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BALANCED FERTILIZATION FOR SUSTAINABLE DEVELOPMENT OF AGRICULTURE IN THE SAVANNAS OF SOUTH AMERICA: TOWARDS A GEOGRAPHICAL APPROACH

ABSTRACT. South American countries still possess considerable land reserves for agricultural development. Huge areas of virgin lands and natural pastures have been converted to agricultural crops and suffer increasing pressure. Growing demand for food in the world and attractiveness for capital investment drive this colonization further deep into the regions that cannot be converted to commercial agriculture without serious negative environmental consequences. Agricultural development in these areas neither can be considered economically sustainable, as high production costs sometimes surpass revenues from the harvest. Most of the recently colonized regions in South America are those under savanna landscapes, where low nutrient availability in the soil restricts agricultural use. Understanding the problem of sustainability of agricultural development in savannas is impossible without geographical analysis. Spatial approach at different scales enables precise vision of weak points of recently established agricultural systems and helps to draw solutions to diminish their instability. The objective of this paper was to develop, with GIS tools, a geographically based analysis that could identify the spatial variation and magnitude of soil potassium, potassium uptake, potassium fertilization, and potassium balance in order to improve the efficiency of mineral fertilizers use.

KEY WORDS: Sustainable development of agriculture, mineral fertilizers, savannas, cerrado, South America, Brazil

INTRODUCTION

South America, perhaps, is one of the last agricultural frontiers of the humanity. Since its conquest by Spain, Portugal and other European powers, agricultural development on this continent is going along with colonization of virgin lands. After the colonial period, the late 19th – early 20th centuries were marked by colonization of the Argentinean Pampa and the southern states of Brazil. The last large-scale colonization campaign started in the 1980s, with colonization of the Center-West region in Brazil. Later on, it also affected the fringe of the Amazon region and the inner parts of the North-East region of this country [Naumov, 2005]. From Brazil, colonization has spread to the neighboring areas of Paraguay and Bolivia. In Colombia and Venezuela, the agricultural frontier also started moving towards the peripheral regions [Naumov, 2010]. These areas, together with some Argentinean provinces, became the ground for the recent soybean production boom in Latin America [International Potash Institute, 2011].

Analysis of the land use data shows that many South American countries still own considerable land reserves for colonization (Table 1). In most cases, these reserves can be found in the regions of tropical savannas. In the authors' estimates, savanna landscapes occupy approximately 25%, 33%, 50%, and 25% of the total land area in Brazil, Venezuela and Colombia, Bolivia, and Paraguay, respectively. Besides, there are areas outside the Tropics, like Argentinean North, with physical-geographical characteristics similar to the savannas.

Until the middle of the 20th century, tropical savannas in South America were almost not used for commercial agriculture. Nevertheless these regions were drawn to the attention of a German origin geographer Leo Waibel (1888–1951), who visited Brazil in the 1940s and predicted, that savannas would become the potential breadbasket of the humanity [Etges, 2000]. Nowadays, about 170 million ha in Brazil are considered suitable for agricultural colonization, and 65 million ha from this huge area correspond to virgin lands in the savannas (for comparison: in the rain forests of the Amazon, only 10 million ha were considered suitable). Another 90 million ha in Brazil that may be converted into fields from natural pastures are also located primarily in savannas [USDA, 2003].

Brazil, no doubt, is the leading country in South America in terms of the potential area for colonization of savannas, and by the size of the already colonized area in these regions. Tropical savannas, locally known as *cerrado*, occupy approximately 204 million ha, mostly in the Center-West region of Brazil and, partly, in the South-East, North-East and the Amazon regions of this country. During the last three decades of the 20th century, some 20 million ha in the Brazilian *cerrado* were colonized for commercial crops planting [Manzatto et al., 2002].

The *cerrado* regions are characterized by hot climate, with the annual average temperatures of over 20°C and the average monthly temperatures of 18–28°C. The annual precipitation varies between 1200–1800 mm,

Table 1. Land Use in Selected Countries of South America, 2003

Country	Land Area (LA)	Agricultural Area (AA)		Arable Land		Permanent Crops		Permanent Pasture	
	1000 ha	1000 ha	% of LA	1000 ha	% of AA	1000 ha	% of AA	1000 ha	% of AA
Argentina	273 669	128 747	47.0	27 900	21.7	1000	0.8	99 847	77.6
Bolivia	108 438	37 087	34.2	3050	8.2	206	0.6	33 831	91.2
Brazil	845 942	263 600	31.2	59 000	22.4	7600	2.9	197 000	74.7
Colombia	103 870	45 911	44.2	2293	5.0	1557	3.4	42 061	91.6
Guyana	19 685	1740	8.8	480	27.6	30	1.7	1230	70.7
Paraguay	39 730	24 836	62.5	3040	12.2	96	0.4	21 700	87.4
Suriname	15 600	89	0.6	58	65.2	10	11.2	21	23.6
Venezuela	91 205	21 640	23.7	2600	12.0	800	3.7	18 240	84.3
South America	1 753 237	584 285	33.3	107 105	18.3	13 645	2.3	463 535	79.3

Source: [Faostat, 2005].

with strongly pronounced wet (October–March in the Southern hemisphere) and dry seasons. Abundant heat and moisture permit planting without irrigation of maize, soybean, sorghum, sunflower, cotton, and harvesting commercial crops twice a year from the same field.

The soil properties, which predominate in the *cerrado*[1], such as high acidity (pH 4–5), low cation-exchange capacity (CEC), low base saturation, and high levels of Al^{3+}, limit their agricultural use. Only after liming and application of mineral fertilizers, these soils become suitable for continuous planting of grains, oilseeds, and other crops. No-till practices on these soils became popular for preventing soil erosion, maintaining stable temperature and moisture regime in the upper soil horizons, and improving low organic matter contents. According to the Brazilian Federation of Direct Planting into the Straw, the area under no-till systems in Brazil in 2005/2006 agricultural year equaled 25.5 million ha; 38% of this area corresponded to the *cerrado* regions [Andrade et al., 2010]

Along with agricultural colonization of the Brazilian *cerrado*, the consumption of mineral fertilizers in this country has been increasing. Potassium is one of the macronutrients highly demanded by crops such as soybean, maize, and sugarcane. For example, for each 1 t of yield of soybeans, 20 kg of K_2O are extracted from the soil. Assuming that the average soybean yield in Brazil approaches 3 t ha^{-1}, this is just enough to maintain the "zero" balance of potassium in the soil; farmers need to apply 100 kg ha^{-1} of KCl, the most widespread potassium fertilizer, containing 60% of K_2O. In 2010/2011 agricultural year, Brazilian farmers harvested 69 million t of soybeans from 24 million ha [Companhia Nacional de Abastecimento, 2011]. For this, they have used 25% of the nearly 7 million t of potassium fertilizers, imported in 2010 to Brazil, making this country the 3rd in the world after USA and China by the volume of their imports [Potash Statistics, 2011].

[1] *Ferralsols* by the FAO soil classification, or *latossolos* by the Brazilian soil classification [Sistema brasileiro de classificação de solos, 1999].

OBJECTS AND METHODS OF RESEARCH

In 2001, after establishing of a formal agreement between the International Potash Institute (IPI) and the Brazilian Corporation for Agricultural Research (EMBRAPA), a joint research project "Fertilize Brazil", aiming to develop and disseminate balanced fertilization practices for Brazilian agriculture, was initiated. In 2004, at the first stage of the project implementation, potassium balance in agricultural systems was estimated at the level of 26 states and for more than 4000 *municipios* (counties) of Brazil.

During 2006-2007, data from 3000 soil profiles, collected by the EMBRAPA National Soils Research Center, were used for mapping potassium contents in the soil. Spatial interpretation of these data proved to be technically difficult, because of complicated linking of the data to the soil types, landscape contours, and the network of administrative units [Prado et al, 2008]. Soil profiles, described by EMBRAPA, are unequally distributed by Brazilian territory. They are very sparse in regions, where the *cerrado* landscapes predominate. However, as soil profiles data comparison showed, soils of the Brazilian *cerrado* and similar savanna landscapes are not uniform and vary in physical and chemical properties. For example, potassium availability in the upper layers of the soil may differ from 15 to 150 mg kg^{-1} [Naumov and Prado, 2008].

The potassium export calculation was done with the crop yield data on agricultural production (for harvestable parts of the crop) from the municipal statistical database of the Brazilian Institute for Geography and Statistics (IBGE). The estimates were based on such indicators as the annual volume of production (t) of 19 main commercial crops: soybean, maize, sugar cane, coffee, cocoa, oranges, beans, etc., including planted eucalyptus, and the average uptake of the nutrient with 1 t of their yields. The estimates of the potassium input in the soil were less precise. The only data source available was statistics on the volume of potassium fertilizers sales by state (t), provided by the National Association of Mineral Fertilizers Dissemination [ANDA, 2004].

From many points of view, those Brazilian agricultural regions that were formed after clearing of the *cerrado* natural vegetation, deserve special attention for evaluation of sustainability of agricultural systems regarding balanced fertilization. Initially, the *cerrado* regions with more fertile soils were colonized, but now agricultural frontier has shifted towards marginal areas with poorer soils. Data on these soils are scarce; farmers, who moved there are mostly from the southern states of Brazil and they often neglect local natural conditions. Until recently, there was a lack of scientific knowledge about how to adopt agricultural practices in these areas. From the technical point of view, extrapolation of the EMBRAPA data on soil profiles to all areas under the *cerrado* vegetation for purposes of further evaluation of potassium balance in the soil and for the development of recommendations for farmers could result in significant discrepancies.

On the next stage of the project implementation, we decided to carry out a more detailed research and to create a GIS-based spatial description of potassium balance in agricultural systems in one of the main grain and oilseed producing regions of the Brazilian *cerrado* – South West of the Goias state (Fig. 1). Large-scale commercial agriculture began to develop in this state in the late 1970s, and nowadays, Goias is one of the main maize and soybean producing regions (8.1 million Mt, or 15% of the total national annual harvest of maize grain in Brazil in 2010, and 7.5 million Mt, or 11% of soybeans). Cotton and sugarcane planting is also spreading in this region, and cattle ranching and poultry industry are developing fast in association with forage production [Projecções do agronegócio, 2010].

In 2005–2006, potassium availability in soil was estimated from the data of soil

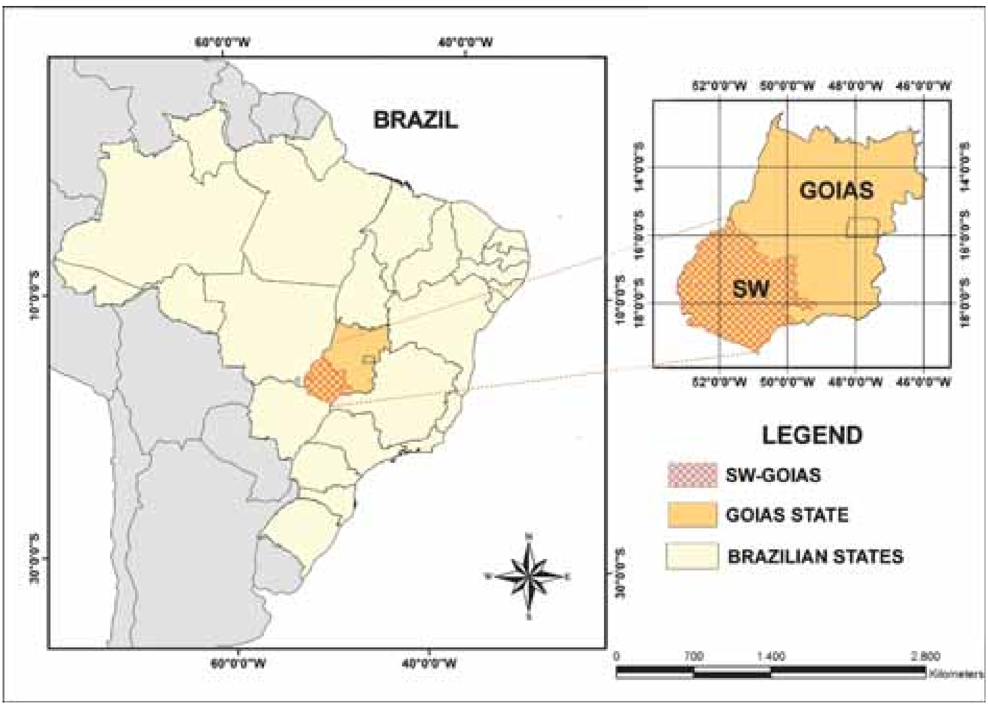

Fig. 1. Research polygon in the South West of the Goias state, Brazil

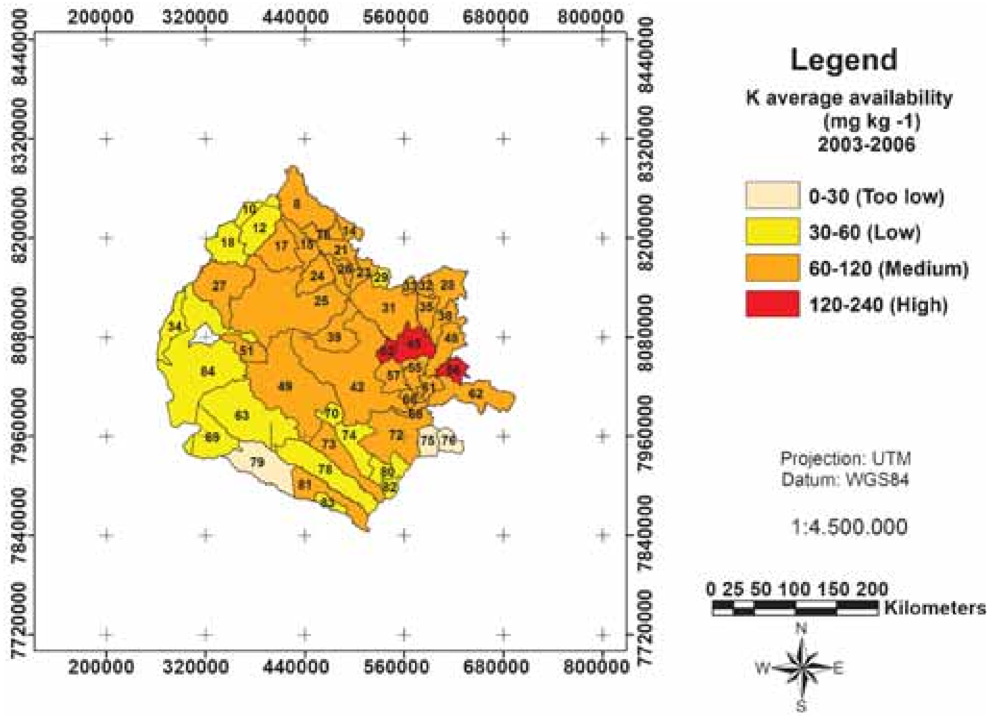

Fig. 2. Potassium availability in the soil in the South West of the Goias state (numerical scale as on the original map, same for the fig. 3 and fig. 4)

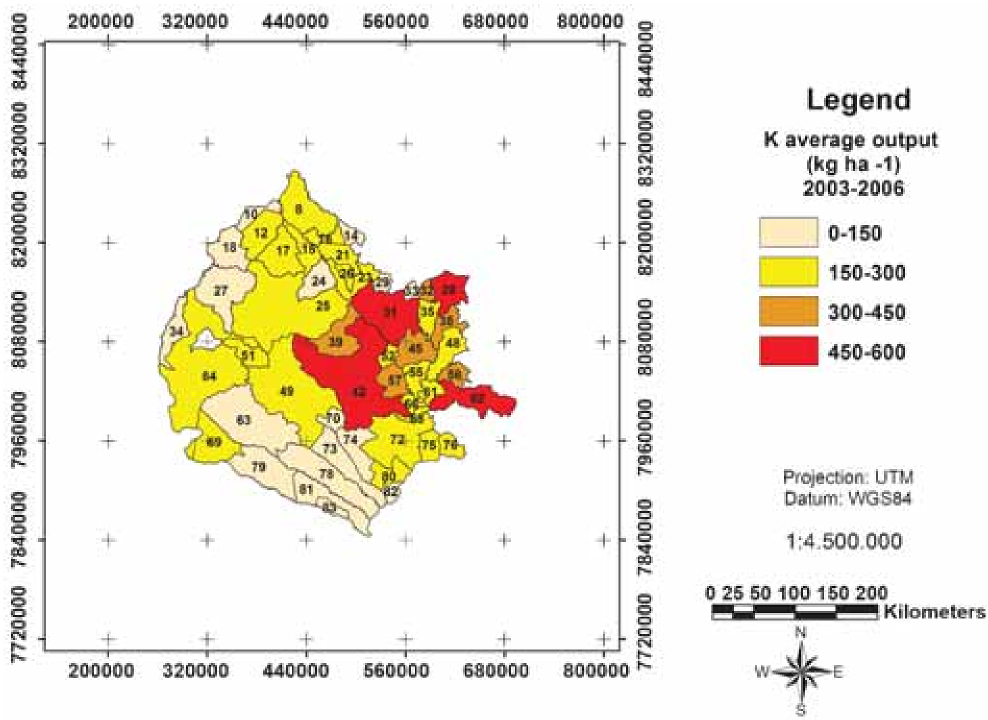

Fig. 3. Potassium uptake from soil with crop yields in the South West of the Goias state

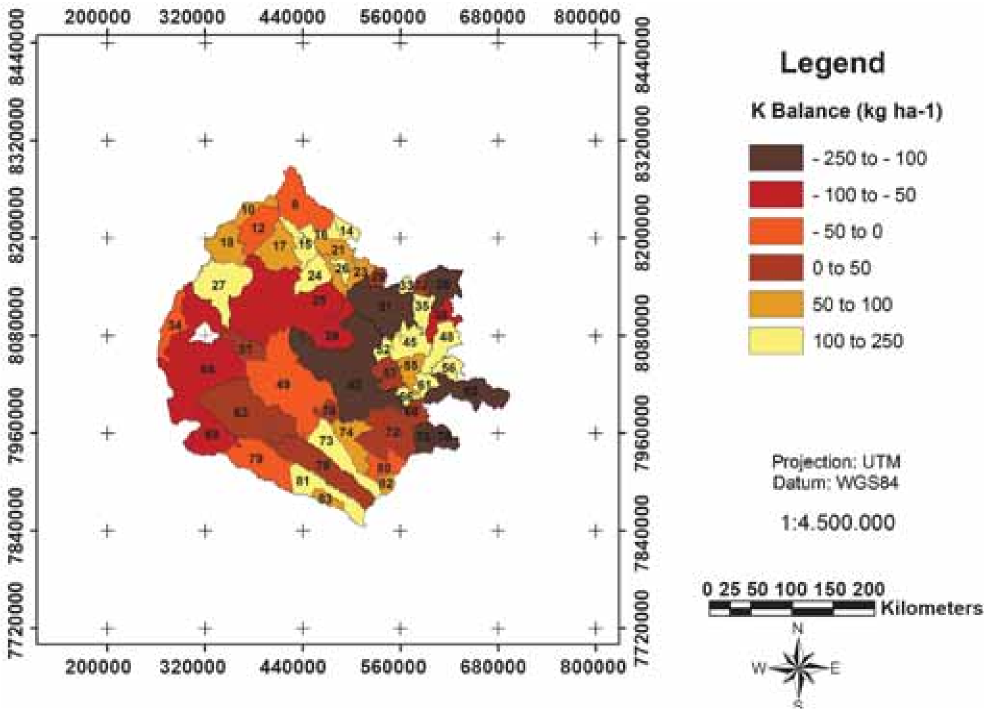

Fig. 4. Potassium balance in the soil in the South West of the Goias state

sampling at the *fazendas* (large farms) of the members of the COMIGO agricultural cooperative. Geo-referenced data on mineral fertilizers consumption were obtained from farmers during a poll in 2005 (about 500 have responded), from surveys of selected farms, and from the COMIGO agronomy database. The relationship of potassium uptake with yields of commercial crops was calculated from agricultural statistics data for 61 *municipios*. These data formed two GIS layers on a municipal level shown in Figures 2 and 3. Overlay of potassium availability, input, and output layers was used to estimate potassium balance in the agricultural region studied (Fig. 4).

Then, we focused on a more detailed territorial analysis of soil properties and agricultural land use in 6 *municipios* of the South West of Goias. For the land use evaluation, satellite images Landsat TM-5 for different periods of the agricultural cycle of 2007 were used. Using software Spring 4.3.3, enabling segmentation of images, and the semi-automatic classifier *Bhattacharrya Distance*, 10 classes of land use, depending on predominant crop, were determined (Fig. 5). Map on soil texture classes were created on the basis of a1:250,000 scale soil map, produced for the RADAMBRASIL project in 1981 (Fig. 6).

By merging consistently data on soil texture, predominant crop, and average potassium uptake with crop yield and average doses of potassium fertilizers applied for each crop for replenishment of the nutrient use[1], we have estimated the potential crop potassium demand levels on agricultural systems. Each soil texture class and land use type by crop was assigned a conventional "weight" regarding potassium demand, e.g. soybean planted under no-till on clayey soils – 1, loam soils – 2, same on sandy soils – 4; sugarcane on clayey soils – 11, loam soils – 12, sandy soils – 13. Results of mapping of these estimates are displayed on the map in Fig. 7.

[2] E.g., for sugarcane 130, for soybean 68, for maize 41 kg K_2O ha^{-1} $year^{-1}$.

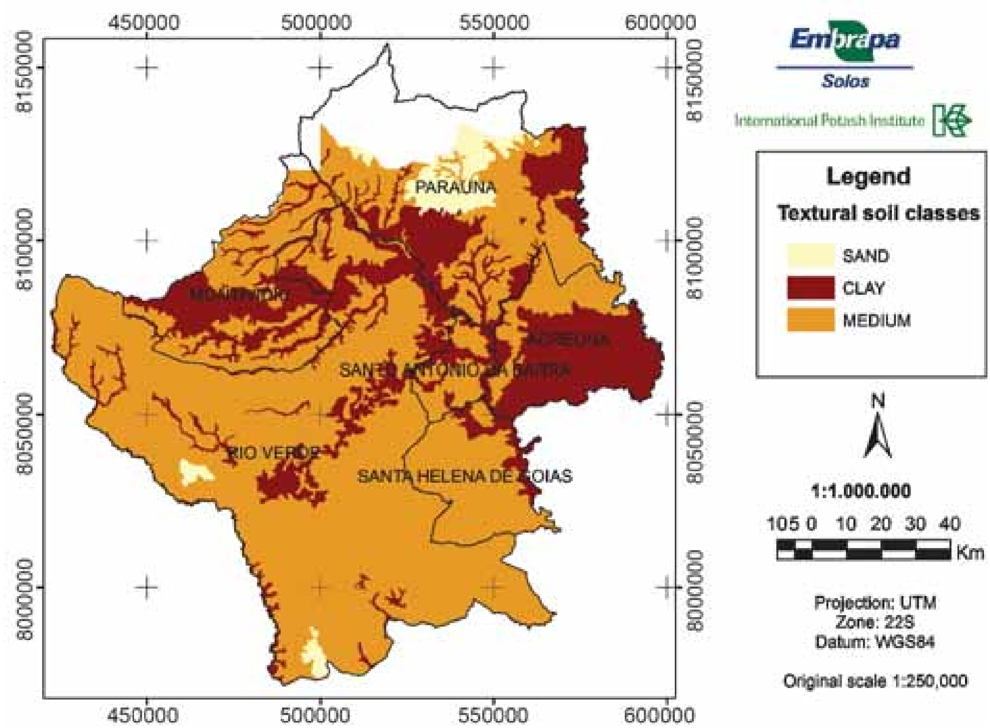

Fig. 5. Predominant land use by crop in 6 *municipios* of the South West of the Goias state

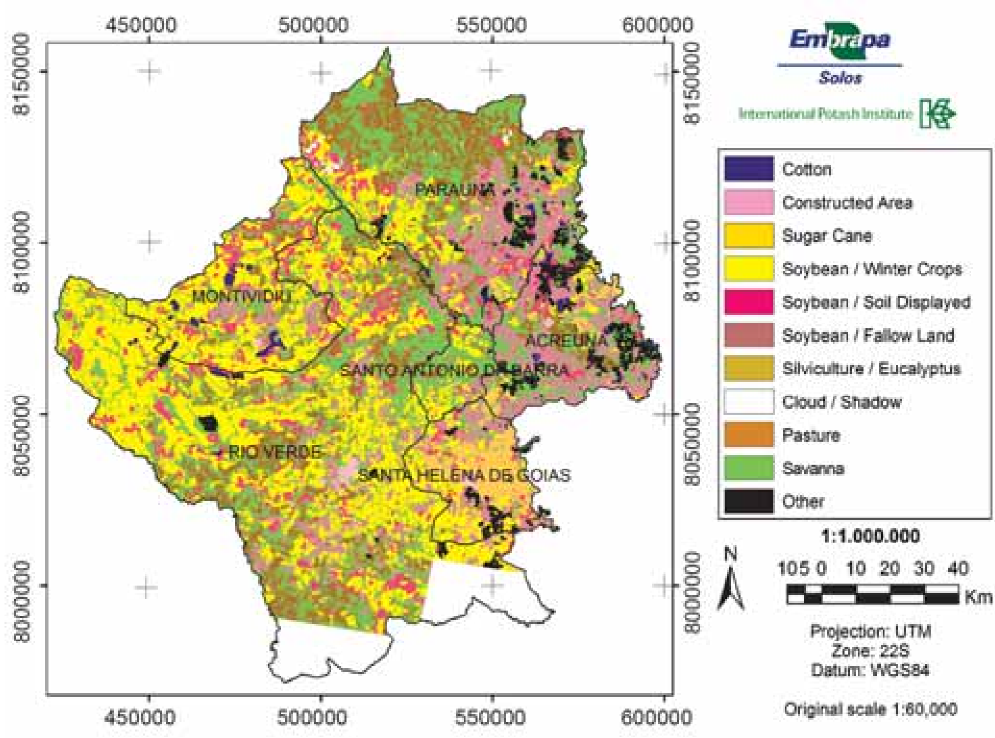

Fig. 6. Soil texture classes in 6 *municipios* of the South West of the Goias state

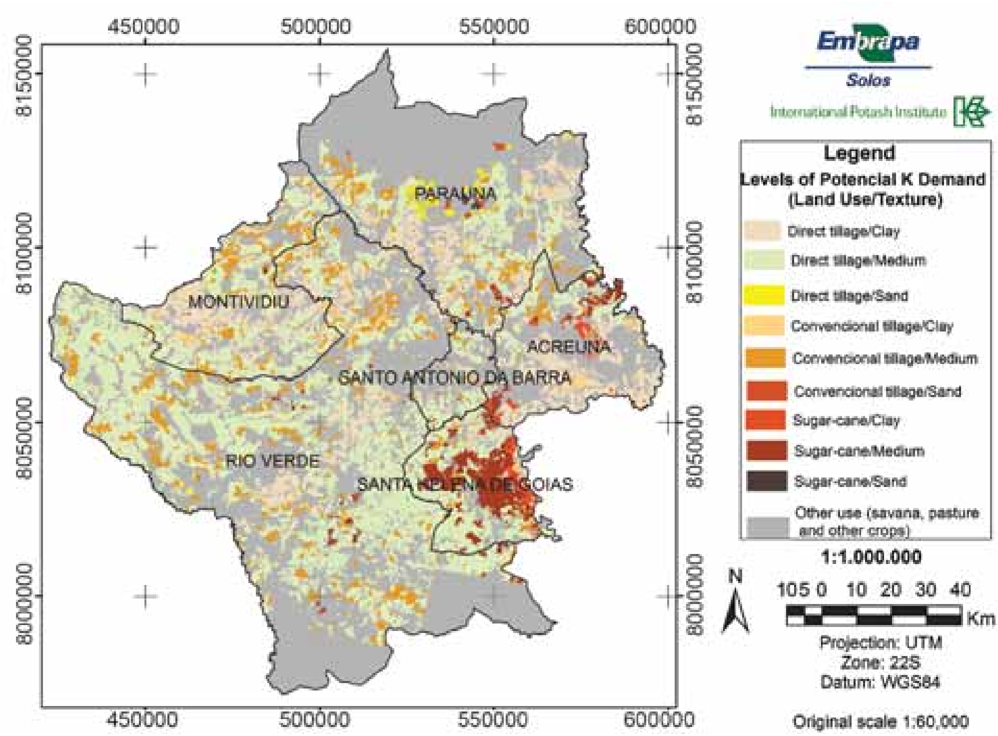

Fig. 7. Estimated potential levels of potassium demand on agricultural systems in 6 *municipios* of the South West of the Goias state

RESULTS AND DISCUSSION

Mapping of potassium uptake with yields on a macro (or national) level clearly showed "hot spots" of agricultural development, where mineral fertilizers consumption is concentrated and doses of their application should be high in order to maintain balance of nutrients in the soil. These are: agricultural regions in the *cerrado* of the states of Mato Grosso, Mato Grosso do Sul, Goias, and the western part of the Bahia state (mostly soybeans and maize planting areas); the interior of the São Paulo state (sugarcane and oranges plantations areas); the littoral of the north-eastern states and the Rio de Janeiro state (sugarcane and tropical fruits plantations areas); Petrolina-Juazeiro tropical fruits growing region on the São Francisco river, etc. [Oliveira et al. 2005].

The estimates of potassium balance in agricultural systems on a medium (or regional) level for 61 *municipios* of the studied region (Fig. 4) show that some areas of the South West of Goias suffer from deficiency of this nutrient to sustain high yields, while for other areas it is obvious that there is excessive use of potassium fertilizers. In other words, agriculture in both cases is not sustainable environmentally or economically. Farmers, applying incorrect (insufficient or excessive) doses of fertilizer, minimize profits. For example, the poll showed that most of the COMIGO associates were applying same doses of fertilizer at the same time (pre-plant), despite differences in soil (texture, depth, acidity) and rainfall regime. On average for the studied area, expenses for fertilizers (total N, P, K and micronutrients) represent 1/3 of the total production cost of soybeans and maize. But those who did not take in consideration local geographical conditions at their farms, often were spending twice as much.

A more detailed study and a small-scale approach for evaluation of potassium demand, based on soil texture and land use analysis, resulted in conclusion of even sharper geographical contrasts in potassium (and, presumably, in other nutrients) demand on micro (landscape contours, fields) level. Soil properties, such as CEC and their physical characteristics, influencing enleaching of nutrients, are very important for the estimate of right doses of mineral fertilizers to be applied. As a side – but important result of this research, we would also like to mention precise data on the predominant crops and agricultural practices by territory. As the land use classification showed, the predominant land use class for 6 *municipios* of the South West of Goias was soybean, planted in no-till systems (for the *municipio* of Montividiu – 54%, for Rio Verde – 45% of the total area). The satellite images data interpretation pointed to expansion of sugarcane in the *municipio* of Santa Helena de Goias where this crop already covers 1/3 of total area. High magnitude of no-tillage practices among the local farmers was also taken in consideration, because of a lower demand for mineral fertilizer, than in conventional practices.

CONSLUSIONS

A spatial approach for determining nutrient balance in agricultural systems enables a precise vision of weak points of agricultural systems regarding the efficiency of mineral fertilizer use, and helps to draw solutions for decreasing their instability.

Recently colonized regions of Brazil seek adaptation of farmers' practices of fertilization to local soils. Extensive growth of agriculture may not be sustainable environmentally (because of pollution of ground and surface waters with chemicals) or economically (because farmers spend more, than needed, for fertilizers). Thus, knowledge of local geographical conditions becomes essential, allowing reduction of production costs, as it helps to increase efficiency of fertilizers use and approach more sustainable models of agricultural production.

Geographic information systems are increasingly widely used in modern agriculture in order to adopt on-farm operations (tillage, planting, etc.) to the micro-geographical properties of the fields (so-called precision agriculture). The authors consider the GIS-technologies be potentially also useful for scientifically based solution of such practical targets as monitoring of nutrients in soil and soil fertility in general, evaluation and forecast of efficiency of fertilizers use, definition of rational doses, and optimal terms and methods of their application on the fields.

Geo-referenced recommendations for farmers, aimed at minimization of production costs, become an important tool for increase efficiency of fertilizers use. The authors are planning to produce even more detailed maps and complete layers of GIS with climatic and phonological data. This will allow synchronization of fertilization data, the life cycle of crops, and rainfall regime, and will help to reduce enleaching of nutrients from fertilizers. The authors expect that extrapolation of different kinds of physical-geographical, social, and economic data on landscape-type maps and, then, on the detailed map of the fields based on LANDSAT images will allow obtaining precise data on potassium availability at the depth of the agricultural horizon and on balance of this nutrient in agricultural systems of the Brazilian *cerrado*.

The results of this research have already attracted the attention of farmers and decision makers in Brazil. Currently, GIS is in the process of being placed on the web for the public use. The authors are planning to reproduce the similar methods of research for the other agricultural area of the Brazilian *cerrado* – the West of the Bahia state. This approach may be also applied for the purposes of sustainable development of agriculture in other savanna regions of South America.

ACKNOWLEDGEMENTS

The authors acknowledge colleagues from The National Soils Research Center and other research units of EMBRAPA, local universities, and agronomic research bodies of the Goias state, who were involved in the research activities

during 2001–2011. Our research also greatly benefited from the support of field workers – agronomists and farmers, who strive to achieve sustainability of agriculture and provided us with useful data on their practices.

The research was supported by the International Potash Institute (IPI) and the Brazilian Corporation for Agricultural Research (EMBRAPA) that cooperate in the Project "Fertilize Brazil". ■

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