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Soil quality and constraints in global rice production

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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.

1. 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., IRRI, 1978, 1985; Kawaguchi and Kyuma, 1977; Moormann and van Breemen, 1978). However, most studies of rice soils concentrated on specific characteristics or processes in flooded rice soils (e.g., Banta and Mendoza, 1984; Kirk, 2004; Kögel-Knabner et al., 2010; Ladha et al., 1992; Ponnamperuma, 1972; Wassmann et al., 2000), 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

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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 and 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 m 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 and 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.

2. 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 and 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-second (~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 Xiao 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 16,327 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 and 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 textures (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