Nelson, A., Thenkabail, P.S., Singh, A.N., 2011. Mapping rice areas of South Asia using MODIS multi-temporal data, *J. Appl. Remote Sens*., Vol. 5. doi:10.1117/1.3619838.

Gupta, P.C., O'Toole, J.C., 1986. Upland rice: a global perspective. International Rice Research Institute, Los Baños, Laguna, Philippines. 360 p.

Haefele, S.M., Hijmans, R.J., 2007. Soil quality in rice-based rainfed lowlands of Asia: characterization and distribution. In: Aggarwal, P.K., Ladha, J.K., Singh, R.K., Devakumar, C. & Hardy, B. (eds.), Science, technology, and trade for peace and prosperity. Proceedings of the 26th International Rice Research Conference, 9-12 October 2006, New Delhi, India. Los Baños (Philippines) and New Delhi (India): International Rice Research Institute, Indian Council of Agricultural Research, and National Academy of Agricultural Sciences, p. 297-308.

Haefele, S.M., Konboon, Y., 2009. Nutrient management for rainfed lowland rice in northeast Thailand. *Field Crops Res*., 114:374-385.

Hijmans R.J., 2013. Raster: geographic analysis and modeling with raster data. R package version 2.1-49. http://raster.r-forge.r-project.org/

Hijmans, R.J., Condori, B., Carillo, R., Kropff, M.J., 2003. A quantitative and constraint-specific method to assess the potential impact of new agricultural technology: the case of frost resistant potato for the Altiplano (Peru and Bolivia). *Agric. Syst.*, 76:895-911.

Homma, K., Horie, T., Shiraiwa, T., Supapoj, N., Matsumoto, N., Kabaki, N., 2003. Toposequential variation in soil fertility and rice productivity of rainfed lowland paddy fields in a mini-watershed (Nong) in Northeast Thailand. Plant Prod. Sci., 6:147-153.

Huke, R.E., Huke, E.H., 1997. Rice area by type of culture: South, Southeast, and East Asia. A revised and updated data base. International Rice Research Institute (IRRI), Los Baños, Philippines, p. 1-59.

IRRI, 1978. Rice and soils. International Rice Research Institute, Los Baños, Philippines, 825 p.

IRRI, 1984. Terminology for rice growing environments. International Rice Research Institute (IRRI), Los Baños, Philippines, 35 p.

IRRI, 1985. Wetland soils: characterization, classification, and utilization. International Rice Research Institute, Los Baños, Philippines, 559 p.

Jennings, P., 2007. Rice revolutions in America. Rice Today, April-June 2007.

Kawaguchi, K., Kyuma, K., 1977. Paddy soils in tropical Asia: their material nature and fertility. Monographs of the Center for Southeast Asian Studies, Kyoto University. 258 p.

Kirk, G.J.D., 2004. The Biogeochemistry of Submerged Soils. John Wiley & Sons, Chichester, UK, 304 p.

Kögel-Knabner, I., Amelung, W., Cao, Z., Fiedler, S., Frenzel, P., Jahn, R., Kalbitz, K., Kölbl, A., Schloter, M., 2010. Biogeochemistry of paddy soils. *Geoderma*, 157:1-14.

Ladha, J.K., George, T., Bohlool, B.B., 1992. Biological nitrogen fixation for sustainable agriculture. Kluwer Academic Publishers, Dordrecht, Netherlands. 209 p.

Mackill, D.J., Coffman, W.R., Garrity, D.P., 1996. Rainfed lowland rice improvement. IRRI, Los Baños, Philippines, 242 p.

Manneh, B., Kiepe, P., Sie, M., Ndjiondjop, M., Drame, N.K., Traore, K., Rodenburg, J., Somado, A., Narteh, L., Youm, O., Diagne, A., Futakuchi, K., 2007. Exploiting partnerships in research and development to help African rice farmers cope with climate variability. Paper presented at ICRISAT and CGIAR 35th Anniversary Symposium

"Climate-Proofing Innovation for Poverty Reduction and Food Security", 22-24 November, 10 p.

Moormann, F.R., van Breemen, N., 1978. Rice: soil, water, land. International Rice Research Institute (IRRI) Los Baños, Philippines, 185 p.

Neue, H.U., Quijano, C., Senadhira, D., Setter, T. 1998. Strategies for dealing with micronutrient disorders and salinity in lowland rice systems. *Field Crops Res*., 56:139-155.

Oberthür, T., Kam, S.P., 2000. Perception, understanding, and mapping of soil variability in the rainfed lowlands of northeast Thailand. *In:* Tuong, T.P., Kam, S.P., Wade, L., Pandey, S., Bouman, B.A.M., Hardy, B. (eds.), Characterizing and understanding rainfed environments. Proceedings of the International Workshop on Characterizing and Understanding Rainfed Environments, 5-9 Dec., 1999, Bali, Indonesia. International Rice Research Institute, Los Baños, Philippines, p. 75-96.

Ponnamperuma, F.N., 1972. The Chemistry of submerged soils. Adv in Agron. 24:29-96.

R Development Core Team, 2012. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0. http://www.R-project.org/

Sanchez, P.A., Buol, S.W. ,1985. Agronomic taxonomy for wetland soils. In: Wetland soils: characterization, classification, and utilization. Proceedings of a workshop held 26 March to 5 April 1984, International Rice Research Institute (IRRI), Los Baños, Philippines, p. 207-229.

Sanchez, P.A., Palm, C.A., Buol, S.W., 2003. Fertility capability soil classification: a tool to help assess soil quality in the tropics. *Geoderma,* 114:157-185.

Singh, A.N., Singh, U.S., 2010. Targeted dissemination of stress-tolerant rice varieties: propagating Swarna-Sub1, Sahbhagi Dhan, and CSR36 in Uttar Pradesh, India. STRASA NEWS, Vol. 3 No. 2 August 2010. Available online at http://strasa.org/attachments/article/35/STRASAVol3No2August2010issue.pdf

Sylla, M., van Breemen, N., Fresco, L.O., Dixon, C., Stein, A., 1993. Temporal and spatial variability of soil constraints affecting rice production along the Great Scarcies mangrove swamps, Sierra Leone. Selected Papers, Ho Chi Minh City Symp. on Acid sulphate soils, Vietnam 1992. ILRI Public. 53, D.L. Dent, M.E.F. van Mensvoort (eds.). p. 247-259.

Tempel, P., van Kraalingen, D., Mendes de Jesus, J., Reuter, H.I., 2013. Towards an ISRIC World Soil Information Service (WOSIS ver. 1.0). ISRIC Report 2013/02, ISRIC - World Soil Information, Wageningen, 188 p.

Thomson, M.J., de Ocampo, M., Egdane, J., Akhlasur Rahman, M., Sajise, A.G., Adorada, D.L., Tumimbang-Raiz, E., Blumwald, E., Seraj, Z.I., Singh, R.K., Gregorio, G.B., Ismail, A.M. 2010. Characterizing the *Saltol* quantitative trait locus for salinity tolerance in rice. *Rice*, 3:148-160.

van Asten, P.J.A., Wopereis, M.C.S., Haefele, S.M., ould Isselmou, M., Kropff, M.J., 2003. Explaining yield gaps on farmer identified degraded and non-degraded soils in a Sahelian irrigated rice scheme. *Neth. J. Agric. Sci.*, 50: 277-296.

van Bremen, N., Pons, L.J. 1978. Acid sulfate soils and rice. In: International Rice Research Institute, Soils and Rice. IRRI, Los Baños, Philippines, p. 739-762.

Verulkar, S.B., Mandal, N.P., Dwivedi, J.L., Singh, B.N., Sinha, P.K., Mahato, R.N., Swain, P., Dongre, P., Payasi, D., Singh, O.N., Bose, L.K., Robin, S., Chandrababu, R., Senthil, S., Jain, A., Shashidhar, H.E., Hittalmani, S., Vera Cruz, C., Paris, T., Robert, H., Raman, A., Haefele, S.M., Serraj, R., Atlin, G., Kumar, A. 2010. Breeding resilient and productive genotypes adapted to drought prone rainfed ecosystem of India. *Field Crops Res.*, 117:197-208.

WARDA, 1983. West Africa Rice Development Association Annual Report. Regional Mangrove Swamp Rice Research Station, Rokupr, Freetown, Sierra Leone.

WARDA, 2001. West Africa Rice Development Association Annual Report. Bouaké, Côte d’Ivoire, 103 p.

Wassmann, R., Lantin, R.S., Neue, H.U. (eds.), 2000. Methane emissions from major rice ecosystems. Special issue of 'Nutrient Cycling in Agroecosystems' (Vol. 58) and as re-print of 'Developments in Plant and Soil Sciences' (Vol. 90).

Windmeijer, P.N., Andriesse, W. (eds.), 1993. Inland valleys in West Africa: an agro-ecological characterization of rice-growing Environments. Publication 52, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, 160 p.

Xiangming, X., Boles, S., Frolking, S., Li, C., Babu, J.Y., Salas, W., Moore III, B., 2006. Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images. *Remote Sens. Environ*., 100:95-113.

Xu, K., Xu, X., Fukao, T., Canlas, P., Maghirang-Rodriguez, M., Heuer, S., Ismail, A.M., Bailey-Serres, J., Ronald P/C., Mackill, D.J., 2006. *Sub1A* is an ethylene-response-factor-like gene that confers submergence tolerance to rice. *Nature*, 442:705-708.

Yadav, M.S., Yadav, P.P.S., Yaduvanshi, M., Verma, D., Singh, A.N., 2010. Sustainability assessment of sodic land reclamation using remote sensing and GIS. *J. Indian Soc. Remote Sens*., 38:269-278.

Table 1. Soil fertility classification system to match the HWSD soil database (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), adapted from the Fertility Capability Soil Classification (FCC) system and the description of modifiers according to Sanchez and Buol (1985), and Sanchez et al. (2003).

Soil property or condition	FCC modifier	FCC definition	HWSD characteristics used
Problem soils			
Saline	s	ECe > 0.4 S m^{-1} OR Solonchak OR salid and salic groups	Topsoil ECe > 0.2 S m^{-1} OR subsoil ECe > 0.4 S m^{-1} (s)
Sulfidic, presence of cat clays	c	pH < 3.5 after drying OR sulfaquents, sulfaqepts, sulfudepts	Presence of a thionic horizon
Organic	O	Organic carbon (OC) > 12% OR Histosols OR histic groups	Topsoil or subsoil OC > 12%
Alkaline or sodic	n	Exchangeable sodium percentage (ESP) > 15%, alkaline OR sodic soils	(Topsoil or subsoil ESP > 15% OR pH**** > 8.5 OR $CaCO_3$ > 40%) NOT thionic
Very poor soils			
Low nutrient capital reserves	k	< 10% weatherable minerals OR exchangeable K < 0.2 cmol per kg.	Topsoil < 20% base saturation OR cation exchange capacity (CEC) < 20 cmol kg^{-1} clay
Al toxicity for most common crops or very low pH	a	> 60% Al saturation in the topsoil OR < 33% base saturation OR pH < 5.5 except in Histosols, Dystric Cambisols, Dystric Gleysols, Dystric Planosols, Haplic Acrisols	Topsoil pH < 5
Very shallow	-	none	Depth ≤ 30 cm
Soil moisture stress (> three months dry season)	d	Ustic or xeric soil moisture regime: dry > 60 consecutive days/year but moist >180 cumulative days/year	Available water capacity (AWC) < 50 mm m^{-1} *
High leaching potential, low buffering capacity, low ECEC	e	CEC < 4 cmol kg^{-1} soil as ECEC or < 7 cmol kg^{-1} soil by sum of cations at pH 7;	Topsoil CEC < 4 cmol kg^{-1} soil
Very low organic C	-	None	Topsoil OC < 0.2%
High P fixation by Fe and Al oxides (**)	i, i-, i+	High %age of free Fe_2O_3; Oxisols or oxic groups with clayey texture > 35% clay; hues redder than 5YR and granular structure	Topsoil texture > 35% clay AND (Ferralsols OR Acrisols OR Alisols OR Plinthosols)
Poor soils			
Limited aluminium toxicity, intermediate weathering	a-	10-60% Al saturation in the topsoil OR < 33% BS	Topsoil: (CEC 4-10 cmol kg^{-1} soil OR base saturation 20-50% OR CEC 20-50 cmol kg^{-1} clay) AND 5 ≤ pH < 6
Low organic C	-	none	Topsoil OC < 0.6%
Shallow/obstacles to roots	R	Rock or hard layer within 50 cm from the soil surface	Depth 30-50 cm OR obstacles to roots between 0 and 40 cm depth
Gravel	r^{+}, r^{++}	Gravel > 10%	Gravel > 15%
Slight alkalinity	n-	ESP 6-15%	Topsoil: ESP 6-15% AND pH 7.2-8.5
Good soils			
Calcareous (basic reaction) common Fe and Zn deficiencies ***	b	Calcareous reaction, pH above 7.3, can be deficient in micronutrients but often very high fertility	(ESP < 6 AND pH 7.2-8.5) OR $CaCO_3$ 2-40%
Cracking clays, vertic properties, very sticky plastic clay	v	>35% clay and >50% 2:1 expanding clays, vertisols or vertic groups	Topsoil: (texture > 30% clay AND CEC > 50-100 cmol kg^{-1} clay) OR vertic properties
Amorphous volcanic, high P fixation by allophane	x	Andosols or andic sub-groups except vitrands and vitric great groups and sub-groups	Andosols (except vitric Andosols) OR CEC > 150 cmol kg^{-1} clay
Waterlogging, gleyic conditions ***	g, g+	Aquic soil moisture regime, saturated with water > 60 days $year^{-1}$	Gley-, Histo-, Planosols, not Thionic Fluvisols
Remaining soils	none	No constraint	No constraint

* Instead of soil moisture regimes, we used the available water storage capacity based on soil texture as a measure of soil being prone to drought spells.

** i- and i+ are the same soils, either recapitalized with P fertilizer or with potential Fe toxicity if waterlogged, but they still have the same basic constraints.

*** Calcareous soils and waterlogging were not considered soil constraints in the case of rice.

**** Here and elsewhere, pH is measured in a soil-water solution.

Table 2: Area and distribution of agricultural land grown with rice every year across the world and in all major rice production systems.

Region*	Rice area	Irrigated, lowland	Rainfed lowland	Rainfed upland	Other (deepwater, mangroves)
	('000 ha)	------------------(% of the regional area)-------------------			
Asia	143,429	60	32	6	2
Africa	10,466	21	44	28	6
Americas	7,147	54	-	46	-
Europe	704	100	-	-	-
Oceania	39	96	-	4	-
Southern Asia	60,526	53	34	9	4
South-Eastern Asia	49,120	45	47	5	3
Eastern Asia	33,425	93	6	2	-
Central Asia	202	100	-	-	-
Western Asia	156	100	-	-	-
Western Africa	5,843	10	42	36	12
Eastern Africa	3,330	30	58	12	-
Northern Africa	558	100	-	-	-
Central Africa	736	7	32	60	-
South America	5,121	42	-	58	-
Northern America	1,259	100	-	-	-
Central America	330	5	-	95	-
Caribbean	437	89	-	11	-
Southern Europe	431	100	-	-	-
Eastern Europe	248	100	-	-	-
Western Europe	25	100	-	-	-
Australia and New Zealand	34	100	-	-	-
Melanesia	5	67	-	33	-
World	161,784	57	31	9	3

* Region names and definitions as reported in FAOSTAT.

Table 3: Area and distribution of soil fertility in the different world regions and sub-regions where rice is grown (for details of the soil fertility groups see Table 1).

Region*	Total rice area	Good soils	Poor soils	Very poor soils	Problem soils
	(000 ha)	(%)			
Asia	143,429	46.7	18.3	29.6	5.3
Africa	10,466	18.2	18.0	60.5	3.1
Americas	7,147	27.8	16.9	49.7	5.6
Europe	704	45.4	14.1	38.1	2.4
Oceania	39	39.9	30.7	7.5	21.9
Southern Asia	60,526	58.4	22.8	13.9	4.7
South-Eastern Asia	49,120	29.4	18.6	43.7	8.3
Eastern Asia	33,425	51.1	9.8	37.6	1.5
Central Asia	202	39.1	13.7	4.8	42.4
Western Asia	156	58.5	9.4	17.1	15.0
Western Africa	5,843	16.8	19.0	62.8	1.3
Eastern Africa	3,330	19.9	13.1	62.3	4.7
Northern Africa	558	27.4	50.4	5.8	16.3
Central Africa	736	15.1	8.6	76.0	0.4
South America	5,121	20.2	12.7	61.8	5.4
Northern America	1,259	47.0	28.9	16.9	7.2
Central America	330	32.2	42.6	23.5	1.6
Caribbean	437	57.7	12.3	22.7	7.2
Southern Europe	431	32.8	13.1	52.8	1.4
Eastern Europe	248	67.9	16.9	10.8	4.3
Western Europe	25	43.8	8.4	46.6	1.3
Australia and New Zealand	34	37.5	33.1	4.6	24.8
Melanesia	5	56.9	13.4	28.8	0.9
World	161,784	44.0	18.2	32.5	5.1

* Region names and definitions as reported in FAOSTAT.

Table 4: Distribution of the different soil fertility groups within the different ecosystems for Asia, Africa, and the Americas (for details, see Table 1).

Ecosystem	Total rice area per system (000 ha)	Good soils	Poor soils	Very poor soils	Problem soils
		(%)			
World					
IRRIGATED, summary	92,301	49.1	17.6	27.7	5.5
RAINFED, summary	69,483	37.3	19.0	38.9	4.7
Other, deepwater/mangroves	4,183	45.9	20.6	25.3	8.2
Rainfed, lowlands	50,373	38.4	19.6	36.7	5.3
Rainfed, uplands	14,927	31.4	16.6	50.2	1.8
Asia					
IRRIGATED, summary	85,503	50.5	17.2	26.9	5.3
RAINFED, summary	57,925	41.2	19.9	33.7	5.2
Other, deepwater/mangroves	3,506	52.5	19.7	18.4	9.4
Rainfed, lowlands	45,762	39.9	19.9	34.6	5.5
Rainfed, uplands	8,657	43.1	20.5	34.7	1.6
Africa					
IRRIGATED, summary	2,215	19.7	25.7	47.8	6.3
RAINFED, summary	8,251	17.8	16.0	63.9	2.3
Other, deepwater/mangroves	678	11.8	25.2	60.8	2.1
Rainfed, lowlands	4,611	22.8	16.7	57.6	2.9
Rainfed, uplands	2,963	11.4	12.8	74.4	1.3
Americas					
IRRIGATED, summary	3,842	35.8	23.0	33.0	8.2
RAINFED, summary	3,305	18.4	9.8	69.2	2.6
Other, deepwater/mangroves	-				
Rainfed, lowlands	-				
Rainfed, uplands	3,305	18.4	9.8	69.2	2.6

Table 5: Distribution of the soil fertility groups (for details, see Table 1) across Asia and within two different sub-regions of Asia.

Region and rice ecosystem	Total rice area per system (000 ha)	Good soils	Poor soils	Very poor soils	Problem soils
		------------------------	(%)	------------------------	
Asia, overall					
Irrigated, lowlands	85,503	50.5	17.2	26.9	5.3
Other, deepwater/mangroves	3,506	52.5	19.7	18.4	9.4
Rainfed, lowlands	45,762	39.9	19.9	34.6	5.5
Rainfed, uplands	8,657	43.1	20.5	34.7	1.6
Southern Asia					
Irrigated, lowlands	31,859	61.2	22.2	10.2	6.4
Other, deepwater/mangroves	2,156	64.2	18.3	13.1	4.4
Rainfed, lowlands	20,842	54.8	24.1	17.9	3.2
Rainfed, uplands	5,565	54.6	23.3	21.0	1.0
South-Eastern Asia					
Irrigated, lowlands	22,226	33.8	20.6	36.9	8.6
Other, deepwater/mangroves	1,350	33.8	21.9	26.9	17.5
Rainfed, lowlands	22,999	26.1	16.8	49.0	8.0
Rainfed, uplands	2,545	17.8	15.6	63.6	3.0

Table 6: Area and distribution of problem soils in rice fields of different world regions according to the HWSD definitions.

Region	Total area of problem soils *	Saline soils	Acid-sulfate soils	Organic soils	Alkaline/ sodic soils
	----------------------------------(000 ha)-------------------------------------				
Asia	7,547	2,500	2,922	1,382	3,021
Africa	327	150	51	29	214
Americas	403	33	49	115	231
Europe	17	5	0	2	14
Oceania	9	2	0	0	7
Total	8,303	2,689	3,023	1,529	3,486

* Note that the sum of individual constraints exceeds the total area of problem soils because soils often have more than one constraint, especially salinity and alkalinity/sodicity often overlap.

Table 7: Relative frequency of specific soil properties or conditions related to soil fertility in the main rice-growing regions and the main production environments.

	Asia	Africa	America	Europe	Oceania	Irrigated	Rainfed	Upland	Other
Total area (000 ha)	143,429	10,466	7,147	704	39	92,301	50,373	14,927	4,183
Soil property or condition	-------(% of the regional total area) *--------					-----------------(%) *----------------			
Problem soils									
Saline	1.7	1.4	0.5	0.7	4.0	2.3	0.9	0.3	1.5
Sulfidic	2.0	0.5	0.7	0.0	0.0	1.5	2.6	0.4	5.1
Organic	1.0	0.3	1.6	0.3	0.1	0.8	1.1	0.9	1.3
Alkaline/sodic	2.1	2.0	3.2	2.0	17.7	2.8	1.5	0.3	1.7
Very poor soils									
Low nutrients	20.3	37.6	38.2	4.2	3.6	18.6	24.9	36.5	16.2
Al-toxic, very acidic	16.3	18.8	23.7	3.9	2.5	14.4	19.2	24.4	11.6
Very shallow	3.6	9.3	5.6	12.0	1.4	3.6	4.2	7.2	3.2
Drought-prone	8.2	19.0	5.7	36.6	2.4	7.3	10.3	14.4	7.8
Highly leached	0.9	9.3	9.2	1.4	1.3	1.3	1.7	5.3	2.9
Very low organic C	0.0	0.3	0.5	0.0	0.0	0.0	0.0	0.2	0.1
High P fixation	4.9	4.2	8.9	0.0	0.8	6.1	2.7	7.4	1.0
Poor soils									
Limited Al-toxic	11.0	9.5	13.7	4.0	2.1	10.3	12.3	9.0	16.9
Low organic C	6.5	7.4	3.5	4.7	26.8	6.3	6.8	7.3	2.5
Shallow	0.0	0.0	0.0	4.1	0.0	0.0	0.0	0.0	0.0
Gravelly	2.1	3.3	1.2	3.9	3.9	2.8	1.1	1.8	2.0
Slightly alkaline	0.5	0.1	0.0	2.0	1.2	0.8	0.1	0.0	0.1
Good soils									
Calcareous	20.0	3.3	3.9	19.2	18.3	23.4	11.7	8.0	17.8
Vertic	5.2	3.6	8.7	16.9	18.4	6.3	3.9	4.6	1.2
Andic, P fixing	0.1	0.0	0.5	0.0	0.0	0.1	0.0	0.3	0.0
Gleyic	10.0	3.3	6.2	4.8	11.6	8.8	11.0	5.7	15.7
No constraints	24.1	12.1	15.8	22.9	20.2	22.0	24.9	20.6	27.5

* Note that, in each column, the sum of percentages exceeds 100 because soils often have more than one property.

Figures and figure captions:

Figure 1: The spatial distribution of the four main rice agroecosystems in the world.

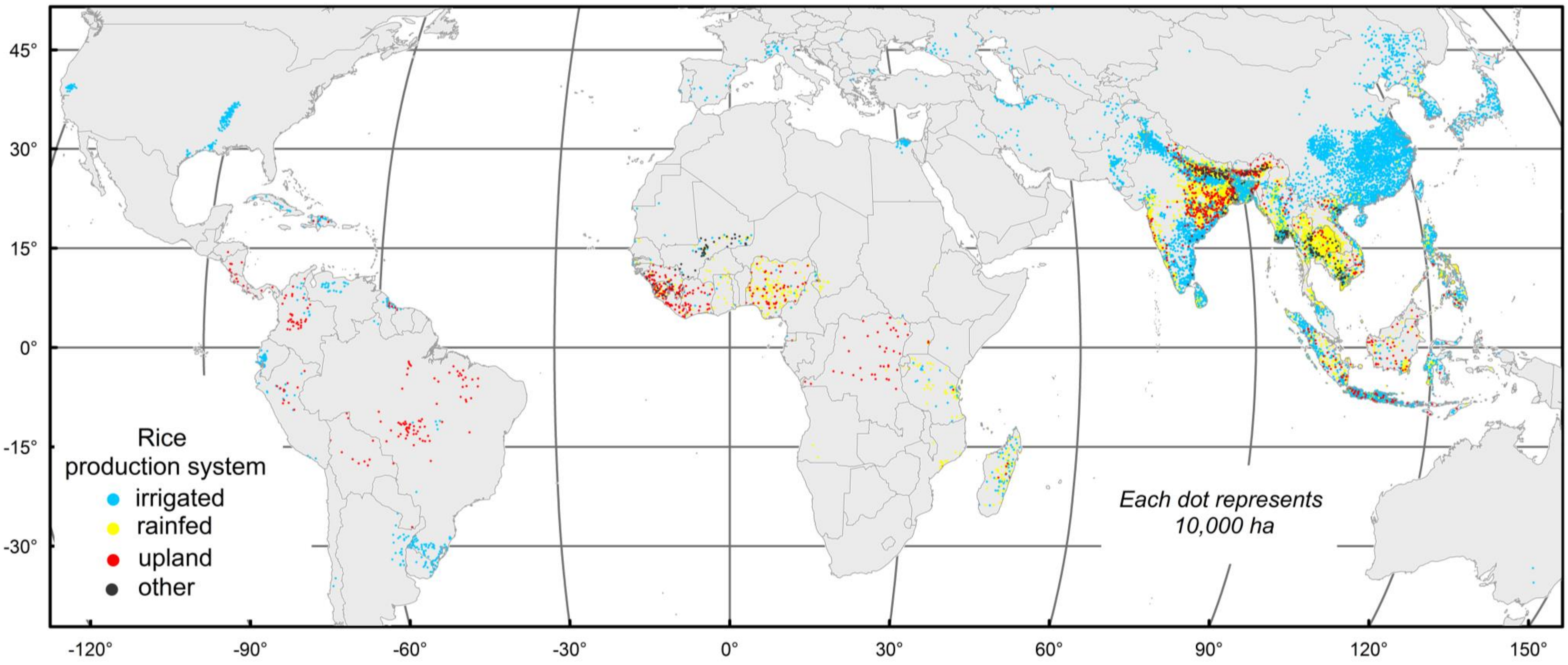

Figure 2: The spatial distribution of rice grown on the four major soil quality groups in the world.