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Full Length Research Paper

Soil conservation practices in three watersheds of Benin: Farmers' cropping systems characterization

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This document addresses the farming practices and their characteristics on three watersheds in southern Benin. These watersheds are located in the villages of Govié, in Allada district, Lokogba in Aplahoué district and Linsinlin in Djidja district. Simple random sampling is used to investigate 417 farm households at the rate of 139 per village. Focus groups are conducted with resource persons and individual interviews according to a survey tool. The observation unit of the survey is the head of the farm household. In the villages of Lokogba and Linsinlin, farm households practice slash and burn agriculture in contrast to those of the village of Govié where residues are not burned. Soil conservation practices (direct sowing, minimum tillage) are made in the village of Lokogba while tillage is widely practiced in the other villages. In the village of Govié, some households use mulch and mineral fertilizers, but the rate is low. Organic fertilizers are used by 40.2% of farmers in Lokogba village. Crop rotation and fallow are still widely practiced in this village by 85.6 and 84.6% of the surveyed households respectively. In other villages, these practices are absent or present at very low levels showing their high level of agricultural intensification. Weeding is the main preventive measures used by farmers in village of Govié (38.8%), Lokogba (93.8%) and Linsinlin (23.2%). Chemical pests control is used by all farmers of village of Linsinlin and Lokogba. The farming practices are significantly specific to the surveyed villages. Soil conservation practices are more observed at Govié than Lokogba. In the village of Linsinlin, these practices are almost absent.

Key words: Soil conservation, farming practices, cropping systems, watersheds, Benin.

INTRODUCTION

Soil and water are basic, vital and essential resources for sustainable agriculture. Sustainability implies here utilizing these resources in ways that ensure little or no damage whilst guaranteeing their continuous usage

(Ahaneku, 2010). Land degradation was a significant global issue during the 20th century and remains of high importance in the 21st century as it affects the environment, agronomic productivity, food security, and quality of life (Eswaran et al., 2001). Soil degradation processes include the loss of topsoil by the action of water or wind, chemical deterioration such as nutrient depletion, physical degradation such as compaction, and biological deterioration of natural resources including the reduction of soil biodiversity (Lal, 2001).

There is also human - induced soil degradation through overgrazing, deforestation and inappropriate agricultural activities. This also poses a serious threat to land productivity. The abandonment of existing degraded pastures and cropland, the move to new land for grazing and crop production are responses to the decline in soil fertility. Unless there are investments in soil conservation, the process will be repeated in a vicious circle overgrazing and continuous cropping causing land degradation and then the search for new pastures and cropland (Barbier, 2000).

African farmers operate in different environments, some having enough resources, others operating in resource constrained environment. Farming system typologies are dictated by climate, production goals and culture with a farming system being described as a unit consisting of a human group (usually a household) and the resources it manages in its environment, involving the direct production of plant and/or animal products (Scherr, 1999). A farming system describes what is currently being done by a group of farmers operating under certain common conditions. The system focuses on farm-household and rural community systems and their interactions with physical, socio-cultural and political environments (Kalisa, 2007). Each individual farm has its own specific characteristics, which arise from variations in resource endowments and family circumstances. The household, its resources, and the resource flows and interactions at this individual farm level are together referred to as a farm system.

Though agriculture in Benin occupies 75% of the population (MAEP, 2010), it is not articulated yet around the techniques and the methods (the most modern) for fully satisfying the needs of the population. Its development as well as the level of production performances as the conservation, the processing and the commercialization of agricultural products are limited (SCRP, 2007).

Several strategies of water and soils conservation (WSC) were developed and spread in Benin by development projects since 1960. Avoidance of soil loss by improved management and the conservation of natural resources is therefore important to maintain the functions of the soil and contribute to food security today and for future generations (Ehui and Pender, 2005). Research on soil conservation has been conducted for many years in Sub-Saharan Africa (Ehrenstein, 2002) and in Benin (Saidou, 2005). Farmers have been slow in adopting appropriate soil conservation measures, which they consider to be high labor and capital requiring during construction and maintenance and also as a waste of land (Khisa et al., 2002).

Access to land is a problem, especially in the south, where the population density is very high. Farm sizes are on average 1.7 ha for a family of 6 to 7 persons, while off-farm activities remain rare. Sloping lands, such as watersheds, are intensively cultivated over the plateau land (MAEP, 2007). But they are more susceptible to degradation and thus could no longer feed farmers. This population of watersheds, out of food insecurity more and more aggravating, must produce more with their limited resources. Accordingly, farming practices need to be more productive and sustainable. It is necessary to make an inventory of agricultural practices on watersheds to identify needed improvements for adequate and sustainable production.

This study aims at characterizing agricultural practices at three watersheds of southern regions of Benin.

MATERIAL AND METHODS

Study area and villages' selection

This study covers three watersheds in southern regions of Benin. These watersheds are characterized by a ferralitic soil called "Terre de barre". This is a very sensitive soil to degradation and mainly to erosion because they are sloped (slope at least 5%). The main activity in these watersheds is agriculture with a very high population density. Their soil is under severe land pressure. They watersheds are located in the district of Allada (watershed of Govié village), the district of Aplahoue (watershed of Lokogba village) and the district of Djidja (watershed of Linsinlin village). Allada district is located between longitude 2° 9 '35' 'East and latitude 6° 39'52 ''North. It covers 381 km^2 with a population density of 240.9 inhabitants per squared kilometer. Aplahoue district is located between longitude 1° 40 '25 ''East and latitude 6° 56'32 '' North. It covers 572 km^2 with a population density of 240.5 inhabitants per squared kilometer. Djidja district is located between longitude 1° 56 '8 ''East and latitude 7° 20'46 '' North. It covers 2,184 km^2 with a population density of 38.7 inhabitants per squared kilometer. Figure 1 shows the location of the study sites. Allada and Aplahoue districts are characterized by a sub-equatorial climate with two (02) rainy seasons and two (02) dry seasons. Annual rainfall ranges from 900 to 1100 mm. But, Djidja district enjoys a climate of sub-equatorial tending to Sudano-Guinean in the northern parts.

Selection of the research units

The research units are the households represented by their heads.

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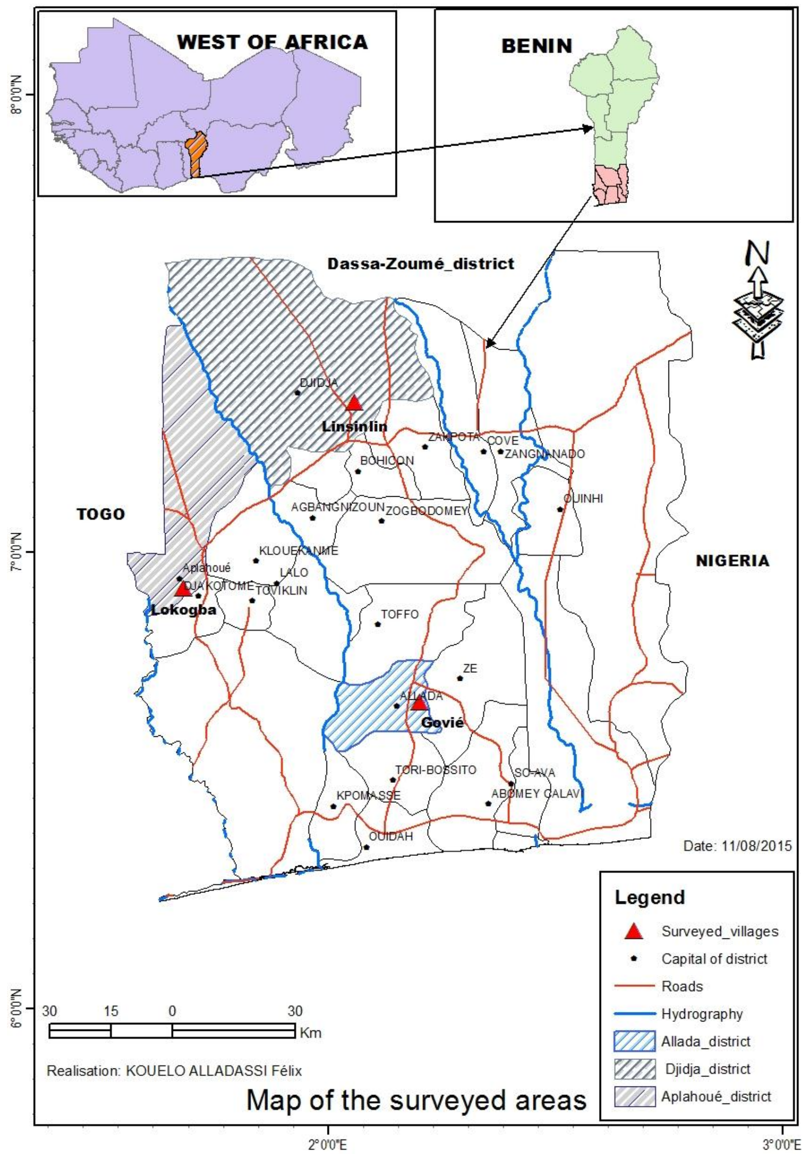

Figure 1. Map of the surveyed areas.

They are chosen randomly in order to be a representative sample of the population. According to Dagnelie (1998), the sample size required can be calculated by applying the following formula:

$$N = [(U_{1-\alpha/2})^2 \times p(1-p)]/d^2$$

with n≥ 50 and p≥ 1/10 of population, N = sample size required per village of study; $U_{1-\alpha/2}$ = confidence level of 95% (typical value of 1.96); p = proportion known or suspected in the parent population; d = margin of error of 5% (typical value of 0.05). To calculate the sample size, we take p = 0.1; thus n = 139. This is the minimum possible size per site for this survey. For the three watersheds' villages, 417 farm households are surveyed.

Data, collection and tools of analysis

The data used consist of variables such as socio-economic and demographic characteristics and farming practices (clearing, tillage, mulching, fertilization, crop rotation, pest management and fallow). Data are analyzed using descriptive statistics and frequencies in SPSS version 16. The Chi square test is conducted to statistically verify whether there is a dependency between agricultural practices and watersheds. This test informs us about the specificity or not of farming practices in relation to watersheds studied.

RESULTS

Profiles (Characteristics) of the sampled households

On Tables 1 to 3, we present the profiles of the sampled farmers. The main characteristics of households considered in the study include among others the socioeconomic, education and demographic characteristics. Household heads are predominantly

Table 1. Social characteristics of farmers in the three surveyed villages.

Variables	Modalities	Frequency (%)		
		Govié	Lokogba	Linsinlin
Gender	Male	122 (87.8)	108 (77.7)	103 (74.1)
	Female	17 (12.2)	31 (22.3)	36 (25.9)
Religion	Animist	62 (44.6)	63 (45.3)	97 (69.8)
	Christian	75 (54.0)	76 (54.7)	42 (30.2)
	Muslim	2 (1.4)	-	-
Marital status	Single	20 (14.4)	9 (5.5)	11 (7.9)
	Married	110 (79.1)	113 (81.3)	126 (90.6)
	Divorced	3 (2.2)	3 (2.2)	2 (1.4)
	Widowed	6 (4.3)	14 (10.1)	-
Household	Native	129 (92.8)	139 (100.0)	123 (88.5)
	Immigrant	10 (7.2)	-	13 (9.4)
	No answers	-	-	3 (2.2)
Land tenure status	Heritage	86 (36.7)	130 (93.5)	117 (83.0)
	Donation	9 (3.8)	8 (5.8)	16 (11.4)
	Renting	53 (22.6)	-	2 (1.4)
	Purchase	50 (21.3)	1 (0.7)	3 (2.1)
	Share cropping	36 (15.4)	-	-
	No answers	-	-	3 (2.1)

Source: Field Survey, 2013.

Table 2. Demographic characteristics of the surveyed farmers.

Variables	Modalities	Frequency (%)		
		Govié	Lokogba	Linsinlin
Age	<30 years	14 (10.1)	26 (18.7)	34 (24.4)
	30 - 40	44 (31.6)	56 (40.3)	55 (39.6)
	40 - 50	41 (29.5)	39 (28.1)	30 (21.6)
	50 - 60	26 (18.7)	18 (12.9)	20 (14.4)
	>60 years	14 (10.1)	-	-
	Mean	44.5 ± 9.4	39.3 ± 8.7	38.6 ± 9.8
	Minimum	20	22	24
	Maximum	75	58	60
Household size	<5	-	1 (0.7)	24 (17.3)
	5 - 10	75 (54.0)	102 (73.4)	91 (65.5)
	10 - 15	63 (45.3)	36 (25.9)	21 (15.1)
	>15	1 (0.7)	-	3 (2.1)
	Mean	09 ± 2	8 ± 2	8 ± 2
	Minimum	5	4	3
	Maximum	15	14	16

Source: Field Survey, 2013.

male, respectively 87.80, 77.70 and 74.10% in the villages of Govié, Lokogba and Linsinlin. Women heads of household are recently widows or women whose husbands have travelled. While they are mostly of

Table 3. Education characteristics and agricultural extension rate.

Variables	Modalities	Frequency (%)		
		Gović	**Lokogba**	**Linsinlin**
Level of education	Illiterate	66 (47.5)	89 (64.0)	118 (84.9)
	Primary level	61 (43.9)	40 (28.8)	17 (12.2)
	Secondary level	12 (8.6)	10 (7.2)	4 (2.9)
Literacy	Not Alphabetized	72 (51.8)	139 (100.0)	117 (84.2)
	Alphabetized	67 (48.2)	-	22 (15.8)
Farmer organization	Not member	121 (87.1)	135 (97.1)	58 (41.7)
	Member	18 (12.9)	4 (2.9)	81 (58.3)
Agricultural extension	Not mentored	96 (69.1)	96 (69.1)	53 (38.1)
	CARDER	41 (29.5)	43 (30.9)	80 (58.3)
	NGO	2 (1.4)	-	5 (3.6)

Source: Field Survey, 2013.

traditional religion (Animist) in the village of Linsinlin (97% of farmers), those from the villages of Govié and Lokogba practice the Christian religions in majority (54 and 54.7% respectively). Most household heads are married. The immigration rate is very low or zero in the surveyed villages. The primary mode of land tenure is heritage (61.87% in the village of Govié, 93.5% in the village of Lokogba and 84.17% in the village of Linsinlin). Age is an important factor, which affect the potential employment and mobility status of respondents. The average age of household heads surveyed is 45 years in Govié, 40 years in Lokogba and 39 years in Linsinlin. The mean size of households is 11 persons in the village of Govié and 8 persons in the villages of Lokogba and Linsinlin (Table 2). In the three villages, household heads are older and adults at majority (30 to 50 years). In the villages of Lokogba and Linsinlin, most farmers are not educated (illiterate). In the first village, nearly 29% of farmers have the primary level unlike farmers of the second village (12%). These results are explained by the fact that the village of Lokogba in Aplahoue district is very close to the urban center of Azovè (2 km) while the village of Linsinlin whose nearest urban center, Bohicon, is approximately 15 km away. In the village of Govié, the level of education is high (44%) for the primary level and 9% for the secondary level. This is because this village in Allada district is closer to its urban center, Allada, and also nearer to the economic capital (Cotonou) of Benin than the other two villages. In the villages of Govié and Lokogba, most farmers do not belong to farmer's organization unlike Linsinlin village where 58% of farmers are members of farmer's organization (Table 3). Most of farmers' organizations are forums where farmers can access useful information and share experiences. The main agricultural extension structure in the three surveyed villages is the Regional Agricultural Centre for Rural Development (CARDER). The rate of agricultural extension services is low in the villages of Govié and Lokogba, but high in the village of Linsinlin (58%). Outside the CARDER, some NGOs are also involved in the technical support to farmers in the villages of Govié and Linsinlin, but at a very low rate.

Farming systems practiced in surveyed villages

Soil preparation practices

Different soil preparation practices are significantly specific to watersheds studied, clearing and tillage type at the 1%. The direction of the ridges is also statistically specific, but at the 10% level at the watersheds where farmers practice ridging (Table 4). In the village of Govié, three clearing practices are observed: the clearing without burning (50.2% of farmers) and clearing with incorporation of residues (12.4%) are soil conservation practices. Clearing and burning, a soil degrading practice, are observed in the fields of 37.3% famers. In the village of Lokogba, two main clearing practices are observed: A soil degrading practice (clearing and burning) is observed in the fields of 54.4% farmers and a soil conservation practices (clearing with incorporation of residues) is observed in the fields of 43% farmers. But, in the village of Linsinlin, most farmers practice slash and burn clearing (91.4%) and thus contribute to soil degradation. Conventional tillage (a soil degrading practice) is the main type of tillage practiced in the villages of Govié (63.5%) and Linsinlin (81%), while in the village of Lokogba, the main type of tillage is a soil conservation practice (minimum tillage by 52.5% of farmers). Direct sowing (recommended soil conservation practice) is observed in Govié and Lokogba villages only. In villages where conventional tillage is practiced, ridges are oriented in different directions. In the village of Govié, the

Table 4. Soil preparation activities.

Variables	Modalities	Frequency (%)			Total	Chi-square	Probability
		Govié	Lokogba	Linsinlin		χ^2	α<0.05
Clearing	LCWB	117 (50.2)	4 (2.7)	9 (6.5)	130 (25.0)	226	0.000
	LCAB	87 (37.3)	81 (54.4)	127 (91.4)	295 (56.6)		
	LCARI	29 (12.4)	64 (43.0)	3 (2.2)	96 (18.4)		
Tillage type	NT	46 (22.1)	66 (47.5)	-	112 (22.7)	311.1	0.000
	MT	4 (1.9)	73 (52.5)	28 (19.0)	105 (21.3)		
	CT	132 (63.5)	-	120 (81.0)	251 (50.8)		
	Tillage	26 (12.5)	-	-	26 (5.3)		
Ridges direction	Parallel	53 (37.3)	-	52 (37.1)	105 (37.2)	5.478	0.065
	Cross slope	58 (40.9)	-	42 (30.0)	100 (35.5)		
	WCD	31 (21.8)	-	46 (32.9)	77 (27.3)		

Source: Field Survey, 2013. LCWB = Land clearing without burning; LCAB = Land clearing and burning; LCARI = Land clearing and residues incorporation; NT = No tillage; MT = Minimum tillage; CT = Conventional tillage; Parallel = Parallel to the slope; Perpendicular = Perpendicular to the slope; WCD = without clear direction.

Table 5. Fertilization practices.

Variables	Modalities	Frequency (%)			Total	Chi-Square	Probability
		Govié	Lokogba	Linsinlin		χ^2	α<0.05
Fertilizers	No	123 (87.2)	3 (1.5)	26 (18.6)	152 (31.3)	378.9	0.000
	Mineral	16 (11.3)	119 (58.3)	113 (80.7)	248 (51.1)		
	Organic	2 (1.4)	82 (40.2)	1 (0.7)	85 (17.5)		
Application	Open seed-holes	3 (15.0)	4 (3.6)	32 (23.7)	39 (14.7)	162.98	<0.0001
	On soil	5 (25.0)	98 (88.3)	14 (10.4)	117 (44.0)		
	Closed seed-holes	10 (50.0)	9 (8.1)	87 (64.4)	106 (39.8)		
	Streak	2 (10.0)	-	2 (1.5)	4 (1.5)		

Source: Field Survey, 2013.

ridges are oriented parallel to the slope by 37.3% of farmers and perpendicular to the slope by 40.8% of farmers. But, 21.8% of farmers do not give specific direction to the ridges. In the village of Linsinlin, 37.1% of farmers do orient ridges parallel to the slope and 30% across the slope. Ridges have no clear direction for 32.9% of farmers. At the clearing, there are more soil conservation practices in Govié village than in the two others. At the tillage, practices are more preservative to soil in Lokogba but more degrading to soils in Govié and Linsinlin.

Fertilization practices

Family farms of surveyed villages use fertilizers to increase the productivity of their crops. In the villages of Govié and Linsinlin, none of the surveyed farmers does use organic fertilizers. The fertilization practices in these villages are completely soil degrading practices (Mining agriculture in Govié: 87.2% of farmers do not use any fertilizers while mineral fertilization is practiced by 80.7% of farmers in Linsinlin village). Farmers in Lokogba village use two main practices in fertilization: mineral fertilization (a soil degrading practice) is used by nearly 58.3% of farmers and organic fertilization (soil conservation practice) is used by 40.2% of farmers. NPK and Urea are the mineral fertilizers used by farmers. Household garbage and animal wastes are organic fertilizers used by farmers. There is a very highly significant dependence between fertilization practices and villages of the studied watersheds (χ^2 = 378.9; p = 0.000). So, fertilization is a practice that significantly discriminates the surveyed sites.

The modes of application of mineral and organic fertilizers by farmers in these villages are: Opened seed-holes, closed seed-holes, on soil and in streak (Table 5). Among these modes, the closed seed-holes' ones are the

Table 6. Crop management practices.

Variables	Modalities	Frequency (%)			Total	Chi-square	Probability
		Govié	Lokogba	Linsinlin		χ^2	α<0.05
Crop rotation	No rotation	20 (14.4)	139 (100.0)	108 (77.7)	267 (64.0)	112.0	0.000
	Rotation	119 (85.6)	-	31 (22.3)	150 (36.0)		
Fallow	No fallow	16 (11.2)	139 (100.0)	71 (80.7)	226 (61.1)	112.1	0.000
	Fallow 1	121 (84.6)	-	16 (18.2)	137 (37.0)		
	Fallow 2	6 (4.2)	-	1 (1.1)	7 (1.9)		
Mulching	No mulching	113 (81.3)	139 (100.0)	139 (100.0)	391 (93.8)	55.46	0.000
	Mulching	26 (18.7)	-	-	26 (6.2)		

Source: Field Survey, 2013. Fallow 1 = 1 to 2 years; Fallow2 = 2 to 5 years.

most widely practiced by farmers from the villages of Govié (60%) and Linsinlin (73%). Farmers in the village of Lokogba (88%) rather apply fertilizers on soil (especially for organic fertilizers). The last practice is not a soil degrading mode.

Crop management practices

Crop rotation, fallow and mulching (soil conservation practices) are crop management practices of farmers in the villages of Govié and Linsinlin. Crop rotation is widely practiced in Govié (85.6% of farmers), but poorly practiced in Linsinlin (22.3%). In the village of Lokogba, no farmers practice these types of crop management (Table 6). Fallow is mainly practiced by farmers (91%) of the village of Govié. In the village of Linsinlin, only short fallow practices are observed by 44% of farmers. These results show that the village of Lokogba is under land pressure unlike other villages where the pressure is still fair. Mulching is practiced in the village of Govié only by 18.7% of farmers. These crop management practices are significantly specific to villages studied at the 1%.

Crop protection practices

Crop losses recorded on farms are due to the damage caused by pathogens through diseases and pests. Preventive measures are implemented by farmers to limit the damage caused by pests. This practice (a soil conservation practice) is statistically specific to villages studied at 1% level. The most used preventive measures in the village of Govié are weeding (38.8% of farmers), traps (26.0% of farmers) and firewall (17.4% of farmers). In the village of Lokogba, weeding is an important preventive measure practiced by 93.8% of farmers. The preventive measures practiced by farmers from the village of Linsinlin are mainly weeding (23.2% of farmers) and firewall (19.2% of farmers). In this village, 53.6% of farmers do not practice any preventive measures (Table 7).

To combat pests, farmers use curative measures such as herbicides, rodenticides, insecticides and aqueous extracts. These curative measures are specific practices that significantly discriminate the surveyed villages at 1% level. Herbicides are used by 11.6% of farmers from the village of Lokogba and rarely used by farmers of Govié village (2.2%). The most used herbicides are Kalach, Lagoon and Glycol. These are bought at the market and sprayed at a dose of 4 L ha^{-1} at least one month before sowing and flowering weeds. Farmers in Linsinlin village do not use herbicides.

Unlike herbicides, farmers in the villages use insecticides against pests. Insecticides are used by the majority of farmers of Lokogba (79.4%). These are K-Lambda Super and K-Optimal sprayed at a dose of 0.5 L ha^{-1} and the Pacha at a dose of 1 L ha^{-1}. These insecticides are purchased supplied by the extension services or CARDER. Crops receive insecticide treatment weekly for three weeks. All farmers of Linsinlin village use insecticides such as K-Lambda Super, Dimethoate and Cypercal. These insecticides are mostly purchased at CARDER and are sprayed at a dose of 0.75 L ha^{-1} in 3 to 4 times weekly applications. The treatments involved after flowering. In the, Rotenticides are used by farmers (9.4%) in the village of Govié only. The use of aqueous plant extracts to combat pests is a recommended soil conservation practice, but is observed rarely in Lokogba village only (5.2% of farmers).

DISCUSSION

Soil conservation is the prevention of soil from erosion or reduced fertility caused by overuse, acidification, salinization or other chemical soil contamination. Slash-and-burn and other unsustainable methods of subsistence farming are practiced in some less developed areas. Degradation of chemical and physical

Table 7. Crop protection practices.

Variables	Modalities	Frequency (%)			Total	Chi-square	Probability
		Govié	Lokogba	Linsinlin			
Preventive measures	No measures	20 (9.1)	3 (2.3)	57 (57.6)	80 (17.9	291.2	0.000
	Firewall	38 (17.4)	-	19 (19.2)	57 (12.8)		
	Weeding	85 (38.8)	120 (93.8)	23 (23.2)	228 (51.1)		
	Trap	57 (26.0)	-	-	57 (12.8)		
	Hunting	17 (7.8)	-	-	17 (3.8)		
	Scarecrow	-	4 (3.1)	-	4 (0.9)		
	Early harvest	2 (0.9)	1 (0.8)	-	3 (0.7)		
Plant protection measures	Herbicides	3 (2.2)	18 (11.6)	-	21 (5.4)	343.4	0.000
	Insecticides	9 (6.5)	123 (79.4)	96 (100.0)	228 (58.5)		
	Rodenticides	13 (9.4)	-	-	120 (30.8)		
	Aqueous extracts	-	8 (5.2)	-	13 (3.3)		
	No pesticides	114 (82.0)	6 (3.9)	-	8 (2.1)		

Source: Field Survey, 2013.

properties following land clearing is usually attributed to the aggressive climatic conditions, soil fragility and the rapid mineralization of organic matter, which increase losses by erosion and drainage. The high rate of soil degradation observed after land clearing is not, therefore, only caused by the accelerated erosion and leaching losses of plant nutrients. Land clearing removes biomass and leaf litter and exposes the soil.

Denudation and burning hasten the mineralization of soil organic matter. A rapid mineralization of humus, roots and surface plant debris continues even for a few years after clearing (Roose, 1986). This decline in organic matter content results in a decrease in the activities of mesofauna and microflora. Tillage causes detrimental changes in soil structure and fertility and greenhouse gas emissions (Mrabet, 2002). Intensive tillage tends to reduce soil organic matter (SOM) levels by causing oxidation of organic matter (Wood et al., 2000).

As SOM declines, soils become more compacted, less able to absorb and retain water, and more prone to water losses from evaporation and rapid run-off. Susceptibility to wind and water erosion increases, thus negatively affecting air and water quality (FAO, 2003). The number and the type of soil micro-organisms also decline, causing a reduction in the nutrient cycling and regulating services these communities provide (Millennium Ecosystem Assessment, 2005). Conservation tillage covers a range of practices which conserve soil moisture and reduce soil erosion by maintaining a minimum of 30% of the soil surface covered by residue after drilling. Generally, conservation tillage includes a shallow working depth without soil inversion, that is, no tillage or reduced or shallow tillage with tine or discs (Peigné et al., 2007). Conservation tillage leaves an organic mulch at the soil surface, which reduces run-off, increases the surface soil organic matter (SOM) promoting greater aggregate stability which restricts soil erosion (Franzluebbers, 2002). Reducing the intensity of soil tillage decreases energy consumption and the emission of carbon dioxide, while increasing carbon sequestration (Holland, 2004). The negative ecological consequences of mineral fertilizers have reached menacing proportions.

This concerns synthetic nitrogen in particular. It reduces the humus content and biodiversity in the soil, causes soil acidification and gives rise to emissions of nitrous oxide, a potent greenhouse gas causing climate change that will harm future food production. The rise in soil acidity diminishes phosphate intake by crops, raises the concentration of toxic ions in the soil, and inhibits crop growth. The depletion of humus in the soil diminishes its ability to store nutrients. Greenhouse gases derive from excess nitrogen that harms the climate (Kotschi, 2015). Chemicals (fertilizers and pesticides) in most Sub-Saharan African (SSA) countries have negative effects on human health and on the environment. In Benin there are 70 deaths in 2000 and 24 deaths in 2001, which were recorded in the cotton growing seasons due to poisonings by chemicals (IAASTD, 2009).

Risk of adverse health effects from pesticide use are often exacerbated in developing countries by poor access to information, farmers' illiteracy and unavailable or unaffordable protective equipment (Maumbe and Swinton, 2003). Knowing that farmers in the southern Benin are strongly integrated into a saving of commercial exchanges, we expected them to adopt most of the soil conservation practices that would have allowed them to maintain the level of income on increasingly small farms. But, paradoxically, this is not the case. These technologies have experienced a very low adoption rate despite the awareness of the farmers of the phenomenon of land degradation (Floquet and Mongbo, 1998). For now, these technologies suffer from a certain irrationality compared to current socioeconomic conditions of farmers and the social relations they face. Eicher and Baker (1984) report the three main obstacles to the adoption of innovative agricultural techniques: the small size of farms and plots, the too great diversity of production and the technical competence of farmers.

Conclusion

Soil conservation practices such as clearing without burning, zero tillage, incorporation of residues in soil ridging perpendicular to the slope, use of organic fertilizers, mulching, crop rotation, fallow, preventive pests control and ecological control are observed in the studies watersheds. However, the adoption of these practices is very low. In the Govié and Lokogba watershed, soil preparation activities are more conserving than degrading contrary to Linsinlin watershed. In the other farming activities such as crop management and crop protection, Govié's farmers are adopted more soil conservation practices. The rapid population growth causing land pressure, reducing the size of farms, rural exodus leading to unavailability of agricultural workforce etc. constitutes obstacles to a widespread adoption of soil conservation practices.

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Conflict of Interest

The authors have not declared any conflict of interest.

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Estimate of the least limiting water range based on relative density of an oxisol in Brazil

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The no-tillage technique has been expanding in the Brazilian Cerrado (savanna), but due to the rapid decomposition of residues and few options for profitable rotation crops, soil compaction can be a problem, seriously reducing water availability to plants. Determination of the least limiting water range (LLWR) is a sensitive method to assess the current soil compaction state, although it is operationally and economically beyond the reach of most farmers. Therefore, the aim of this study was to determine the LLWR of a highly loamy typic Oxisol (dystrophic red Latosol) and to evaluate the possibility of estimating it by using the relative bulk density (RBD), determined based on the soil compaction curve, which in comparison is a relatively fast and inexpensive method. The results showed that RBD was strongly correlated with LLWR, with coefficient of determination between 0.69 and 0.95, besides having low mean standard estimation error of at most 0.016 m^3 m^{-3} ($P < 0.0001$), making measurement of the RBD satisfactory, to estimate the LLWR. Besides this, the RBD values corresponding to $BD_{critical}$, that is, when LLWR = 0, were very near the RBD value (≈ 0.90), taken as the upper limit of physical quality for adequate plant growth. Therefore, because of the high cost and laboratory time necessary to determine the LLWR for each type of soil, a viable alternative is to use the reference value or maximum acceptable RBD limit value of 0.90 for management of soil compaction, obtained through geostatistical analyses, to ascertain the variability in the cultivated areas where RBD ≥ 0.90. In short, it is technically and economically feasible to estimate the LLWR based on the RBD.

Key words: Soil compaction curve, proctor normal test without sample reuse, no-till farming in Mato Grosso, Midwest region of Brazil.

INTRODUCTION

Farmers in the Brazilian Cerrado biome have widely adopted no-tillage techniques, mainly involving rotation of soybeans and corn, along with precision farming methods to define the use of inputs, instead of conventional management practices, which in the 1990s caused various problems associated with soil erosion and subsurface compaction (Altmann, 2010). However, no-till farming in the Cerrado region still faces problems of

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adaptation due to the rapid decomposition of residues and few economically feasible alternatives for rotation crops. These factors hinder control of surface compaction, one of the main obstacles to water availability to plants (Nawaz et al., 2013).

Several studies have described determination of the “least limiting water range” (LLWR) as a method that is sensitive and closely representative of the structural soil quality and the degree of soil compaction. This is important because to maximize crop yields, the water in the soil must be maintained at optimal levels (Collares et al., 2006; Moreira et al., 2014; Ramos et al., 2015). Furthermore, this method enables estimating the critical bulk density value ($BD_{critical}$), when the LLWR = 0, and hypothetically using it to monitor the physical soil quality (Betioli et al., 2012; Moreira et al., 2014; Safadousta et al., 2014).

However, routine use of LLWR measurement is not yet possible in Brazil, mainly for large farms and/or those employing precision agricultural techniques, where it is necessary to take a large number of samples to enable specific local correction of compaction. More important than the cost and time for sampling is the relative lack of laboratories equipped with the necessary infrastructure for testing samples. The few technically qualified laboratories that exist are either associated with universities, where research is the priority, or are privately run, with high cost for determining water retention curves, making it economically unfeasible for most farmers. This situation is unlikely to improve in the short or even medium term. Therefore, a satisfactory alternative can be the use of simpler methods to obtain one-time measures for each soil type and management method, having strong correlation with the least limiting water range. This will enable using the values obtained as references to estimate the LLWR to a sufficient degree of accuracy.

One of the laboratory techniques derived from geotechnical engineering used to reproduce compaction conditions for civil construction projects and farming operations is the Proctor test (normal or modified). It can determine the soil compaction curve quickly and inexpensively. For agronomic purposes, the importance of the compaction curve is related to determining the optimal compaction moisture, which is fast and at low cost. This allows inferring whether the soil moisture is too high for traffic of heavy machinery, because when this is the case, the bulk density and compaction can rise to unacceptable levels. The configuration of the compaction curve depends on, among other factors, the granulometry and organic carbon content. For agricultural purposes, it is recommended to determine the curve without reuse of soil samples (Ramos et al., 2013).

Therefore, because the relative bulk density, measured by the ratio between actual and maximum density through fitting, soil compaction curves can be useful to characterize compaction and the response of crops to different soil types (Hakansson and Lipiec, 2000; Suzuki et al., 2007). It was hypothesized that the LLWR can be estimated by using the relative bulk density, which can be measured quickly and inexpensively, to accelerate the mapping of compaction in agricultural areas in the Cerrado biome. To test this hypothesis, the ability to estimate the LLWR was assessed by correlation with the relative bulk density, using a highly loamy typic Oxisol (dystrophic red Latosol) under no-tillage management for 10 years.

MATERIAL AND METHODS

The study was carried out in the municipality of Diamantino (Mato Grosso State), located at 14° 07’ 40” S latitude and 56° 58’ 39” W longitude, at an altitude of 539 m. The region’s climate is Aw by the Köppen classification, with well defined seasons (dry from May to September and rainy from October to April). The average annual rainfall is 1816.9 mm, with maximum average temperature of 25.5°C and minimum of 16.2°C. The soil in the experimental field is classified as typic Oxisol (dystrophic red Latosol), moderate “A” horizon, with very loamy texture, in the semideciduous tropical forest phase, with flat relief (Santos et al., 2013). This soil class was chosen because it is the most representative of the State of Mato Grosso, Brazil.

The area was cleared in 1987 and rice was planted (1987 to 88 crop), after which soybeans and corn were rotated until the 1999 to 2000 seasons, with harrowing to a depth of 0.20 m every three years and banding fertilization. Cotton was then grown from 2000 to 01 and 2003 to 04, after which soybeans and corn were again planted in succession from the 2004 to 05 and 2013 to 14 seasons, without harrowing but with broadcast application of lime and fertilizer. The present study was conducted during the 2013 to 14 growing season, specifically on the soybean crop (*Glycine max* L.), 7639 RR Monsoy cultivar, in an experimental plot measuring ≈ 12 hectares (300 by 405 m), part of a field covering 56 ha (Table 1). The plants were cultivated with row spacing of 0.45 m and an average of 15 plants per linear meter. The seeds were sown on October 23, 2013 and the plants were harvested on February 5, 2014.

Soil samples were collected at depths of 0 to 0.10, 0.10 to 0.20, 0.20 to 0.30 and 0.30 to 0.40 m, taking into account the root depth of plants. The sampling scheme was in irregular mesh, due to the varying level curves (recently restored), oriented between the rows, with 117 sampling points for each layer. These points were geo-referenced with maximum error, vertical and horizontal, of 5 mm, determined using a Topcon Hiper® Pro global positioning device (Figure 1).

One hundred and seventeen samples was collected from each layer to have the best set of statistical equations and to determine the spatial variability of soil relative bulk density, described later. The undeformed soil samples were collected when the plants were in the R7.2 stage, using an apparatus to dig and smooth the surface, after which the undeformed samples were obtained by inserting a Kopeck device with stainless steel cylinders (50 mm in diameter by 50 mm height) in the intermediate part of the layers. The samples were collected at the stadium R7.2 in order not to hinder the transit harvesting machinery, because it took seven days to collect all samples. 5 days to the end of the sample collection, the soybeans were harvested.

In the laboratory, the samples were saturated with distilled water and submitted to different matrix potentials, with 14 repetitions (to get better statistical adjustment): 2, 6, and 10 kPa, using a sandbox

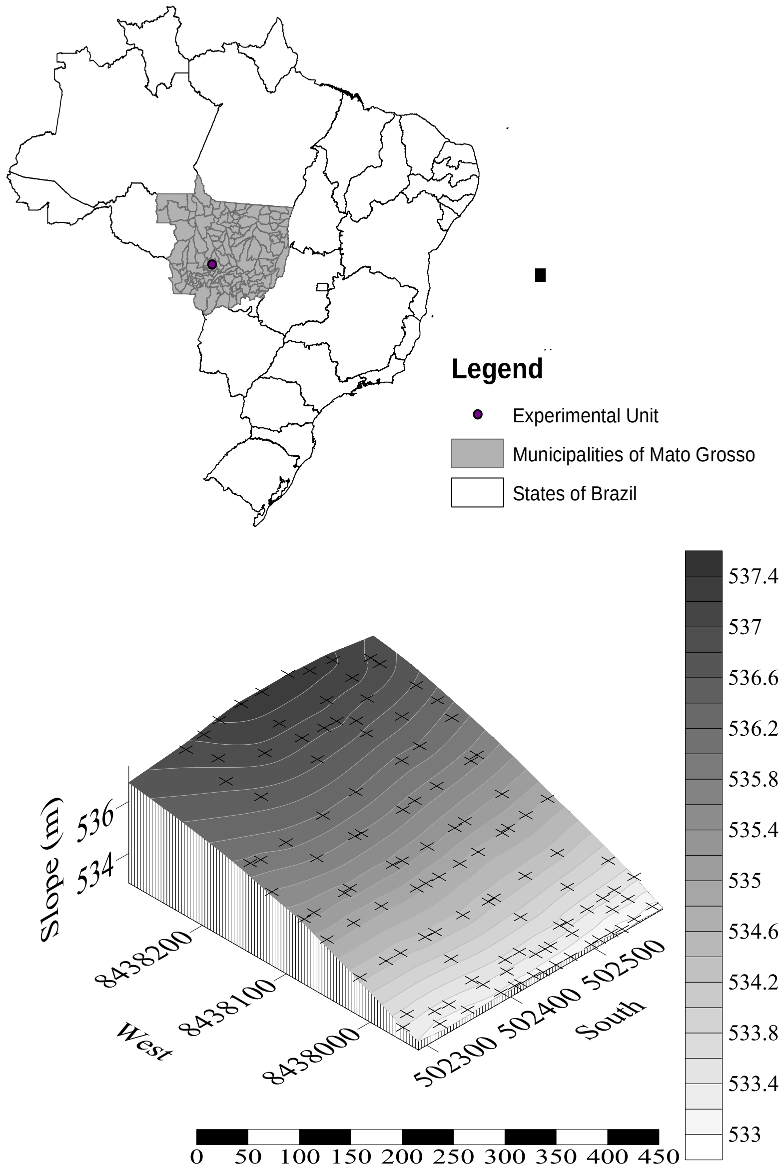

Figure 1. Location of the experimental unit and the map indicating the sampling points.

(Eijkelkamp Agrisearch Equipment model 08.01); and 33, 66, 100, 300 and 1500 kPa, using a Richards chambers (Soilmoisture Equipment Corp., model 1500F1). After the samples at each potential reached the water balance point, they were weighed and then transferred to an electronic bench penetrometer with constant penetration speed of 10 mm min^{-1} (0.167 mm s^{-1}), with a load cell having nominal capacity of 196.13 N (20 kgf), shaft with cone having diameter of 3.7407 mm and semiangle of 30°. The device was connected to a computer to record the readings (Bianchini et al., 2013). Then the samples were dried at 105°C for 48 h to calculate the bulk density (Donagema et al., 2011). These data were used to fit the water retention curve (WRC) and the mechanical penetration resistance (MPR) for each layer evaluated. The WRC was determined according to Moreira et al. (2014), using Equation 1:

$$\theta = a\Psi^{b}.Ds^{c} \quad (1)$$

Where: θ = soil water content (m^3 m^{-3}); Ψ = soil water potential (kPa); and BD = bulk density (Mg m^{-3}), with a, b and c being the estimated coefficients.

In turn, the MPR was expressed as the ratio between θ and BD, according to Moreira et al. (2014), applying Equation 2:

$$MPR = d\theta^{e}.Ds^{f} \quad (2)$$

where: MPR = the mechanical penetration resistance (MPa); and d, e and f are the estimated coefficients. The curves from equations 1 and 2 were fitted using a script programmed in the R Development

Table 1. Results of physical and chemical variables of soil horizons, sampled in the soybean R7.2 phenological stage.

Horizons	Depth (m)	Physical variables			Chemical variables [(1)]										
		Granulometry (%)			pH	P	K	Ca	Mg	Al	H	OM	SB	CEC	BS
		Sand	Silt	Clay	Water	mg dm^{-3}		.... cmo_c dm^{-3}				g dm^{-3}	cmo_c dm^{-3}		(%)
A	15	34.71	5.18	60.11	5.50	8.60	40.00	2.20	0.80	0.20	5.10	34.80	3.10	8.40	37.20
AB	27	33.21	6.85	59.94	5.30	3.50	28.00	1.30	0.50	0.30	3.50	21.30	1.90	5.70	32.90
BA	46	28.57	5.64	65.79	4.90	2.90	25.00	0.60	0.30	0.60	3.50	19.30	1.00	5.00	19.20
B1	89	27.34	4.02	68.63	5.30	3.20	36.00	0.80	0.30	0.30	2.10	10.70	1.20	3.70	32.50
B2	128	27.42	5.17	67.41	4.80	2.30	22.00	0.40	0.20	0.60	2.10	8.70	0.70	3.30	19.90
B3	157	29.88	3.65	66.47	4.90	3.50	26.00	0.20	0.20	0.70	2.10	8.20	0.50	3.20	14.50
B4	164+	29.19	4.80	66.01	4.70	2.00	18.00	0.20	0.10	0.70	2.00	7.80	0.30	3.00	11.40

[(1)] pH in $H_2O_{(L)}$ in the proportion 1: 2.5 (soil-water); P and K, extracted with solution of HCl 0,05 N and H_2SO_4 0,025N (Mehlich I); Ca, Mg and Al, extracted with solution of KCL 1 N; H, extracted with solution of calcium acetate at pH = 7; organic matter determined by the oxidation method with potassium dichromate and colorimetric determination; SB = sum of bases; CEC = cation exchange capacity; BS = base saturation (Silva, 2009).

Core Team software, version 3.0.1.

By ranking the bulk density values in increasing order, the upper limit of the LLWR was defined as the water content value related to the field capacity at water stress of 10 kPa (Silva et al., 1994), or by the aeration porosity of 10% (Silva et al., 1994), according to Equation 3:

$$\theta_{AP} = \left[(1 - \mathrm{Bd}/\mathrm{PD}) - 0{,}1\right] \quad (3)$$

Where: AP = soil aeration porosity (m^3 m^{-3}); BD = bulk density (Mg m^{-3}) (Donagema et al., 2011); and PD = average particle density: 2.40 (0 to 0.10), 2.50 (0.10 to 0.20), 2.55 (0.20 to 0.30) and 2.68 Mg m^{-3} (0.30 to 0.40 m). In turn, the lower limit of the LLWR was defined as the moisture corresponding to the permanent wilting point based on water stress of 1500 kPa (Silva et al., 1994), or mechanical penetration resistance at a limiting value of 2.0 MPa (Silva et al., 1994), using Equation 2 rewritten in the form of Equation 4:

$$\theta_{\mathrm{MPR}} = \left[\left(\mathrm{MPR}/\mathrm{d.Bd}^{\mathrm{f}}\right)^{1/\mathrm{e}}\right] \quad (4)$$

To determine the soil compaction curve without sample reuse, the dug transversal trenches was used in the experimental plot and approximately 80 kg of soil was collected, with a preservation of the natural structure of the clumps for each layer evaluated. The samples were placed in polyethylene boxes and taken to the laboratory, and the techniques described in Ramos et al. (2013) was applied. Based on the data pairs of the gravimetric moisture (GM) and bulk density (BD) the model were adjusted, that is by regression, applying a polynomial quadratic equation (BD = y0+aGM – bGM^2), where y0, b and c are the estimated coefficients. The relative bulk density (RBD) was determined according to Klein (2006) by Equation 5:

$$\mathrm{R}BD = \left(\mathrm{BD}_{\mathrm{observed}}/\mathrm{BD}_{\mathrm{maximum}}\right) \quad (5)$$

Where: $BD_{observed}$ = bulk density at the sampling point (Mg m^{-3}); and BD = maximum bulk density for each layer evaluated (because of a possible influence of the vertical variability of soil organic matter, shown in Table 1), obtained by calculating the maximum point for each compaction curve ($y_{vertex,}$ Mg m^{-3} = - (b^2 – 4ac)/4a).

The bulk density data were normally distributed according to the Shapiro-Wilk test (P > 0.05), with coefficients of variation lower than 5.83%. The accuracy of the linear regressions was evaluated by the F-test ($\alpha = 0.05$) and the coefficient of determination (R^2), using the SigmaPlot 12.5 software. Analysis and modeling of the spatial structure of the relative bulk density was carried out by the ordinary Kriging method, in 2 × 2 m squares (Yamamoto and Landin, 2013). The isotropic semivariograms were fitted using the Gamma Design GS^{+TM} version 10.0 software from Geostatistics for the Environmental Sciences.

RESULTS AND DISCUSSION

The results of fitting the data on water retention and penetration resistance explained more than 90% of the soil volumetric moisture and 76% of the penetration resistance at the 5% probability level ($\alpha = 0.05$) (Table 2). Besides this, the coefficients of the models, besides differing from zero based on the t-test, had the expected signs according to the theory, that is, the volume of water retained in the soil samples was inversely proportional to the reduction of the matrix potential and directly proportional to the increase in bulk density, while the mechanical penetration resistance was inversely proportional to rising water content and directly proportional to increasing bulk density. These results are consistent with other studies (Collares et al., 2006; Moreira et al., 2014; Ramos et al., 2015).

With increasing bulk density, the volumetric water content values at which the mechanical penetration resistance reached the critical value (θPR) occurred above all the water content values equivalent to the permanent wilting point limit (θPWP), causing a sharper reduction of the LLWR (Figure 2A to D). This stronger influence of θPR on the configuration of the LLWR has been reported for different soil classes, when native environments are converted to farming and livestock breeding uses (Betioli et al., 2012; Moreira et al., 2014;

Table 2. Equations of the water retention and mechanical penetration resistance curves for the different layers.

Layers (m)	DF	Equations[(1)]	R^2	P F-test
		Soil water retention		
0-0.10	109	θ = 0.452484***(2). │Ψ│-0.091415***. BD0.367267***	0.9262	< 0.0001
0.10-0.20	109	θ = 0.359406***. │Ψ│-0.073829***. BD0.709454***	0.9400	< 0.0001
0.20-0.30	109	θ = 0.342344***. │Ψ│-0.067328***. BD0.752035***	0.9194	< 0.0001
0.30-0.40	109	θ = 0.351184***. │Ψ│-0.068738***. BD0.695019***	0.9236	< 0.0001
		Soil mechanical penetration resistance		
0-0.10	109	MPR = 0.021079**. θ -3.411566***. BD5.497318***	0.7944	< 0.0001
0.10-0.20	109	MPR = 0.0011860*. θ -5.3030664***. BD6.4934087***	0.8418	< 0.0001
0.20-0.30	109	MPR = 0.0002144*. θ -6.3108083***. BD8.7075859***	0.8247	< 0.0001
0.30-0.40	109	MPR = 0. 0008966*. θ -5.7298635***. BD5.5783504***	0.7616	< 0.0001

[(1)] DF - degrees of freedom of the residual; *** (P < 0.0001), ** (P < 0.01), * (P < 0.05) – significant at 5% probability by the t-test; θ - volumetric moisture (m^3 m^{-3}); |Ψ| - matrix potential (kPa); BD - bulk density (Mg m^{-3}); MPR – soil mechanical penetration resistance (MPa); R^2 - coefficient of determination.

Safadousta et al., 2014).

The critical bulk density values found for the depths of 0 to 0.10, 0.10 to 0.20, 0.20 to 0.30 and 0.30 to 0.40 m were, respectively, 1.257, 1.360, 1.374 and 1.468 Mg m^{-3} (Figure 2). $BD_{critical}$ was attained with smaller bulk density values in the surface layer, although a compensating effect occurred of smaller bulk density values and increased amplitude of the LLWR (Figure 2A). According to Altmann (2010), this result can be associated with the direct and indirect benefits from the longer time to accumulate organic matter when the soil is left fallow. The accumulation possibly improved the soil structure, culminating in larger macropores in the soil under no-till farming, because based on compound analysis of the 117 sampling points, we found the following average organic matter values: 38.90 g dm^{-3} (0 to 0.10 m); 35.80 g dm^{-3} (0.10 to 0.20 m); 26.3 g dm^{-3} (0.20 to 0.30 m); and 23.4 g dm^{-3} (0.30 to 0.40 m). Furthermore, although the layer thickness were different, it was also possible to observe the decrease of soil organic matter in depth (Table 1).

With respect to the soil compaction curves, the statistical models were satisfactory because the results were significant (P < 0.05), with standard estimation error of at most 0.042 Mg m^{-3} and equality of residual variance (P > 0.05). Besides this, the bulk density values obtained with compaction of the deformed samples in the cylinder, according to the Proctor normal test, presented satisfactory explanatory power, because the coefficient of determination was higher than 78% (Table 3). The reason this was not higher might be that the soil in the present study is very plastic and sticky, as reported by Santos et al. (2013), which hindered compaction of the samples in the cylinder.

The optimal compaction moisture ($M_{optimal}$) and corresponding maximum bulk density values for each layer evaluated were 0.281 kg kg^{-1} and 1.399 Mg m^{-3} (0 to 0.10 m), 0.263 kg kg^{-1} and 1.506 Mg m^{-3} (0.10 to 0.20 m), 0.275 kg kg^{-1} and 1.496 Mg m^{-3} (0.20 to 0.30 m) and 0.274 kg kg^{-1} and 1.477 Mg m^{-3} (0.30 to 0.40 m) (Figure 3). The $M_{optimal}$ value indicates where traffic of machinery should be avoided, because the increase in water content makes the soil easier to compact. In contrast, according to Ramos et al. (2013), reduction in the water content can cause stronger coherence of the particles, making the soil less susceptible to compaction.

Based on this, it was found that the gravimetric water contents that resulted in the highest compaction density in each soil layer were approximately 5% below the volumetric moisture equivalent to the field capacity (θCC = 10 kPa) for each layer, that is, by substituting the values in the water retention equations (Table 2), the respective values of $BD_{critical}$ (Figure 2) produced corrected values for gravimetric moisture of 0.257, 0.277, 0.271 and 0.266 kg kg^{-1} for layers 0 to 0.10, 0.10 to 0.20, 0.20 to 0.30 and 0.30 to 0.40 m, respectively (Figure 3). Therefore, the water content values near field capacity indicate the maximum susceptibility of the soil to compaction. This means that determining the water content in the soil before use of heavy machinery in the field is important, because small variations in water content can cause substantial increases in bulk density.

The relative bulk density (RBD) values presented strong correlation with the LLWR, higher than 0.80 by the Pearson test. Besides this, the ability of the RBD value to explain the LLWR was satisfactory, with a coefficient of determination varying from 68 to 94%. Furthermore, the adjustments for all layers were highly significant by the F-test, with intercept and coefficient other than zero by the t-test, besides small standard estimation error of at

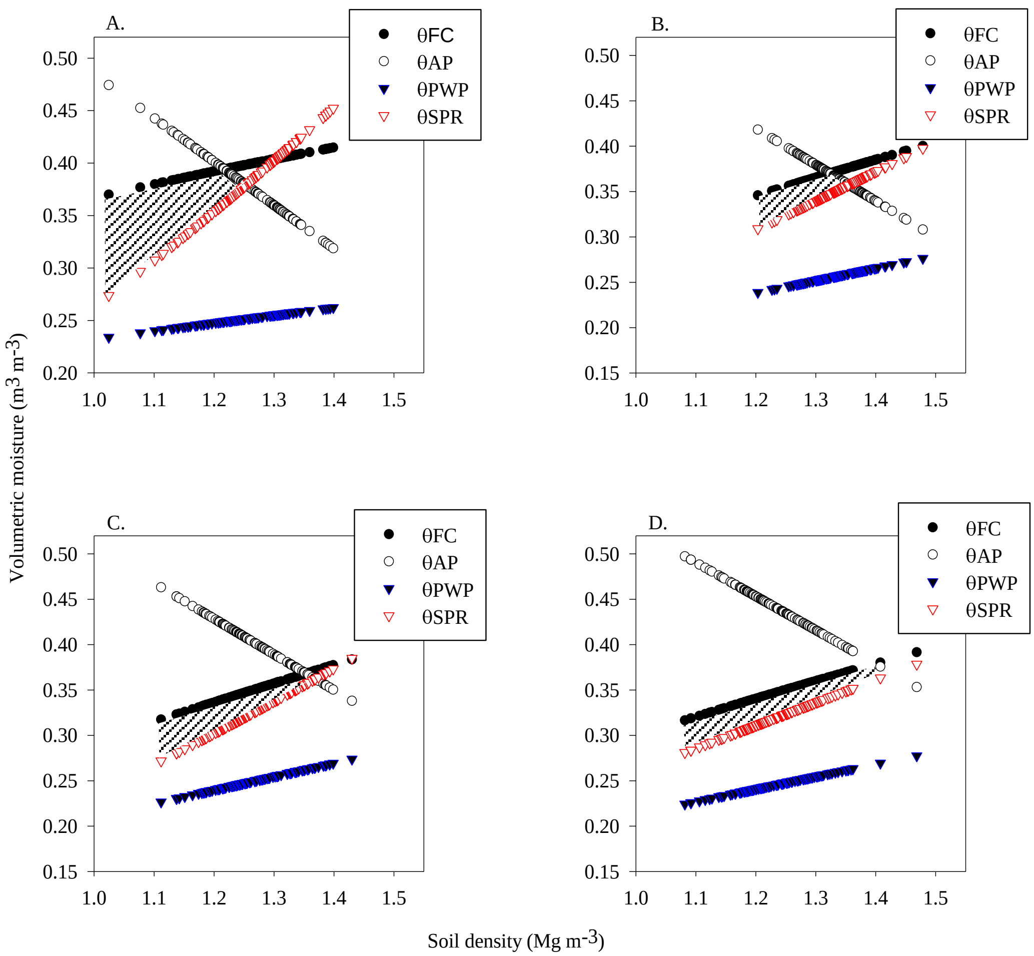

Figure 2. Volumetric moisture in function of soil bulk density at depths of 0-0.10 (A), 0.10-0.20 m (B), 0.20-0.30 m (C), 0.30-0.40 m (D), with the gray shaded area representing the LLWR, considering the limits of field capacity (θFC), aeration porosity (θAP), permanent wilting point (θPWP) and mechanical penetration resistance (θSPR).

Table 3. Results of fitting the compaction curves for each layer evaluated.

Layer (m)	Intercept	Coefficients		N (2)	r (3)	R^2 (4)	P F-test	SEE (5)	EVT (6)
	Y0 (1)	*a*	B						
0-0.10	0.046*	9.605**	-17.056**	7	0.983	0.967	0.0011	0.014	0.4383
0.10-0.20	0.646*	16.318**	-30.928**	6	0.961	0.924	0.0058	0.027	0.6602
0.20-0.30	0.506*	7.178**	-13.004**	6	0.941	0.886	0.0131	0.041	0.0735
0.30-0.40	0.025*	10.565*	-19.213*	7	0.884	0.782	0.0477	0.042	0.4907

(1) BD = y0+aUg – bUg^2; (2) N = number of data pairs; (3) r = Pearson's coefficient; (4) R^2 = coefficient of determination; (5) SEE = standard estimation error (Mg m^{-3}); (6) EVT = equality of residual variance test by Spearman correlation (P > 0.05). Remarks: ** (p < 0.01), * (P < 0.05), ns = not significant (P > 0.05) by the t-test.

most 0.017 m^3 m^{-3} (Table 4). However, the occurrence of independent residual error appeared to depend on something not controllable, namely the intersection of the curves that configure the LLWR. In other words, when the data pairs are discontinuous (Figure 4A), there appears to be a higher probability that the variance test will not

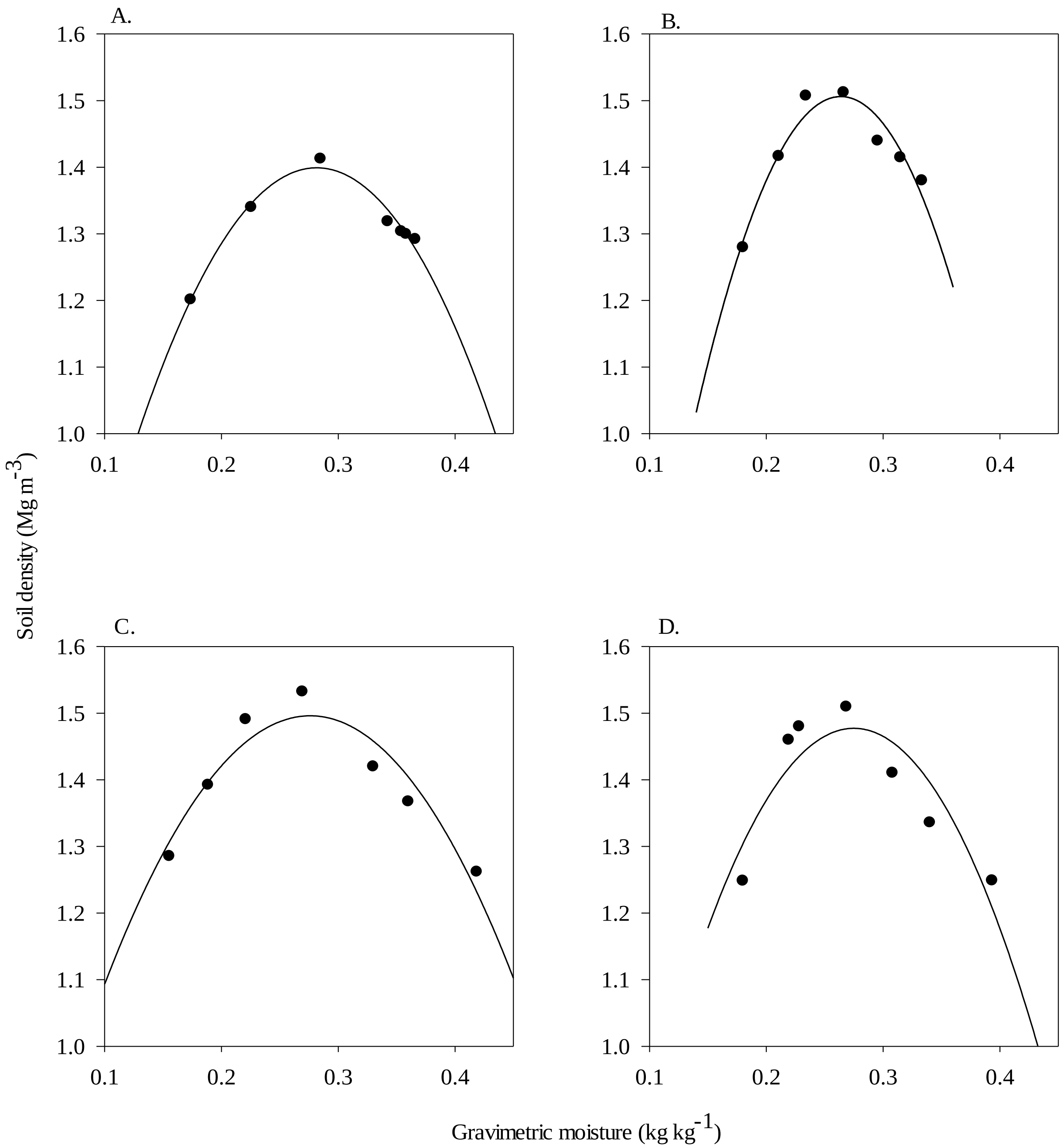

Figure 3. Compaction curves obtained by the Proctor normal test, without sample reuse, for depths of 0-0.10 (A), 0.10-0.20 (B), 0.20-0.30 (C) and 0.30-0.40 m (D).

indicate residual equality.

The ratios between RBD and $BD_{critical}$ for the four soil layers were 0.913 (0 to 0.10 m, Figure 4A), 0.903 (0.10 to 0.20 m, Figure 4B), 0.918 (0.20 to 0.30 m, Figure 4C) and 0.953 (0.30 to 0.40 m, Figure 4D). According to the literature, the interval of values considered ideal for optimal soybean crop yield vary between 0.82 and 0.91 (Hakansson and Lipiec, 2000; Beutler et al., 2005; Suzuki et al., 2007; Betioli et al., 2012). Therefore, the values of RBD = $BD_{critical}$ (LLWR = 0) found in this study (Figure 4) were approximately in line with the ideal maximum limit for plant development found in the literature. Therefore, it would be technically practical to use a reference value of RBD = 0.90 to monitor the compaction of any agricultural soil, since RBD values greater than 0.90 are not ideal for plant growth. This would make it unnecessary to

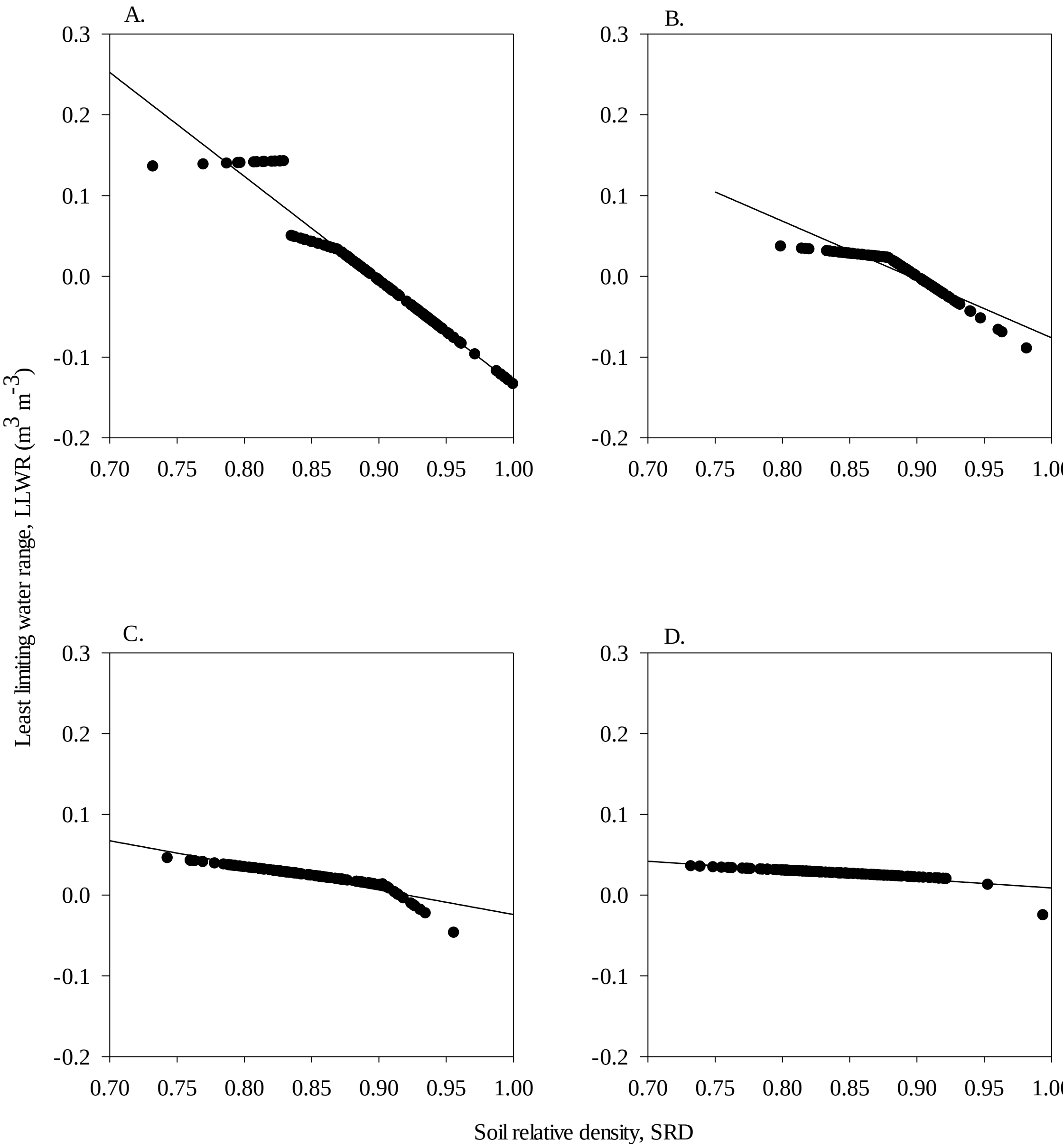

Figure 4. Linear fit of least limiting water range versus relative bulk density for the layers 0-0.10 (A), 0.10-0.20 (B), 0.20-0.30 (C) and 0.30-0.40 m (D).

determine the LLWR for each type of soil, because it would be sufficient to estimate the RBD value and use 0.90 as the upper threshold. However, it is important to standardize the method for determining the compaction curve to obtain the maximum soil density, preferably without reuse of samples for considering the soil structure, as urged by Ramos et al. (2013).

In this study, the proportion of the BD or RBD values ≥ $BD_{critical}$ (LLWR = 0) for the depths of 0.20 to 0.30 m and 0.30 to 0.40 m were, respectively, only 8 and 2% of the 117 samples collected. In contrast, for the 0 to 0.10 and 0.10 to 0.20 m layers, 50 and 34%, and of the values were above the $BD_{critical}$. Since soil management typically occurs in the topmost layer, and the best estimates of the LLWR by using the RBD were provided by the 0 to 0.10 and 0.10 to 0.20 m layers, special attention should be paid to these two layers. Based on these findings, since the LLWR was satisfactorily estimated by the RBD, our hypothesis can be accepted, meaning that the variability in space of the RBD can help support decisions on actions to prevent soil compaction, making it a useful technique for farmers using precision techniques for

Table 4. Results of the regression between LLWR and relative bulk density (RBD).

Layer (m)	Intercept	Coefficient	N [(2)]	r [(3)]	R^{2} [(4)]	P F-test	SEE [(5)]	EVT [(6)]
	y0 [(1)]	*A*						
0-0.10	1.152***	-1.286***	117	0.972	0.946	<0.0001	0.016	<0.0001
0.10-0.20	0.646***	-0.722***	117	0.937	0.877	<0.0001	0.009	0.0567
0.20-0.30	0.280***	-0.304***	117	0.919	0.845	<0.0001	0.006	0.0654
0.30-0.40	0.119***	-0.110***	117	0.830	0.689	<0.0001	0.003	0.0571

(1) LLWR = y0 + aRBD; (2) N = number of data pairs used in the fit; (3) r = Pearson's coefficient (P < 0.0001); (4) R^2 = coefficient of determination; (5) SEE = standard estimation error (Mg m^{-3}); (6) EVT = equality of residual variance test by Spearman correlation (P > 0.05). Remarks: *** (P < 0.0001) by the t-test.

Table 5. Parameters obtained in fitting the relative bulk density per layer.

Layer (m)	Parameters [(1)]							SWT [(2)]
	Model	N	R^2	C_o	$C_o + C$	$C/C_o + C$	*A*	
0-0.10	Exponential	113	0.812	0.0003	0.0022	0.873	53.7000	0.216
0.10-0.20	Exponential	111	0.832	0.0001	0.0009	0.894	67.5000	0.978
0.20-0.30	Exponential	112	0.771	0.0000289	0.0017	0.983	21.9000	0.416
0.30-0.40	Exponential	112	0.915	0.0003	0.0021	0.835	70.2000	0.626

(1) R^2 = coefficient of determination, C_O = nugget effect, C = level, A = range (m); (2) SWT = Shapiro-Wilk test of normality of the RBD values (P > 0.05).

Table 6. Cross-validation by interpolation (Kriging) of the relative bulk density.

Layer (m)	Intercept	Coefficient	r	R2	SEE(1)	F-test probability	EVT(2)
	y0	*a*					
0-0.10	0.778***	0.133***	0.350	0.122	0.016	0.0002	0.7571
0.10-0.20	0.646***	0.269***	0.517	0.267	0.014	<0.0001	0.0957
0.20-0.30	0.738***	0.133**	0.332	0.110	0.016	0.0003	0.0518
0.30-0.40	0.751***	0.104**	0.311	0.097	0.014	0.0008	0.1748

1 SEE = standard estimation error (Mg dm^{-3}); 2 EVT = equality of residual variance test by Spearman correlation (P > 0.05). Remarks: *** (P < 0.0001) = significant by the t-test.

localized correction of soil compaction. The results also indicate that exponential isotropic semivariograms explained from 77 to 91% of the RBD, with lower range value in the 0.20 to 0.30 m layer, showing smaller spatial homogeneity. Nevertheless, all the layers evaluated presented high spatial dependence, demonstrating the data are not random, based on the value of $C/C_o + C$ near 1.0 (Table 5).

Next the cross-validation of the observed and estimated data was analyzed by Kriging. The majority of published works do not provide the result of this validation. Although the coefficients of determination of the fitted semivariograms were high, that is, greater than 0.771 (Table 5), with the cross-validation test we obtained weak explanation ($R^2 < 0.30$) and moderate linearity (0.30 < r < 0.50), although with standard estimation error of at most 0.016 for the RBD value. Additionally, the models' results were significant for the layers evaluated (P < 0.05 by the F-test) (Table 6). Therefore, it is essential to analyze the semivariogram along with the cross-validation results, because it is possible for the coefficient of determination to be high in the semivariogram, but with error probability greater than 5% (α = 0.05) by the F-test in the cross-validation, thus invalidating the fitted semivariogram.

In this study, since the linear regressions were significant at probability of 5% (α = 0.05) by the F-test, the models were accepted. Therefore, we generated the maps of spatial variability of the RBD values for the layers evaluated based on data interpolation by Kriging at

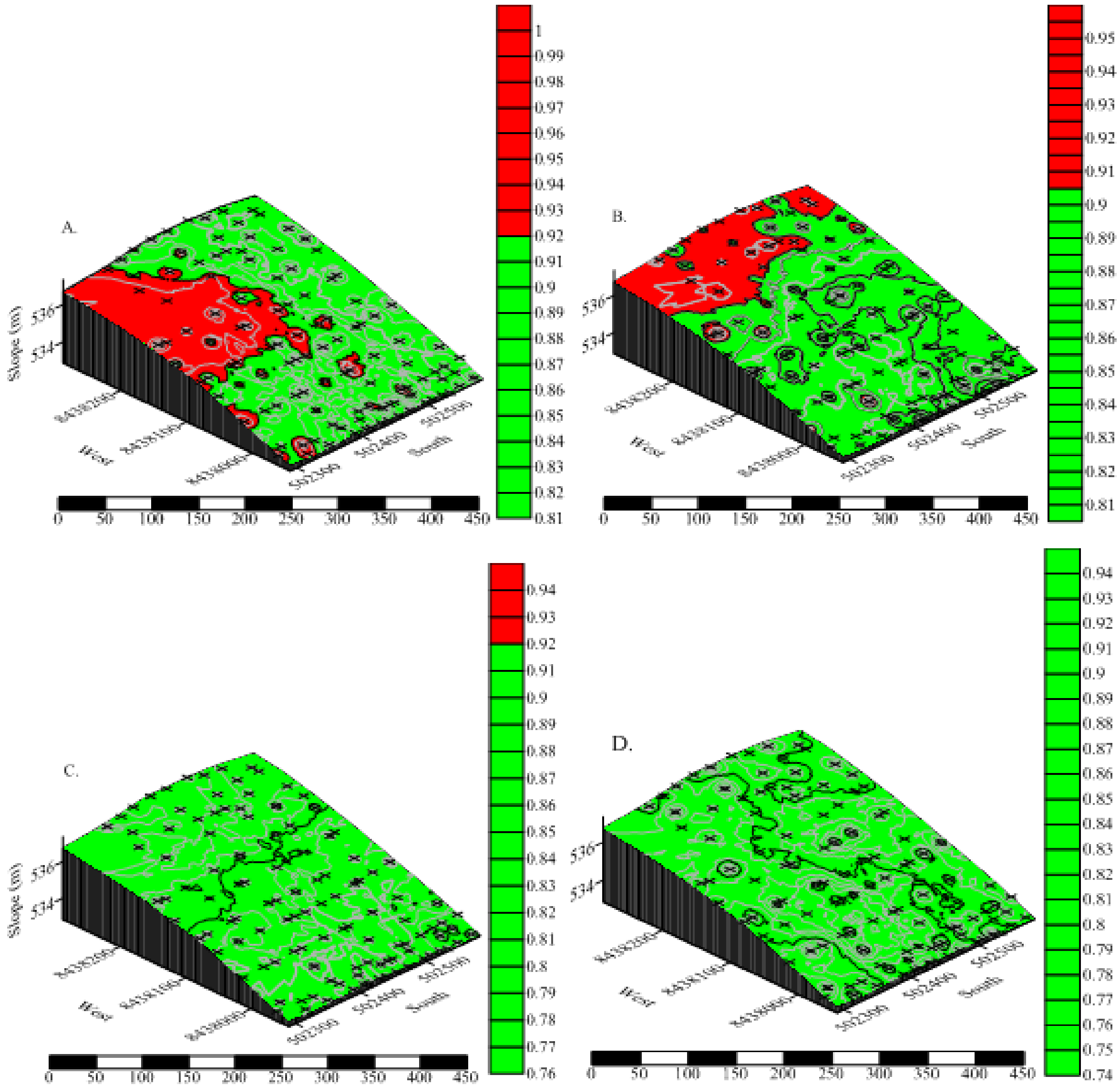

Figure 5. Maps of the relative bulk density at depths of 0-0.10 (A), 0.10-0.20 (B), 0.20-0.30 m (C) and 0.30-0.40 m (D). Remarks: The crosses on the maps indicate the sampling points.

regular intervals of 1.0 by 1.0 m, considering the limits of the RBD values (Figure 4), that is, when LLWR = 0 (Figure 5).

It can be seen that the area with RBD values ≥ 0.913 was greater in the surface layer and concentrated to the west, and in the 0.10 to 0.20 m layer to the north. In the 0.20 to 0.30 m layer, although the legend shows the presence of RBD ≥ 0.918, the locations of these values coincide with the sampling points. This means a sub-area for specific management was not created, because of the low number of RBD values ≥ 0.918, but if RBD values < 0.918 were chosen, sub-areas in red would appear, that is, a cutoff limit on the map. For this reason, it is important to define this limit to know whether or not it is financially sound to carry out localized soil compaction correction.

The number of samples collected in this study, 117, to cover a small area of approximately 12 ha, was in line with the sampling density recommended by Yamamoto and Landin (2013), of at least 100 observations for a first study in any area. In the deepest layer (0.30 to 0.40 m) we did not observe RBD values > 0.953, because although this occurred according to Figure 4, when the LLWR = 0, it was necessary to remove a small percentage of the data (under 5%) to improve the fit of the semivariogram, a valid procedure according to

Yamamoto and Landin (2013). In light of this, for future studies using the RBD to monitor the variability of compaction, we recommend distance between sampling points of between 21 and 70 m (Table 5), preferably arranged in a regular grid, which was not possible here. According to Yamamoto and Landin (2013), a regular arrangement of sampling points can improve the semivariogram fit, the cross-validation and the quality of the data interpolation, and consequently the configuration of the final map.

CONCLUSIONS

1. The relative bulk density (RBD) was strongly correlated with the least limiting water range (LLWR), so the ability of the RDB to explain the LLWR was satisfactory, presenting a coefficient of determination between 0.69 and 0.95, besides having a low standard estimation error, of at most 0.016 m^3 m^{-3}, which corresponds to only 3.1% to the total soil porosity, and a highly significant fit ($P < 0.0001$).
2. Besides this, the RBD values found corresponding to $BD_{critical}$, that is, when LLWR = 0, were very near RBD ≈ 0.90, taken as the upper limit for physical quality for adequate plant growth reported in the literature. Therefore, because of the high cost and laboratory time necessary to determine the LLWR for each type of soil, a viable alternative is to use the reference value or maximum acceptable RBD limit of 0.90 for management of soil compaction, obtained through geostatistical analysis, to ascertain the variability in the cultivated areas where RBD ≥ 0.90. In short, it is technically and economically feasible to estimate the LLWR based on the RBD, although it is important to standardize the method for determining the compaction curve to obtain the maximum soil density, preferably without reuse of samples to consider the soil structure.

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Conflict of interests

The authors have not declared any conflict of interest

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Full Length Research Paper

Systemicity of banana bunchy top viral infection in the Kisangani region of the Democratic Republic of Congo

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In order to evaluate the systemicity of BBTV from one plant of the mat to the physically attached shoots, 60 mats both of "Yangambi Km5", *Musa* AAA and those of the false horn plantain "Libanga Likale", *Musa* AAB showing severity levels from 0 to 5 were selected in backyards in Kisangani. In addition, 30 sucker corms per genotype were put under macro-propagation and leaf samples of lateral shoots that had emerged were tested using triple antibody sandwich-enzyme linked immuno sorbent assay (TAS-ELISA). In the backyards, for mats with no visible banana bunchy top disease (BBTD) symptoms, none of the analyzed mats with a total of 29 plants of "Yangambi Km5" and of 35 plants of "Libanga Likale" tested ELISA positive, indicating the absence of the BBTV infection. However, for the severity levels of one to five, 32 to 63.5% of plants in the mats were ELISA positive for "Yangambi Km5", while 34.9 to 73.2% of plants from "Libanga Likale" tested positive for BBTV. After macro-propagation, 100% of lateral shoots of both cultivars at BBTD severity levels 4 and 5 tested positive. On the other hand, none of the lateral shoots at level 0 tested ELISA positive. However, for levels 1 to 3 some ELISA negative plantlets (40 to 23% for "Yangambi Km5" and 53 to 15% for "Libanga Likale") were observed. This study indicates the need for the complete destruction of all mats harbouring plants with BBTD severity levels of 3, 4 and 5. Macro-propagation of suckers with severity level 1 symptoms could produce virus-free plantlets but ELISA testing of the lateral shoots is essential to pinpoint the virus-free plantlets.

Key words: Banana bunchy top viral infection (BBTV), macro-propagation, mat, systemicity, triple antibody sandwich-enzyme linked immuno sorbent assay (TAS-ELISA).

INTRODUCTION

Banana bunchy top disease (BBTD) caused by the banana bunchy top virus (BBTV) is one of the most damaging banana diseases in affected tropical regions of Africa, Asia and the Pacific. Potential yield losses of 90 to 100%, especially with 'Cavendish' subgroup of the AAA cultivar group (AAA), have been reported in both

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small-scale farms and in large commercial plantations (Moffat, 2001). The history of the spread of the disease in Africa has been described by Blomme et al. (2013).

Currently, the impact of BBTD has been felt in 15 African countries: Egypt (first recorded in 1901), the Democratic Republic of Congo (DR Congo) (1958), Eritrea (1964), Gabon, Congo-Brazzaville and Equatorial Guinea (1982), Burundi and Rwanda (1987), Malawi, Angola, Cameroon, Central African Republic and Zambia (1990), Benin (before 2011), and Nigeria (2012) (Fahmy, 1927; Wardlaw, 1961; Saverio, 1964; Fouré and Manser, 1982; Sebasigari and Stover, 1988; Pillay et al., 2005; Kumar and Hanna, 2008; Kumar et al., 2011; Blomme et al., 2013; Kumar et al., 2015). In the DR Congo, BBTD has been reported in all 11 provinces (Kumar et al., 2011; Ngama et al., 2014). In DR Congo, BBTD was first identified in the 1950s at the Institut National pour l'Etude et la Recherche Agronomique du Congo Belge (INEAC), Yangambi research station (Kumar et al., 2011) and has since spread to all 11 provinces (Ngama et al., 2014; Mukwa et al., 2014). Disease severity is however low, and only a minority of mats (10%) exhibit the severity levels 4 and 5 characterized by the typical bunchy top aspect of the plant (Ngama *et al.*, 2014). In eastern DR Congo and the Congo basin, the disease seems not to affect mats which includes the fruit-bearing mother plant, its suckers and the underground rhizome in a rapid and systemic way, though one lateral shoot after another do get affected in diseased mats (Walangululu et al., 2010).

Generally, viral diseases are considered systemic, except in the meristematic apex tissues which can be, according to species, free of virus (Thomas et al., 1994). BBTV can be transmitted through the use of vegetative planting material including suckers and *in vitro*-derived plantlets. Generally, when a parent plant is infected, it is considered that all the physically attached suckers (that is, lateral shoots) will be infected (Gregory et al., 1995). The infections result in a range of symptoms, starting with streaks on the leaf lamina, petioles and midribs, progressing to partial leaf chlorosis, leaf dwarfing and necrosis (Caruana, 2003). Precise identification of the disease at the initial stages (that is, streaks or slight to be backed up with an immuno-enzymological test triple discolorations on the leaves) is often difficult and needs antibody sandwich-enzyme linked immuno sorbent assay (TAS-ELISA) (Hu et al., 2007). It is therefore recommended to destroy the entire banana mat when one plant on it shows BBTD symptoms at any level of severity (Ferreira et al., 1989; Thomas and Dietzgen, 1991). However, very few scientific papers or reports describing BBTV systemicity, are currently available.

The aim of this study was to assess the systemicity of the transmission of BBTV from parent plants to physically attached lateral shoots, taking into account various initial disease severity levels of the parent plant, to elucidate the level of systemicity in banana mats, and to verify if some of the attached lateral shoots could possibly escape the virus. The results of these studies could guide control strategies for fighting BBTD in a region where people find it difficult to destroy a complete mat (and often very large mats) when only one or a few plants are visibly infected.

MATERIALS AND METHODS

This study was conducted in Kisangani, Oriental Province, DR Congo. The city is located near the Equator and experiences a continental equatorial climate of Köppen Af classification (Bultot, 1950, 1977). The mean temperature is relatively high (23.5 to 25.3°C) and the mean annual precipitation is about 1,728 mm, with a minimum of 1,417 mm and a maximum of 1,975 mm. Relative humidity is about 82% (www.accuweather.com). The studies were conducted on diseased mats grown in backyards in Kisangani town and using infected corms which were put into macro propagation. The city is entirely located in the bioclimatic zone of ombrophile dense forest. The experimental site was located at an altitude of 409 m above sea level, at latitude 0°30'41.4'' N and longitude 25°12'24.2'' E. The study was conducted from September, 2013 to September, 2014.

Unmanaged mats (that is, a cluster of physically interconnected/attached plants) can have a very large number of plants, comprising fruit baring plants, flowering plants and plants at various stages of vegetative development. For example, from 10 to 20 plants can be counted on un-managed mats of the 'Yangambi Km5' cultivar. Each larger plant in a mat will have one or more lateral shoots.

To evaluate the systemicity of BBTV from one plant of the mat to the physically attached shoots, 60 mats (30 mats of 'Yangambi Km5', *Musa* AAA and 30 mats of the False Horn plantain 'Libanga Likale', *Musa* AAB cultivars) comprising a total of 530 plants, showing severity levels from 0 to 5, were selected in backyards in Kisangani town (Table 1) (level 0: no symptoms, 1: dark green streaks on the leaf lamina, 2: dark green streaks on the leaf midribs and petiole, 3: marginal chlorosis of the leaf margin, 4: reduction in leaf size/dwarfing of leaves and 5: bunchy top appearance). Visual observations were made on all plants per mat to determine the highest severity level of the disease in the population of plants on a mat and the severity level of the other plants in the mat. For instance, a mat containing a plant with highest severity level 5 could bear plants with levels 4, 3, 2, 1 and 0, while a mat containing a plant with highest severity level 4 could bear plants with severity levels 3, 2, 1 and 0. The immuno-enzymological status of all plants in a mat was then tested using TAS-ELISA.

In addition, five sucker corms for each of the two cultivars (as aforementioned) and for each of the BBTD severity levels 0, 1, 2, 3, 4 and 5 were put in macro-propagation in a screen house after removal of their apical meristem. The screen house was devoid of aphids. Before screen house establishment, all suckers were tested using TAS-ELISA and were confirmed as positive, except for the 0 level suckers where ELISA results were negative. A total of 30 suckers were thus used for each genotype. All plants were allowed to grow until progenies (lateral shoots) had developed at least one expanded leaf. Samples from the expanded leaf were used to assess the presence of BBTV in the lateral shoots using the TAS-ELISA AgdiaBioford ELISA reagent kit. A total of 216 leaf samples were analyzed (Table 3). The TAS-ELISA method used involved BBTV extraction from the leaves, incubation and addition of monoclonal antibody and antibody coupled to alkaline phosphatase B in the presence of positive and negative BBTV controls

Table 1. Number of plants that tested positive with TAS-ELISA according to the highest severity level observed on a plant in a mat. Mats were assessed in home gardens in Kisangani town, Oriental province, DR Congo.

Cultivar	Highest severity level observed in a mat #	Total number of plants	Number of plants that tested positive with ELISA	% of ELISA positive plants
'Yangambi Km5' (*Musa* AAA)	0	29	0	0
	1	46	15	32
	2	55	23	41.8
	3	32	11	34.4
	4	28	17	60.7
	5	52	33	63.5
'Libanga Likale'(*Musa* AAB)	0	35	0	0
	1	43	15	34.9
	2	37	24	64.9
	3	65	29	44.6
	4	56	41	73.2
	5	52	32	61.5

#: 0: no symptoms, 1: dark green streaks on the leaf lamina, 2: dark green streaks on the leaf midribs and petiole, 3: marginal leaf chlorosis of the leaf margin, 4: reduction in leaf size/dwarfing of leaves and 5: bunchy top appearance

(Sastry et al., 1980; Soweha, 2005).

RESULTS

For mats assessed in the backyards, none of 29 plants analyzed of the 242 plants in the 30 mats of 'Yangambi Km5' and 35 plants of the 288 plants from 30 mats of 'Libanga Likale' with no visible BBTD symptoms tested ELISA positive, indicating the absence of BBTV infection (Table 1). However, for the severity levels one to five, 32 to 63.5% of plants in the mats were ELISA positive for 'Yangambi Km5', while 34.9 to 73.2% of plants tested positive for 'Libanga Likale'. When looking at plants with similar severity levels across all assessed mats, for severity levels one to five, 100% of plants of 'Yangambi Km5' with BBTD symptoms tested positive for BBTV infection, while none of the 143 plants without BBTD symptoms tested positive (Table 2). For 'Libanga Likale', the situation was a little different, with some variations observed for level 1 (54% ELISA positive plants) and level 3 (86% ELISA positive plants). Plants of other severity levels (2, 4 and 5) had 100% positive scores, while none the 100 symptomless plants tested positive.

After macro-propagation 100% of lateral shoots derived from parent plants of both cultivars, at BBTD severity levels 4 and 5, tested positive (Table 3). On the other hand, and for both cultivars, none of the lateral shoots at level 0 tested ELISA positive. However, for levels one to three some ELISA negative plantlets (23 to 40% for 'Yangambi km5' and 15 to 53% for 'Libanga Likale') were observed. There was a clear positive relationship between the BBTD severity level of the parent plant and the proportion of lateral shoots showing positive ELISA tests (Figure 1).

DISCUSSION

In the home backyard gardens, a tendency for a higher percentage of BBTV infected plants was observed with an increase in highest severity level observed within a mat. These results hint at a systemic transmission *in situ*, especially visible at higher BBTD severity levels, although some transmission could have occurred via aphids.

Concerning macro-propagation, all the lateral shoots of ELISA positive parent plants of both genotypes at severity levels four and five were infected, indicating a truly systemic infection. Few lateral shoots from severity level 1 to3 (23 to 40% for 'Yangambi km5' and 15 to 53% for 'Libanga Likale') were ELISA negative, that is, virus free. It is however very clear that the infection was systemic (as the trial was conducted in the absence of aphids) and the few remaining clean suckers, if left on the mother plants would possibly also become infected in a systemic way.

The results presented here have important implications: the need for the complete destruction of all mats harbouring plants expressing disease severity levels 3, 4 and 5. However, for mats containing only a few plants that show severity levels 1 or 2 (mild symptoms that have not been reported as affecting plant growth or yield), an

Table 2. Total number of TAS-ELISA positive plants in the mats according to the severity level observed on the plant. Mats were assessed in home gardens in Kisangani town, Oriental province, DR Congo.

Cultivar	Severity level observed on the plants[#]	Total number of plants	Number of plants that tested positive with ELISA	% of ELISA positive plants
'Yangambi Km5' (*Musa* AAA)	0	143	0	0
	1	36	36	100
	2	17	17	100
	3	19	19	100
	4	13	13	100
	5	14	14	100
Total		242	99	40.9
'Libanga Likale'(*Musa* AAB)	0	100	0	0
	1	92	50	54.3
	2	36	36	100
	3	35	30	85.7
	4	17	17	100
	5	8	8	100
Total		288	141	49
Overall total		530	240	45.3

[#]: 0: no symptoms, 1: dark green streaks on the leaf lamina, 2: dark green streaks on the leaf midribs and petiole, 3: marginal leaf chlorosis of the leaf margin, 4: reduction in leaf size/dwarfing of leaves and 5: bunchy top appearance.

Table 3. Number of suckers that tested positive for BBTV according to disease severity level of the parentplant/corm in macro-propagation.

Cultivar	Parent plant severity level[#]	N° of emerged lateral shoots	N° of emerged lateral shoots that were ELISA positive	% of ELISA positive emerged lateral shoots
'Yangambi Km5' (*Musa* AAA)	0	16	0	0
	1	15	9	60
	2	19	14	74
	3	13	10	77
	4	25	25	100
	5	15	15	100
Total		103	73	70.9
'Libanga Likale' (*Musa* AAB)	0	16	0	0
	1	17	8	47
	2	17	13	77
	3	26	22	85
	4	24	24	100
	5	13	13	100
Total		113	80	70.8
Overall Total		216	153	70.8

[#]**:** 0: no symptoms, 1: dark green streaks on the leaf lamina, 2: dark green streaks on the leaf midribs and petiole, 3: marginal leaf chlorosis of the leaf margin, 4: reduction in leaf size/dwarfing of leaves and 5: bunchy top appearance.

option could be to only remove these mats if or when more advanced symptoms appear. It was observed that plants with severity levels 1 or 2 still produce harvestable bunches. Macro-propagation of suckers with severity level 1 symptoms could be envisaged for the production of virus-free plantlets as 40 to 50% of lateral shoots on these corms were temporarily observed to be virus free. TAS-ELISA testing of the lateral shoots would however be required to identify the virus-free plantlets.

The results from both the backyard and macro-propagation studies strongly hint at a complete systemic movement of the BBTV and are in accordance with

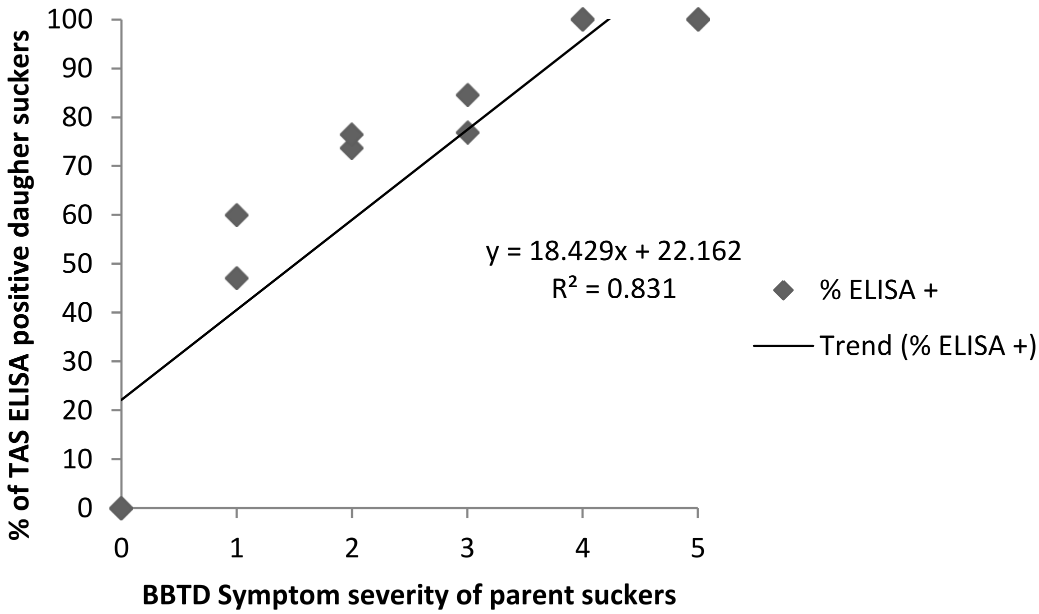

Figure 1. The relationship between the severity level of the parent suckers (source of corms) and the frequency of ELISA positive laterally emerged shoots after macro-propagation.

reports from Magee (1927), Ferreira et al. (1989), Thomas and Dietzgen (1991) and Gregory et al. (1995).

Conflict of interests

The authors have not declared any conflict of interest

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Impact of resettlement on vegetation status and rangeland condition in southwestern Ethiopia

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This study was conducted with the objectives of comparing range condition of an area under different land use practices (resettled and non-resettled) and assessing the possible effect of resettlement on range condition in Meinit-Shasha district of Bench-Maji zone, southwest Ethiopia. Two kebeles were selected purposively where vegetation and soil conditions were investigated in 40 quadrats across 20 sampling sites using 20 × 20 m (400 m^2) quadrat, which was distributed along transects. The investigation included the assessment of grass composition, basal cover, litter cover; age distribution of dominant grasses, number of seedlings and soil conditions (erosion and compaction), which were investigated on 1 × 1 m (1 m^2) area. Data from range vegetation survey was analyzed using SAS software. The study results showed significant differences ($P < 0.05$) between kebeles in terms of grass composition, basal cover, number of seedling and soil condition. The total score for range condition rating showed that the resettled kebele was in the category of poor range condition, whereas the non-resettled was in fair condition. Expansion of crop cultivation and the establishment of permanent settlements as a result of resettlement program were considered to be the main contributing factors to the reduction of grazing lands and poor range condition scores in the resettled kebele. The study showed a higher level of degradation in the resettled kebele than non-resettled kebele. Generally, the results of this study indicated that unplanned resettlement program had a negative influence on rangeland vegetation dynamics. Cautious planning and implementation of resettlement programs in recognition of differences in land use between the host communities and resettlers is suggested. Securing inhabitants' land tenure would facilitate the recovery of rangeland vegetation and conservation of biodiversity.

Key words: Resettlement, rangeland condition, land use.

INTRODUCTION

Forced by natural disasters and increased frequency of food crisis, people in many parts of rural Ethiopia have relatively remained deprived (Brown and Amdissa, 2007). In response to the vulgarity of climate change and resultant poverty, resettlements of people to various habitable localities has been implemented as a development

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strategy by successive regimes in Ethiopia with the aim of alleviating poverty and securing food self-sufficiency. As in the case in many developing nations, resettlement has been becoming a dominant development discourse in Ethiopia since the middle of the last century (Belay et al., 2005; Asrat, 2006).

For example, in Bench-Maji and Kaffa zones, massive state-sponsored resettlements have been ongoing since the 1980s (BoA, 2009). Both the past and present resettlement programs have been focused on and implemented predominantly in the lowland areas of the country where population densities are expected to be low and unutilized lands are assumed to be found. However, the lowland areas in Ethiopia including the Bench-Maji and Kaffa zones are usually inhabited by pastoralists and agro-pastoralists, which are still subsistence-oriented where local livelihoods largely depend on extensive livestock production. Generally, the pastoral and agro-pastoral communities in the study areas largely depend on rangeland vegetation and water resources for their livestock. On the other hand, resettlement in the study area has been carried out without considering the potential land use impacts on the local environmental and people's livelihood. Moreover, resettlement programs have been ongoing in pastoral areas with no justification and evidence on the transformation of traditional land use practices despite the ecological potentials of the area. This has also been done with little attention on the follow up of impact assessment on natural resources and communities' way of life. In conjunction with this, there is a gap with regard to land use policy in the country and appropriate development intervention strategies for pastoralists. Most studies in the past were only focused on the socio-economic status of resettlers and their new environment, while impacts on the environment of the host community, their local resources base and livelihoods received little research attention (Wolde-Silassie, 2002; Elizabeth, 2003; Asrat, 2006). The high level of interest in resettlement of rural communities in pastoral areas has greatly affected the historical natural resource and biodiversity of most resettled regions in the country (Elizabeth, 2003; Asrat, 2006). Despite the potential environmental and socio-economic effects of resettlement on the host community, little attention has been given in evaluating the environmental impact of resettlement and status of rangeland vegetation as a follow up of resettlement programs. More focus on securing food self-sufficiency of the new settlers might have contributed to severe environmental degradation and deterioration of pastoral land use. Although resettlement programs may temporarily improve the food security problems of resettlers, the ongoing massive state-sponsored resettlement programs have a tendency to cause intended and long-term environmental consequences, which in turn accelerate vulnerability of pastoralists to the impact of climate change and food insecurity. Consequences of resettling farmers in pastoral areas where the type of land use is mostly suitable for extensive livestock production is likely to cause environmental changes thereby creating crisis on sustainable land use and the future of pastoralism. Thus, if food self-sufficiency of resettlers is to be improved, it should be redesigned in such a way to match with the local land use practices to minimize impacts on rangeland biodiversity. A study on the environmental impact of resettlement in pastoral areas and its implication on land use changes, resource utilization and local livelihoods would be useful to realize how resettlements of people could influence the status of rangeland vegetation. Our objective was to assess the effect of resettlement on rangeland condition in relation to different land use practices. Generally, we raised the following research questions: (i) Does resettlement in southwest Ethiopia in its current form have a negative effect on rangeland vegetation?; (ii) What are the impacts of resettlement in terms of land use change on the fragile lowland ecology in terms of change in range vegetation condition?; (iii) How important is changing land use practices which affect vegetation condition in the area?

MATERIALS AND METHODS

Study area

The study was conducted in Meinit-Shasha district of Bench-Maji zone, which is situated in the Southern Nations Nationalities and Peoples' Region (SNNPR) of Ethiopia (Figure 1). Bench-Maji zone comprised of ten districts, five of which are inhibited by pastoral and agro-pastoral communities and the other five are inhabited by agricultural communities and it include Bench, Sheko, Meinit, Dizi and Surma ethnic groups among which Surma, Meinit and Dizi ethnic groups are recognized as pastoral and agro-pastoral communities. The study district is an area of semi-sedentary combined with transhumant pastoralism. It is located about 617 km from the country's capital, Addis Ababa, to the southwest part. According to the FDRE-PCC (2008) Population and Housing Census report, the human population of the area is estimated to be 44,766. The elevation ranges from 800 to 1500 m above sea level with varying landscapes ranging from rolling plains to occasional hills and mountains (BoA, 2009). The area is characterized by bimodal rainfall pattern with mean annual rainfall of about 850 mm. The annual maximum temperature in the area is 40°C and the annual minimum temperature is 20°C (BoA, 2009). The vegetation of the study area commonly consists of shrubs and grasses interspersed with numerous large trees such as *Entada abyssinica* and *Acacia* species. The vegetation ranges with rainfall from tropical montane rainforest to savanna grasslands. However, the forest exists in very small pockets with wild coffee to the west of the district. Soils of the study area are predominated by sandy-loam textural classes and are generally dark brown to reddish brown. The agricultural landscape is one of relatively small patches of cropland around settlements, with extensive areas of woodland, savannah grassland and shrub land that are used for extensive grazing. The agro-pastoral communities in the area are traditionally dependent on livestock production and some lately started cultivation of sorghum, cassava and maize for their subsistence livelihood. The animals in the area are maintained on rangeland vegetation all year round. The study district is one of the regions with the highest livestock population density. According to BoA

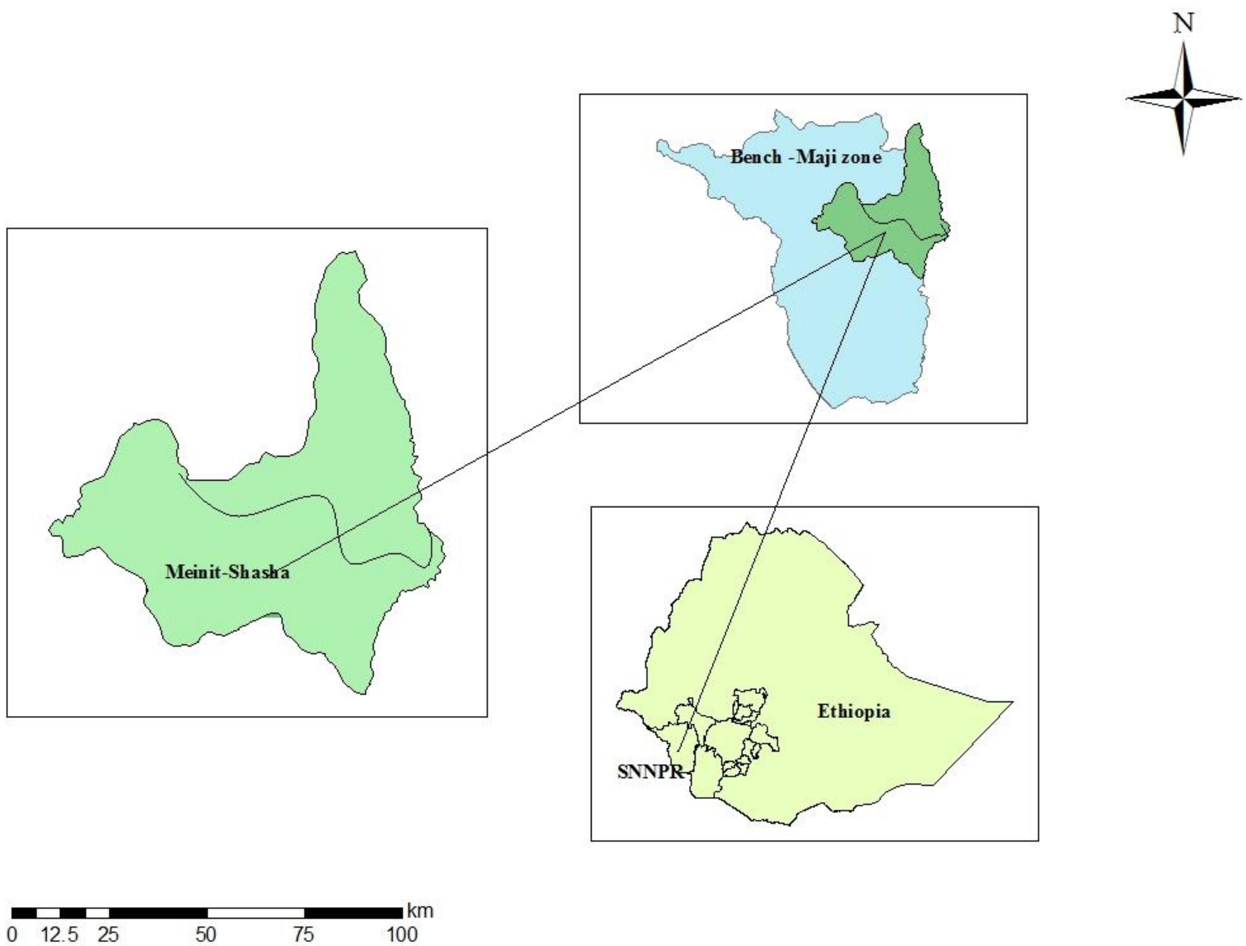

Figure 1. Map of the study area, Meinit-Shasha district, Bench-Maji zone, southwest Ethiopia.

(2009), the livestock population was estimated to consist of 56752 of which cattle accounted for 28364, goats 25585 and 2803 sheep. This area was selected because it was a focal point where the Ethiopian government has conducted the resettlement schemes.

Sampling design and data collection procedure

A combination of different methods and techniques including participatory approaches, field observations and vegetation assessment were employed to obtain the objective of this study. Figure 2 depicts the general approaches used in the study.

Two kebeles (peasant associations), that is, one resettled and the other non-resettled were selected for the purpose of this study. The selected kebeles had similar altitudes (800-1490 m) with varying landscapes, climate and soil types but with comparable household and livestock numbers. In this particular case, Eara was the non-resettled kebele and represented the vast rangeland areas that had been used by pastoralists for centuries. On the other hand, Bass was the resettled kebele where the degree of pastoral land use was reduced. Recent and intense expansion of cultivation in Bass kebele was a major challenge to the pastoral land use resulting in the reduction of available grazing lands.

In each kebele, two parallel transects of 8 km long were established in a south-north direction following the path towards a water point and in this particular study water point refers to a permanent River called *Kilu* (one of the tributaries of Baro River after joining the River Akobo) in the study area. Transects were placed 1 km apart and the sampling plots were established at regular intervals along 800 m transect. Each transect had 10 sampling plots of 20 × 20 m (400 m^2), which were fixed using a measuring tape and Silva compass to supply a total of 40 plots (20 plots/kebele). For the range condition factors, a smaller plot size of 1 × 1 m was placed within the edge of 20 × 20 m plots. Sampling was conducted at the time when herbaceous vegetation was in flowering stage towards the end of the main rainy season for the identification of species. Plant specimens were pressed and taken to Haramaya University's Herbarium for proper identification. To assign the corresponding scientific names, nomenclature of the plant species followed the Flora of Ethiopia (Hedberg and Edwards, 1989; Azene et al., 1993). Overall, parameters recorded included: species composition, basal cover, litter cover, number of seedlings and age distribution.

Range condition assessment

Details of factors considered and criteria employed for rating range condition included: grass composition, age distribution, basal and litter cover, number of seedlings and soil conditions in terms of soil erosion and compaction in each sub-plots based on the criteria developed by Tainton (1981) in South Africa and modified to fit

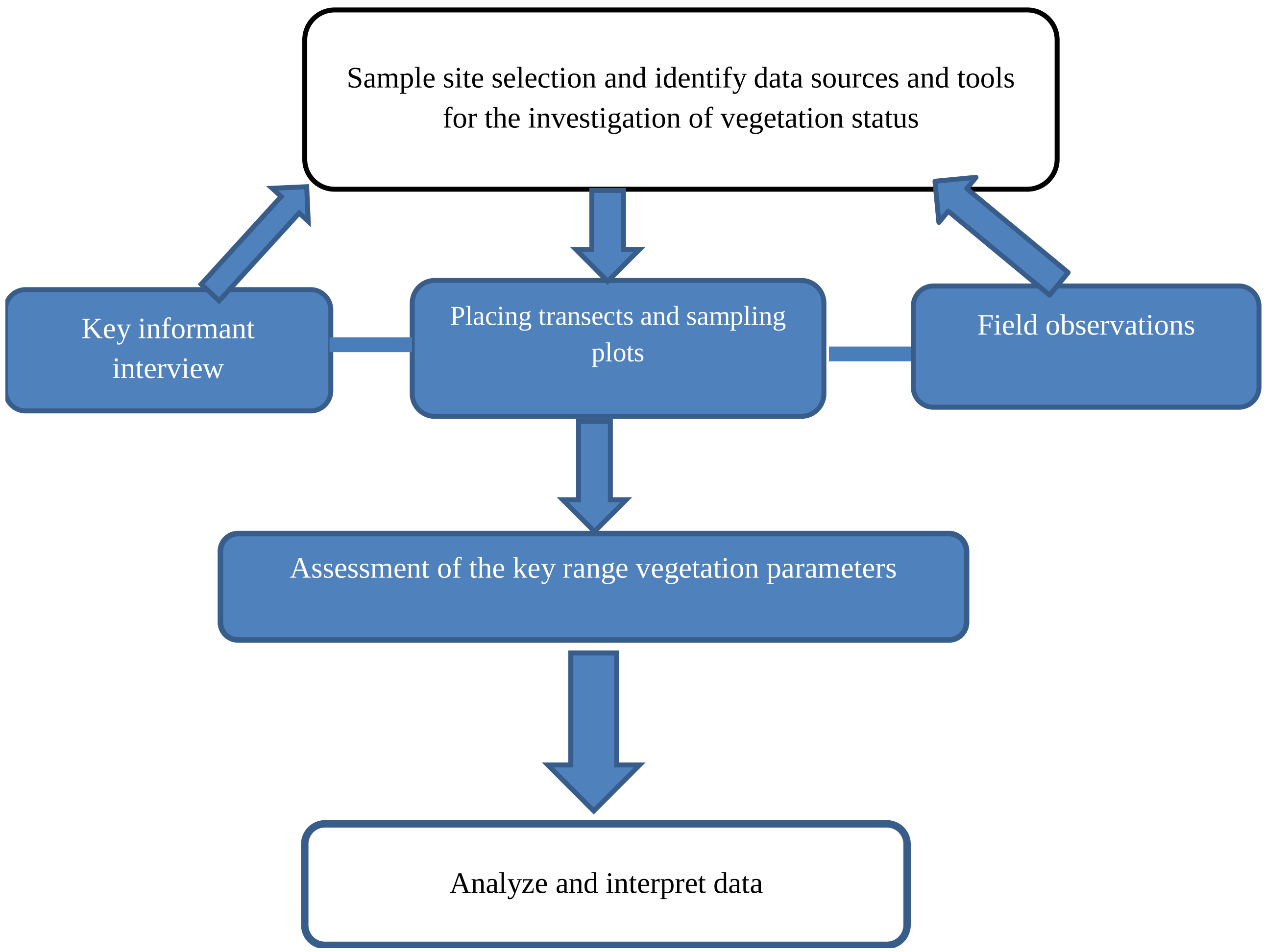

Figure 2. Schematic summary of the major methodological steps followed for analyzing resettlement impacts on vegetation in the context of southwest Ethiopia rangelands.

semi-arid and sub-humid environments by Baars et al. (1997). A maximum score of 10 points each given for 3 of the factors, that is, grass composition, basal cover and litter cover, and a maximum score of 5 points each for age distribution and the number of seedlings, soil erosion and soil compaction were given, summing to a maximum possible score of 50 points to obtain a total range condition score for each kebele. The total rating was interpreted as follows: very poor (≤ 10); poor (11 - 20); fair (21 - 30); good (31 - 40); and excellent (41 - 50) points (Tainton, 1981; Baars et al., 1997).

Grass species composition

Classification of grasses was based on the succession theory of Dyksterhuis (1949), which is also documented in Baars et al. (1997) to classify grasses into desirable species likely to decrease with heavy grazing pressure (decreasers), intermediate species likely to increase with heavy grazing pressure (increasers) and undesirable species likely to increase or invade with heavy grazing pressure (invaders). Information was gathered from pastoralists on vigor and palatability of a particular species. A species with high palatability was considered as decreaser, whereas a species with medium palatability, which is not affected by grazing pressure, was considered as increaser. The score for the grass species composition was determined from the proportion of decreasers, increasers and invaders at each sampling site. A range of 1-10 points was designated for scoring grass composition and the maximum score of 10 points were given if the contribution of decreasers were 91 - 100%, and score of 1 point was given if the decreasers were less than 10 and 50% increasers, respectively and with the rest falling in between 1 and 10 points.

Basal area and litter cover

A representative area of 1 m^2 was selected at each sampling site for detailed assessment of basal area and litter covers and divided into 2 halves. One half was further divided into quarters, one of which was divided into eighths. For basal area and litter cover, a score of 0 to 10 points was used. Plant basal cover in the selected 1 m^2 was cut, transferred while kept together, and drawn in the eighth segment to facilitate visual estimations of basal cover. Only living plant parts were considered for basal estimation. The highest score of 10 point was given for the basal cover of tufted species if the eighth was completely filled (12.5%). Accordingly, classes of <3, 3-6, 6-9, 9-12% were distinguished. A score of 0 was assigned for no basal cover. Similarly, the rating for the litter cover within the

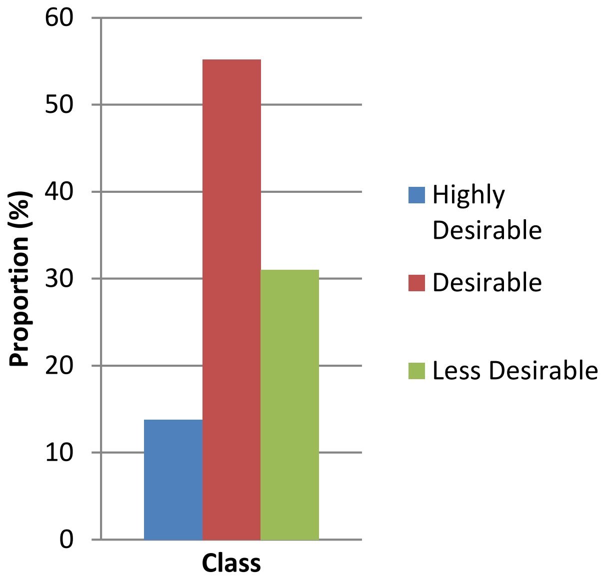

Figure 3. Proportions (%) of desirable herbaceous species in the study area.

same square meter was given the maximum score of 10 points when it exceeded 40% and the minimum score when the litter cover was less than 3% (Tainton, 1981; Baars et al., 1997). The rating for basal cover of tufted grasses was considered ‘excellent’ when the eighth was completely filled (12.5%) and ‘very poor’ when the cover was less than 3%. The rating for litter cover within the same area of 1 m^2 was considered ‘excellent’ when it exceeded 40% and ‘poor’ when less than 10%.

Number of seedlings

The number of seedlings and age categories at each sampling site was counted from 3 randomly selected plots, equal to the size of an A4 paper (30 x 21 cm). The paper was dropped from a height of 2 m above the ground. Scores of 0, 1, 2, 3, 4 and 5 were given if the number of seedlings in the area outlined by the A4 paper were 0, 1, 2, 3, 4 and >4, respectively. Similarly, the size distribution, which was considered to reflect the age distribution of plants, was estimated based on visual observation of the size of the grass tussocks. When all age categories (young, medium aged and old) plants of the dominant species were present, the maximum score points of 5 were given. Young and medium aged plants were defined as having approximately 20 and 50%, respectively, of the biomass of old and mature plants of the dominant species. A score of 4 point was given when both young and medium-aged groups of grasses were present, while scores of 3 and 2 were given when only old and medium-aged groups of plants, respectively, were present. When there were only young plants, the minimum score of 1 point was given.

Soil erosion and soil compaction

The extent of soil erosion and compaction was evaluated from 1 m^2 sub-plots subjectively by visual observations. Soil erosion was based on the amount of pedestals (higher part of soils, held together by grass roots, with eroded soil around the tuft of grasses), and in severe cases, the presence of pavements (terraces of flat soil, normally without basal cover, with a line of tufts between pavements) (Baars et al., 1997). If there was no soil movement, a maximum score of 5 point was given and a minimum score of 0 was given in situations where gully formation was observed due to soil erosion. The occurrence of slight sand mulch, weak pedestals, steep-sided pedestals and pavements coincided with scores of 4, 3, 2 and 1, respectively. Soil compaction (1-5) was evaluated based on the amount of crust formation of surface soil. If there was no compaction, a maximum score of 5 was given and the rating was decreased with increasing capping of the soil. Scores of 4, 3, 2 and 1 were given for soils with isolated capping, >50% capping, >75% capping and almost 100% capping, respectively.

Woody vegetation layer

In each sample plot of the 20 x 20 m (400 m^2), all woody plant species with diameter at breast height (DBH; 1.30 m above the ground) and shrubs were identified and counted to investigate the woody vegetation density and composition. The height was measured by hypsometer, while diameter of trees was measured with the use of a caliper. The density of woody plants (trees and/or shrubs) was enumerated in each plot and an area with less than 5 trees/shrubs was given 0 point and that with more than 50 trees/shrubs were given a score of 10 points, while other estimates failed in between these limits. Information on the classification of trees/shrubs into preferred and not preferred was obtained in discussion with pastoralists and the corresponding range of scores (0-10 points) was designated.

Data analysis

A one way analysis of variance (ANOVA) using the GLM procedure in SAS (SAS, 2004) was used to verify significant differences in terms of range condition factors in response to the predictor variable, that is, status of settlement between the two kebeles. Means were separated using Duncan’s multiple range test (DMRT). Statistically significance difference was determined at $P<0.05$.

RESULTS

Composition of herbaceous species

A total of 29 herbaceous species were identified in both kebeles, while the plant species included: 5 grass species, one legume species, eighteen forbs and 5 other herbs (Table 1). Of the total herbaceous species identified, 24 species were recorded in both kebeles, while 4 additional species were only recorded in the non-resettled kebele. On the other hand, one species was only found in the resettled kebele. Among the herbaceous vegetation recorded, species in the categories of highly desirable, desirable and less desirable plant species accounted for 13.8, 55.2 and 31% in both kebeles, respectively (Figure 3). The proportion of highly desirable species was generally lower than the desirable and less desirable ones (Figure 3). Although there is existence of limitations with subjective classification, it gives an indication of deterioration explained by higher grazing impact. There was a significantly higher ($P<0.05$) score for grass species composition of the non-resettled kebele

Table 1. Desirability and life form of the different grass species in Bench-Maji zone, southwest Ethiopia.

Species	Local name	Life-Form	Desirability
Abutilon hybridium	Kirjach	Forb	Desirable
Ageratum cynzaides	Kufach	Herb	Less Desirable
Amaranthusspinopsis	Katila eaten	Herb	Less Desirable
Asystasiaschimperi	Antidy	Forb	Desirable
Bidenspilosa	Jongu	Forb	Less Desirable
Brachiariadeflexa	Bosho/tabal	Forb	Highly Desirable
Brachiaria spp.	Bangui	Forb	Highly Desirable
Cajanus species	Kukunit	Forb	Less Desirable
Commelinabenghalensis	Zabut	Forb	Desirable
Commelina spp.	Tesut	Forb	Desirable
Commelina spp.	Shindabot	Forb	Less Desirable
Convolvulus arvensis	Shamtit	Forb	Desirable
Conyzaboranensis	Gamach	Forb	Less Desirable
Cynodondactylon	Kukunit	Grass	Desirable
Galinsogaparviflora cav.	Baytena	Forb	Desirable
Gynandropsisgynandra	Tikawoch	Legume	Desirable
Hygrophilaauriculata	Yesatmilas	Forb	Desirable
Hyparreheniacymbaria	Sololit	Grass	Highly Desirable
Lactuca sativa	Tenty	Grass	Desirable
Leucasmartinicensis	Shuntu	Grass	Desirable
Leucasmollis	Alemit	Grass	Desirable
Ocimumurticifolium	Hiregnit	Forb	Desirable
Cymbopogon commutatus	Hapia	Forb	Highly Desirable
Spilanthesmauritiana	Gemut	Forb	Desirable
Tephrosialiniaris	Kereba	Forb	Less Desirable
Tephrosiavogelii	Kolokolo	Herb	Desirable
Trifoliumbaccarinni	Nidaldalaw	Forb	Desirable
-	Tiatut	Herb	Less Desirable
-	Kistmody	Herb	Less Desirable

(mean=3.73±0.18) than the resettled kebele (mean 3.01±0.18) (Table 2). The basal cover of the herbaceous vegetation of both kebeles (Table 2) was in fair to poor range condition classes for Eara and Bass, respectively. Statistically, our results also showed a significant (P<0.05) difference in terms of basal cover between the two kebeles (Table 2). The mean score for the basal cover was lower for the resettled kebeleas as compared to the non-settled kebele. Overall, litter cover showed no significant difference between the resettled and non-resettled kebeles, although the mean value for the resettled kebele was lower.

There were no significant differences (P>0.05) in ratings for age distribution between the two kebeles. However, the number of seedlings showed significant differences (P< 0.05) between the non-resettled and resettled kebeles (Table 3). The mean score for the resettled kebele in terms of seedling count was lower. The result of this study revealed that, soil erosion and compaction showed a significant difference (P<0.05) between the two kebeles (Table 2). Accordingly, the resettled kebele had a significantly lower score than the other kebele impling the existence of soil erosion and compaction in a particular kebele. The total score for the non-resettled kebele was significantly different (P<0.05) from that of resettled. Based on the total score, the overall condition of the rangeland was in fair range condition (21.99±0.19) class in the non-resettled kebele, but that of resettled kebele was under poor (15.11±0.19) condition class (Table 2).

Species composition of the woody layer

A total of 13 woody plant species were encountered in the study district. Of the identified woody plant species, 61.54 were preferred and the remaining 38.46% were less preferred or not at all preferred for different uses in the study area. Generally, variation existed in composition of the preferred and less preferred woody plants (Table 4). Accordingly, the proportion of tree and shrub

Table 2. Rangeland condition scores in Bench-Maji zone, southwest Ethiopia.

Parameters	Kebele		±se	CV
	Eara	Bass		
Grass composition	3.73^a	3.01^b	0.18	11.52
Basal cover	3.14^a	2.52^b	0.16	10.9
Litter cover	2.13	1.74	0.43	33.3
Seedling number	3.23^a	1.67_b	0.25	18.55
Seedling age	2.85	2.48	0.20	14.18
Soil erosion	3.28^a	1.95^b	0.20	14.43
Soil compaction	3.34^a	1.73^b	0.28	19.73
Total score	21.99^a	15.11^b	0.19	5.74
Range condition class	fair	poor		

Within rows, means followed by different letters are significantly different at $P < 0.05$; CV = Coefficient of variation; se = standard error.

Table 3. Score values for woody vegetation density in Bench-Maji zone, southwest Ethiopia.

Density	Score
> 50	10
46 - 50	9
41 - 45	8
36 - 40	7
31 - 35	6
26 - 30	5
21 - 26	4
16 - 20	3
11 - 15	2
6 - 10	1
< 5	0

vegetation revealed higher values for Eara. A clear difference (P<0.05) was observed in terms of the score value of woody density between the resettled and non-resettled kebeles (Table 3). The score for woody species density was lower for the Bass kebele than Eara (Table 4).

DISCUSSION

One of the main objectives of this study was to investigate whether resettlement of farmers and subsequent changes in pastoral land use had influenced range condition. The findings of this study indicate that rangeland condition in the resettled kebele greatly differed from that of non-resettled kebele. The findings further confirm that resettlement of farmers' that had different ways of land use practices as opposed to the pastoral land use system significantly affected the condition of rangeland vegetation. The overall range condition scores for the non-resettled kebele as compared to resettled kebele could attribute to differences between the two kebeles in most of the parameters studied. The lower condition score for the resettled kebele could be attributed to heavy grazing pressure, poor management by newcomers, expansion of crop cultivation and increased resettlement that strongly affected the composition, structure and productivity of rangeland vegetation (LUCID, 2006). Similar results were reported by Amaha (2006), Fikirte (2008), suggesting that increased pressure and population growth are factors for the decline in rangeland condition. Expansion of crop cultivation resulted in a decline in range condition score due to the loss of herbaceous species in terms of reduced basal cover and litter covers. In addition, the establishment of permanent settlements together with the shrinkage of grazing areas substantially affected pastoralists' grazing strategies as a result of high population and increased grazing pressure.

Herbaceous composition and rangeland condition

These findings indicate that grass composition was in poor condition in the resettled kebele of Bass where traditional grazing management and pastoral land use were no longer practiced. A similar result was reported by Angassa et al. (2006), indicating that range condition reduded with increased sedentarization in Dida-Hara area of Borana rangeland. Overall, changing management conditions linked to settlement and encroachment of cropping in the communal rangelands and deforestation of natural vegetation caused by land preparation for agricultural activities largely contributed to the reduction in grazing lands. As a result, intensive grazing resulted in the loss of herbaceous layer in the resettled kebele. On the other hand, grass species composition was higher in the non-resettled kebele. The probable explanation could be due to the traditional land management practices and presence of extensive grazing areas as compared to the resettled kebele. Earlier report (Macharia and Ekaya, 2005) indicate that anthropogenic factors could have an adverse effect on the composition and productivity of rangeland vegetation, which is consistent with the present finding.

The existence of significant difference in terms of basal cover between the study kebeles suggested that concentrated grazing and poor management practices may lead to the loss of vegetation cover. Basal cover become lower with poor range condition or the vegetation is under degradation (Amaha, 2006). In this study, the relatively good basal cover in the non-resettled kebele could be associated with reduced grazing pressure due to sufficient grazing areas and the role of local institution in resource management. The results of this study indicate that increased resettlement with intense grazing pressure had resulted in the reduction of grass seedlings. The number of grass seedlings generally declined with

Table 4. Proportion of preferred woody species and density of woody layer in Bench-Maji zone, southwest Ethiopia.

Parameters	Kebele		±se	CV
	Eara	Bass		
Trees and shrubs composition	6.85a	4.45b	1.53	27.13
Trees and shrubs density	2.60a	0.70b	0.74	44.95

Within rows means followed by a different letter are significantly different at the 0.05 level; CV = Coefficient of variation; se = standard error.

the advancement of continuous grazing due to lack of mobility. The result of the present study indicates that crop cultivation and overexploitation of the rangeland vegetation could lead to resultant reduction in seedling numbers. According to Amaha (2006), Amiri et al. (2008), heavy grazing, livestock trampling and encroachment of crop cultivation in the rangelands would contribute to the decline in seedling germination and further deterioration of rangeland condition.

Several findings in arid and semi-arid rangelands (Amaha, 2006; Fikirte, 2008; Asheber, 2009) have shown high levels of bare soil due to the hoof action of grazing animals, overgrazing and mismanagement considered as an important factor for soil erosion to occur. The result of this study revealed that soil erosion and compaction showed significant difference (P<0.05) between the two kebeles in which the resettled kebele showed lower values. The likely reasons for this might be the resettlement program which forced agro-pastoralists to be confined to small plots of land following extensive communal land dispossessions, which have put pressure on indigenous communities' grazing lands to be restricted in small grazing areas particularly on fallow land with the result of overgrazing.

Moreover, expansion of cropping by the resettlers has led to signs of rapid soil erosion in this kebele, exacerbated by reduction of vegetation cover by clearance for cultivation and cutting of wood for fuel and other uses. This result is consistent with a study conducted in Kenya, where fragmentation of the communal rangelands following immigrant farmer's settlement in the lower parts of Mt. Kenya such as Mbeere and Tharake have confined agro-pastoralists to only family plots. Thus, such pressure resulted in bush clearing and land use change together with continuous cropping contributed to the reduction of vegetation cover, increased soil crusting and compaction, which is believed to encourage rapid soil degradation (LUCID, 2006).

It was observed that the total score for rangeland condition in the non-resettled kebele was significantly (P <0.05) higher than that of resettled areas. The introduction of crop cultivation, establishment and expansion of permanent settlements, and concentrated grazing resulted from the reduction of grazing areas which appear to be the main factor contributing to the relatively lower total score attained in the resettled kebele. Pastoralists in the study area were previously free to move with their livestock and graze across vast communal grazing lands. These patterns of grazing left the rangelands less overgrazed and resilient (Angassa et al., 2006). However, crop cultivation and large population of human settlements were established following the resettlement of farmers since 2004. Accordingly, grazing strategies and land use patterns practiced by the pastoral communities through generation had altered and confined to graze on small plots of land because of reduction of grazing areas and restricted free movement of livestock.

Similarly, the demarcation of enclosed rangelands for the resettlement and encroachment of crop farming into these lands following resettlement that led to a year-round grazing and conversions of the communal rangelands to crop lands, seem to be the main factors contributing to the relatively low condition for range condition scores in resettled kebele.

Although, the sample size used for the assessment was minimal, the observation from the study would suggest that the observed results are indicative of the overall image for the study area. In general, the mean range condition of the study area varied from fair to poor range conditions for the different parameters used in the assessment of Eara and Bass, respectively. The results support earlier findings (Amaha, 2006; Angassa et al., 2006; LUCID, 2006) that reported that heavy grazing, poor management, expansion of cultivation and permanent settlement strongly affect the composition, structure and productivity of range vegetation and generally resulted in the deterioration of rangeland condition in arid and semi-arid rangelands of Ethiopia.

Impact of settlement on woody vegetation

Results on the species composition and density of tree and shrub revealed that there was a significant difference (P< 0.05) between the two kebeles. The results of this study clearly showed that land management and resource utilization practices had different effects on the density and composition of woody layer in the study area. The mean score for woody plants density was significantly lower for Bass, as compared to Eara. Such lower score could be largely attributed to human activities.

These activities which are mainly related to land clearance for cultivation, extensive utilization for fuel and construction material and selective cutting and uprooting to avoid competition with cereal crops, are processes which have caused vegetation destruction. The result indicated that the shrub and tree layers had already been overexploited by inhabitants and the extent of vegetation clearance could be increased following resettlement. The prevention of complete clearance and restricted extraction of woody plants may help in the conservation and management of the natural vegetation. Such measure could not only help for the maintenance of rangeland diversity but also meet the basic needs of livelihoods of the local community in the study area. In line with the present study, Belaynesh (2006) observed that over utilization of trees and/shrubs for fuel and construction material resulted in the loss of woody vegetation with the resultant deterioration of rangelands in arid and semi-arid regions of Eastern Ethiopia. Conversely, the highest mean score of the non-resettled kebele could perhaps be little disturbance for cultivation and other uses.

Conclusion

From the results of these findings, there is a clear indication of rangeland degradation following resettlement of farmers in pastoral lands of southwest Ethiopia. Apart from the permanent settlements on the communal rangelands, expansion of crop cultivation, grazing pressure and reduced mobility of livestock were expected to decrease the status of vegetation cover. The influence of newcomers on the former communal rangelands with increased demand for cereal production than before may block pastoralists' access to common pool resources. In addition, differences in land use practices between the host community and newcomers could be major factors in triggering land degradation and loss of biodiversity in the region. Fragmentation and alienation of the communal rangelands had undermined the collective role of pastoral land use and management, threatening local institution and indigenous knowledge in resource management.

Generally, given the status of land use and management activities by resettlers, one can safely argue that resettlement in pastoral area is a threat to the local environment, indigenous institutions and rangeland biodiversity. Therefore, better understanding and recognition of the ecological potential of a given region in terms of appropriate land use policy is essential. An integration of indigenous knowledge with modern conservation approaches in planning and implementation is crucial with the full participation of the local community.

Moreover, resettling farmers in pastoral lands may not be a viable policy option to secure food self-sufficiency in the long-term. It seems that alternative policy option that fully recognizes the customary land use tenure may be more practical.

Understanding the influence that resettlement and lack of proper land use policies have had on pastoral land use and consequently rangeland degradation, the development of pastoral land policy and ensure sustainable rural development should be guided.

Conflict of interest

The authors have not declared any conflict of interest.

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Full Length Research Paper

Steel slag to correct soil acidity and as silicon source in coffee plants

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Slags from the iron and steel industry may be used in agriculture to correct soil acidity. Current assay assesses the effect of iron and steel industry´s slag, derived from stainless steel, and compares it to limestone as soil acidity corrective and silicon source in coffee plants. The experiment was conducted between December, 2012 and January, 2014 in the municipality of Machado MG Brazil, in a 4-year-old coffee plantation, cultivar Catuaí Amarelo IAC 30. Experimental design comprised randomized blocks in a 2x4 factorial scheme, with control and four replications. Treatments combined two soil acidity correctives, namely, stainless steel slag ("Agrosilício") and limestone; 4 corrective doses corresponding to 0.5; 1; 1.5; 2 times the amount required to raise index base saturation (V%) of the soil´s surface layer (0 to 0.2m) by 60%. Control did not contain any soil correction. Soil samples were collected during the experiment at depths 0 to 0.1m; 0.1 to 0.2m; 0.2 to 0.4m; similarly, samples of coffee leaves, at 180 and 390 days, respectively, after the application of correctives. Stainless steel slag showed the same efficiency as limestone in soil acidity correction at 0 to 0.1m layer, and in providing Ca^{2+} to the coffee plant. Stainless steel slag does not correct soil acidity at 0.1 to 0.2 and 0.2 to 0.4 m layers in coffee plants within a 180 day period. Stainless steel slag increases silicon rates in the soil and in the coffee leaves, and increases yield when compared to limestone.

Key words: Silicate, liming, coffee, nutrient.

INTRODUCTION

Since high acidity rates characterize most soils in Brazil, soil acidity is one of the main causes of low yield, regardless of the production system (Corrêa et al., 2009; Nogueira et al., 2013). In areas with perennial crops, such as coffee plantation, acidity corrective is applied on the soil surface, although its incorporation to the soil is difficult and causes phytosanitary problems to the shrubs. Since limestone has low water solubility and must contact the soil to react, in systems where it is not incorporated in soil the efficiency of liming and acidity correction at deeper layers decreases (Natale et al., 2012). The same authors report that liming at the soil surface, without any

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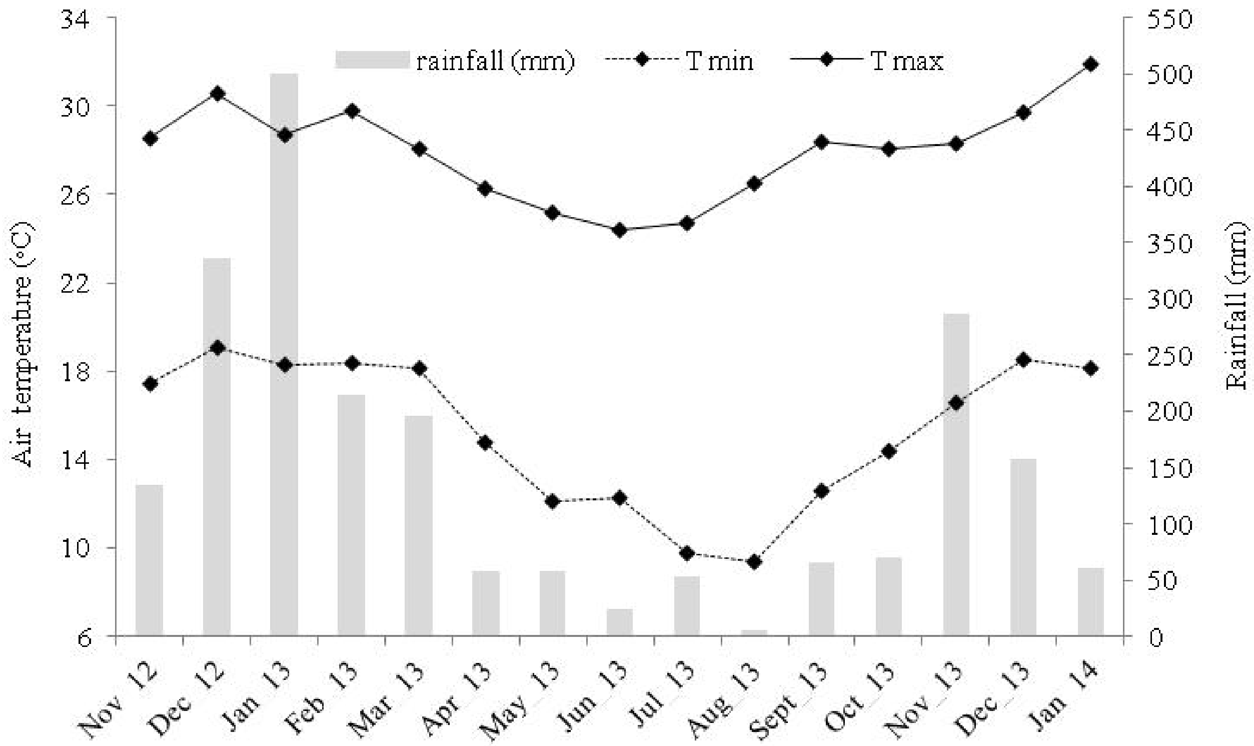

Figure 1. Climate conditions during experimental period.

incorporation, provides low movement of the corrective towards deeper layers, which depends on time, fertilization and the dose of the corrective agent.

Limestone is the main acidity corrective agent in agriculture and its employment in acid soils enhances a rise in the soil´s pH and the neutralization of Al^{3+}, provides calcium and magnesium, and causes a greater development in the plant´s root system, with a greater efficiency in the use of nutrients and water (Raij, 2011). Certain industrial slags, such as iron and steel industry slag, may be used in agriculture to replace liming (Prado et al., 2003; Oliveira et al., 2010). Iron and steel industry slag derive from high temperature processing within the limestone and silicon (SiO_2) reaction are present in the mineral iron (Deus and Büll, 2013). Approximately 6.25 million tons of slags are annually produced in Brazil but their use in agriculture is still fledging (Deus, 2014).

Since steel slags are more soluble than limestone, they may correct soil acidity faster and deeper when applied at the soil´s surface (Deus and Büll, 2013). These material contain silicon whose effects have been the object of several assays in rice (Artigiani et al., 2014), potato (Pultz et al., 2008), tomato (Marodin et al., 2014), bean (Deus and Büll, 2013), soy and corn (Castro and Crusciol, 2013) and sugarcane (Reis et al., 2013). However, the use of steel slag in agriculture is still rare in Brazil.

The acidity in the soil inhibits the full development of coffee culture. Thus, many farmers resort to techniques in order to increase the intensity of land use (Valipour et al., 2015a). Irrigation is one of the most used technology (Valipour, 2015b), and must point out that with the recent climate change producers will increase their irrigated areas and thus lead to water resources management issues (Valipour, 2014a; Valipour,2014b,2014c). Current assay evaluates the effect of iron and steel industry's slag, obtained from stainless steel, on soil acidity and as a source of silicon in coffee plantations.

MATERIALS AND METHODS

The experiment was conducted between December, 2012 and January, 2014 in the municipality of Machado MG Brazil, in a 4-year-old coffee plantation with coffee plants, cultivar Catuaí Amarelo IAC 30. Figure 1 shows climate conditions (temperature and rainfall) during the experimental period.

The soil of the experimental area was classified as Oxisol, medium texture with initial chemical routine analysis (Silva, 1999) at 0 to 0.2 m depth layer (Table 1). Following Camargo et al. (2009), results of granulometry at this layer comprised: 279 g kg^{-1} clay; 114 g kg^{-1} silt; and 607 g kg^{-1} sand.

Experimental design comprised randomized blocks in a 2 x 4 factorial scheme, with control and 4 replications, totaling 36 split-plots. Treatments were composed of a combination of two soil´s acidity correctives, namely, stainless steel slag ("Agrosilício") and limestone, with four doses 0.5; 1; 1.5; 2 times the amount required to raise soil base saturation (V%) of the surface layer (0 to 0.2m) by 60%. No soil acidity corrective was used in control.

The necessary amount of each corrective was calculated by the

Table 1. Initial chemical routine analysis of layer 0 to 0.2 m of the soil in the experimental area.

pH($CaCl_2$)	Mehlich- P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al
	mg dm^{-3}	-------------------------- $cmol_c\ dm^{-3}$				------------------------------
4.7	14	0.6	1.7	0.9	0.2	4.8
SB	ECEC	CEC	V	m	OM	P-rem
---------------- $cmol_c\ dm^{-3}$	-------------		------------- %	-----------	g dm^{-3}	mg L^{-1}
3.2	3.4	8.0	40	6	35	14

H+Al = potential acidity; SB = sum of bases; ECEC = effective cation exchange capacity; CEC = cation exchange capacity at pH 7; V = soil base saturation index; m = aluminum saturation index; OM = organic matter; P-rem = remaining phosphorus.

formula suggested by Raij (2011), which comprised base saturation required by the coffee plant, soil base saturation of the surface layer (0 to 0.2m); cation exchange capacity (CEC) potential of soil at layer 0 to 0.2 m; and the neutralization capacity of the corrective (NCC). Correctives had the following chemical characteristics, limestone: CaO = 22%; MgO = 14%; NCC = 85%; stainless steel slags: CaO = 25%; MgO = 6%; silicon = 10.5%; NCC = 60%.

Each split-plot contained 6 coffee plants with 3.0 m spacing between the rows and 0.8 m between the plants, in a total area of 14.4 m^2. Useful area (9.6 m^2) of each split plot was made up of the four plants at the center of the split-plot. Soil correctives were applied manually in December, 2012, on the soil surface, within the projection of the coffee plant canopy, without any incorporation. The following doses C1 = 0.95; C2 = 1.90; C3 = 2.85; C4 = 3.80 t ha^{-1}; stainless steel slags: E1 = 1.35; E2 = 2.70; E3 = 4.05; E4 = 5.4 t ha^{-1}.

All the split-plots were fertilized uniformly according to the initial chemical analysis of 0 to 0.2 m layer and the intended crop yield. After 180 days from the application of acidity corretictive, soil samples at depths 0 to 0.1m; 0.1 to 0.2 m and 0.2 to 0.4 m were retrieved by a drill from the useful area of each split-plot. Each composed sample was the result of 15 simple samples from each depth. Routine chemical attributes (Silva, 1999) and silicon rates extracted by $CaCl_2$ solution were evaluated in soil samples (Korndörfer et al., 2004).

Crop treatment (weed control and spraying of pesticides) was applied uniformly in all the split-plots according to crop requirements. In June 2013, after 210 days on the application of the acidity correctives, the first harvest of the coffee plants was undertaken, by hand, within the useful area of each split-plot. The coffee berries of each plant were harvested and weighed. The grains were then dried and yield for each split-plot was calculated, in 60-kg bags containing processed coffee grains, following the study of Carvalho et al. (2006).

On the 390th day after the acidity correctives were applied, the leaves of the fruitful branches from each split-plot were harvested, following the study of Raij et al. (1997) to calculate macro- and micro-nutrients (Carmo et al., 2000) and silicon (Korndörfer et al., 2004). Results underwent analysis of variance, Tukey´s mean test and polynomial regression analysis.

RESULTS AND DISCUSSION

There were no significant differences (p> 0.05) between the two acidity correctives studied (limestone and stainless steel slag) with regard to changes in pH, in potential acidity (H+Al), in the base saturation (V) and in Ca^{2+} concentration in the 0 to 0.1 m soil layer rather, the correctives had a similar behavior in the soil when these factors were taken into consideration. Mg^{2+} and Si concentration in the soil at the 0 to 0.1m layer were affected differently (p<0.01) by stainless steel slag when compared to limestone. Doses of the acidity correctives (0; 0.5; 1; 1.5 and 2 times correction requirements) affected significantly (p<0.01) the chemical factors evaluated at the 0 to 0.1 m layer. There was no interaction of the factors under analysis (acidity correctives and doses) in the chemical factors pH; H+Al; V; Ca^{2+}; Mg^{2+} of the soil layer at a depth of 0 – 0.1m. The interactivity correctives x doses affected the silicon concentration in the soil at a depth of 0 to 0.1m.

Corrective doses at depths 0.1 to 0.2m and 0.2 to 0.4m did not influence the evaluated chemical factors and revealed that after 180 days of application the activity of limestone and stainless steel slag remained restricted to the 0 to 0.1 m layer. Whereas mean rates of pH, H+Al, V, Ca^{2+} and Mg^{2+} were respectively 4.6; 5.5 $cmol_c\ dm^{-3}$; 32%; 1.2 and 0.7 $cmol_c\ dm^{-3}$ at layer 0.1 to 0.2m, the mean rates of these factors at 0.2 to 0.4 m deep were 4.2; 5 $cmol_c\ dm^{-3}$; 25%; 1.0 and 0.5 $cmol_c\ dm^{-3}$.

Although silicate minerals are approximately seven times more soluble than limestone, with great mobility in the soil (Alcarde and Rodella, 2003), stainless steel slag in current assay failed to have a greater capacity in correcting acidity in the soil at a certain depth, when compared to limestone. Results may have occurred due to the interval between the application correctives and soil sampling (180 days), the NCC of stainless steel slag and soil texture of the experimental area.

Natale et al. (2012) report that the correction of acidity at the soil´s sub-surface layers with surface application of correctives in areas with perennial crops, such as fruit trees, may occur due to such factors as granulometry of the corrective agent, since the finer particles may easily move throughout the soil´s profile; the displacement of the corrective particles in the soil through canals formed by root decomposition; formation of pairs between bases (Ca^{2+} and Mg^{2+}) and organic acids (RO^- and $RCOO^-$) with high solubility and low molecular mass, which carry them to the deepest layers of the soil, besides the formation of other compounds, such as $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$;

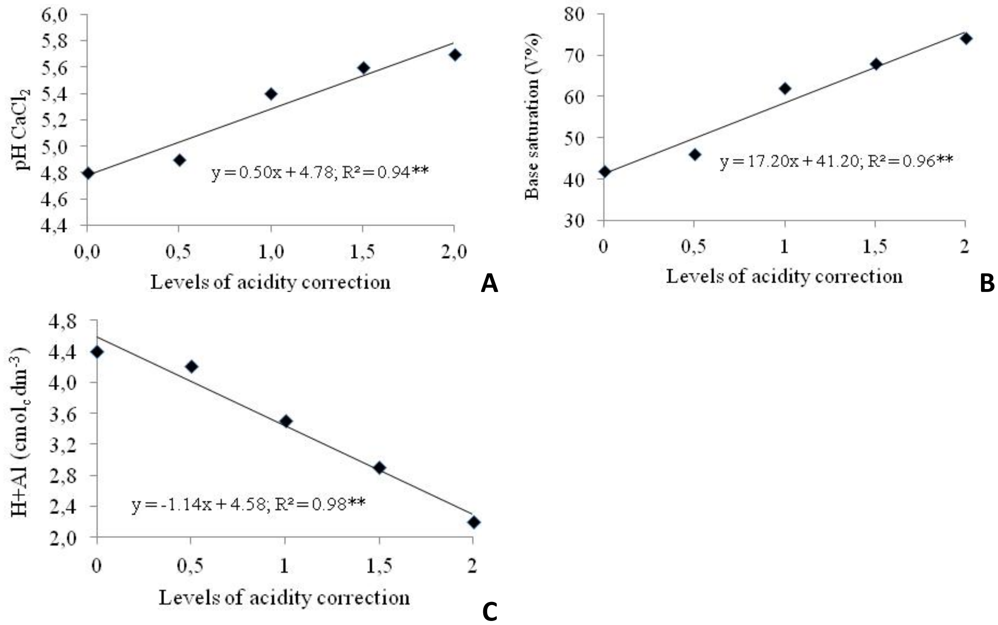

Figure 2. Mean values of pH in $CaCl_2$, saturation per base and potential acidity (H+Al) in the the 0 to 0.1 m soil layer, according to dose for the correction of acidity (0; 0.5; 1; 1.5 and 2 times the need for correction).

d) nitrogen fertilization which triggers the formation of soluble salts, such as $Ca(NO_3)_2$, that percolate through a descending movement of water within the soil profile. According to these authors, the movement of corrective particles within the soil profile depends on the dose used, the interval after application, soil type, fertilization, land slope and type of vegetal covering.

Silva et al. (2004) also reported the correction of acidic soil at 0 to 0.1 m layer with surface application of limestone in coffee crops and they insisted that correction at the sub-surface layers of the soil only occurred 34 months after the first application of the corrective agent and 13 months after the second one. Deus and Büll (2013) registered that in an area with bean tillage system, the corrective effect of stainless steel slag was limited to a depth of 5 cm whereas limestone neutralized soil acidity at the 0 to 0.2 m layer sixty days after their application on the soil surface. In an assay with coffee crops, Melo and Sartori (2013) showed that industrial slag behaved similarly to limestone when correcting soil acidity at a depth of 0 to 0.1 m. However, the two corrective agents did not correct acidity at a depth of 0.1 to 0.2 m after 90 days of application on the soil surface.

Castro and Cruciol (2013) reported that stainless steel slag (Agrosilício) in a tillage system was successful in correcting soil acidity. It was also capable of increasing the soil´s base exchange rates (Ca^{2+} and Mg^{2+}) at a depth of 0.4m, when compared to limestone, in assessments 12 and 18 months after the application of correctives on the soil´s surface.

Further, pH linear increase occurred in base saturation and in Ca^{2+} and Mg^{2+} rates at 0 – 0.1 m depth with the surface application of stainless steel slag and limestone (Figures 2 and 3). According to regression equations, pH in $CaCl_2$ values and bases saturation varied for the two corrective agents, respectively from 4.8 and 41% to 5.8 and 76% in control treatment and in treatment with the highest corrective dose (Figures 2A and 2B). In other words, pH in $CaCl_2$ increased by one unit and V% rates practically doubled in the 0 – 0.1m layer, with the highest level in acidity correction.

Potential acidity (H+Al) of the soil at a depth between 0 and 0.1m decreased linearly with doses, regardless of the corrective agent applied (Figure 2C).

Nogueira et al. (2012) reported similar results in experiments with coffee plants in vases placed in a greenhouse. They registered that slug and limestone with doses featuring 0; 25; 50; 75; 100 and 125% of correction requirements increased pH and decreased potential (H+Al) and exchangeable acidity (Al^{3+}) of clayey latosol. They also reported that slag had a behavior similar to that of limestone in the correction of acidic soil. The effect of silicate slag in soil reaction is due to the neutralization of H^+ and release of OH^- by silicate anion (SiO_3^{-2}) available in the solubilization process of the materials (Prado et al., 2003).

Mean increase in Ca^{2+} and Mg^{2+} concentrations in the 0 to 0.1 m soil layer was 2.4 times when the highest slag or limestone dose was employed, when compared to control (Figures 3A and 3B). Mean concentrations of the

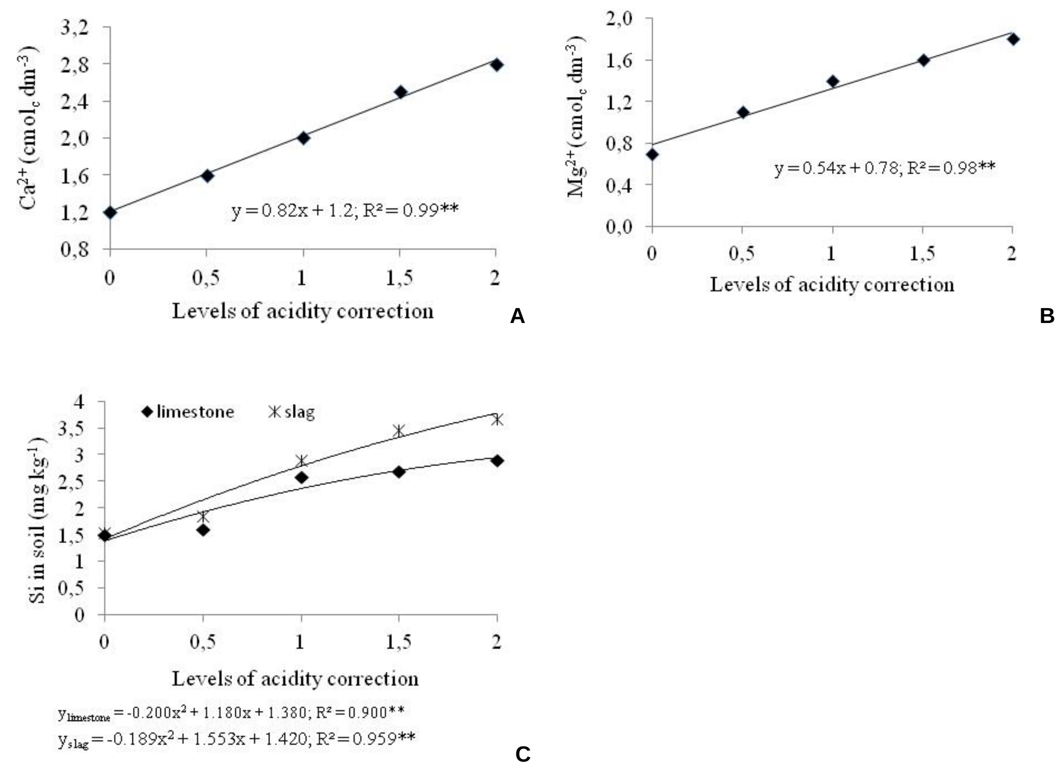

Figure 3. Mean concentrations of Ca^{2+} (A); Mg^{2+} (B); Si (C) in the 0 to 0.1 m soil layer due to dose of acidity corrective (0; 0.5; 1; 1.5 and 2 times correction requirements).

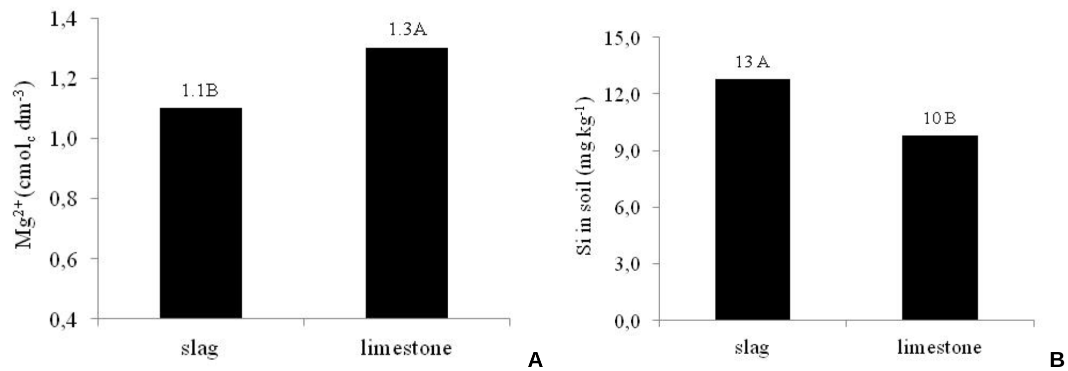

Figure 4. Mean concentrations of Mg^{2+} (A) and Si (B) in the 0 to 0.1 m soil layer due to acidity correctives (stainless steel slag and limestone).

nutrients varied according to dose of the corrective agents, or rather, from 1.2 to 2.8 $cmol_c$ dm^{-3} in the case of Ca^{2+} and from 0.8 to 1.9 $cmol_c$ dm^{-3} in the case of Mg^{2+}, which CFSEMG (1999) have considered respectively average and good for Ca^{2+} and average and very good for Mg^{2+}. Mg^{2+} rates in soil with limestone treatments averaged 20% higher than those with stainless steel slag (Figure 4A). Higher Mg^{2+} rates in the soil with limestone are due to a greater concentration of the nutrient in the corrective agent (14% of MgO) than in stainless steel slag (6% of MgO).

Silva and Coelho (2010) also reported a linear increase in Ca^{2+} and Mg^{2+} rates in soil when silicate slag and limestone were applied, in a field assay, in medium texture soil with eucalyptus. The authors also revealed that Ca^{2+} rates of the soil were similar when the two corrective agents (silicate slag and limestone) were employed, and that treatments with limestone had higher Mg^{2+} rates in the soil than those with silicate slag. Linear increases in Ca^{2+} and Mg^{2+} rates in clayey soil were also

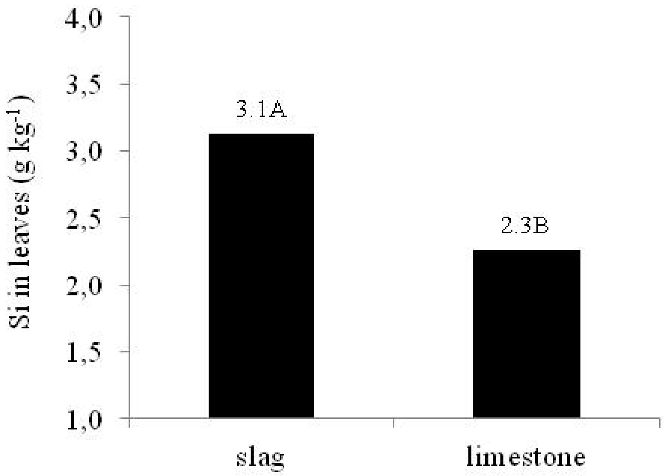

Figure 5. Mean concentrations of silicon in the leaf tissue of the coffee plant due to the acidity corrective agents used (stainless steel slag and limestone).

reported by Nogueira et al. (2012) in an experiment with coffee plants and slag.

Silicon concentration of soil increased when dose of the corrective agents were applied (Figure 3C), or rather, mean rate of silicon in the soil was 1.3 times greater in treatments with stainless steel slag than in those with limestone (Figure 4B). Stainless steel slag is not only a source of silicon (10.5% of silicon). Rise in the soil´s pH due to corrective agents increases silicon availability caused by decrease of the element´s adsorption caused by the soil´s inorganic colloids (Silva and Coelho, 2010). Korndörfer et al. (1999), Camargo et al. (2007), Silva and Coelho (2010) and Deus and Büll (2013) reported similar results and detected increase in c rate in the soil when silicate slag was applied. There were no changes in the nutrients concentrations in the leaf tissue of the coffee plant when stainless steel slag and limestone were applied. Mean concentrations of macronutrients were 34; 1.4; 25; 16; 2.9 and 1.8 g kg^{-1} respectively for N, P, K, Ca, Mg and S. Concentrations were within range for leaf tissues suggested by Raij et al. (1997) for the coffee plant, namely 26-32; 1.2-2.0; 18-25; 10-15; 3.0-5.0; 1.5-2.0 g kg^{-1} respectively for N, P, K, Ca, Mg and S.

Mean concentrations of micronutrients in the coffee´s leaf tissue were 30; 23; 85; 146 and 22 mg kg^{-1}, respectively for B, Cu, Fe, Mn and Zn, and were within range for leaf tissues suggested by Raij et al. (1997) for the coffee plant, namely, 50 to 80, 10 to 20, 50 to 200, 50 to 200, 10 to 20 mg kg^{-1}, respectively for B, Cu, Fe, Mn and Zn. Silva et al. (2004) did not report any decrease in micronutrient absorption in coffee plants due to the application of acidity corrective agents.

There was an increase of silicon concentrations in the plants´ leaves by simply applying stainless steel slag, even though no definite behavior (linear or quadratic) was reported in its rates in coffee plants with doses of the acidity corrective agent. Mean silicon concentrations in coffee leaves in treatments with stainless steel slag were 1.5 times greater when compared to those with limestone (Figure 5). Silicon concentrations in coffee leaves ranged between 2 and 3 g kg^{-1} (Reis et al., 2007), similar to those in current assay.

In their tillage experiment in which stainless steel slag and limestone were applied on the soil surface with a clayey texture to raise base saturation at 70% before the succession culture of soybean, Congo signal grass and corn, Castro and Crusciol (2013) failed to report variations in leaf rates of N, K and S of soybean and of P, K and S of corn when correctives were applied. However, the authors registered increase in P concentrations of soybean leaves, N concentrations in corn leaves and in Ca, Mg and silicon concentrations in the two crops when acidity correctives were applied.

Marques (2013) employed different percentages for calcium silicate and limestone to correct soil acidity and failed to report changes in N, P, K, Mg and Zn concentrations in corn leaves, but registered a linear increase in silicon rates in leaves with an increase in calcium silicate amounts applied to the soil. Lopes et al. (2013) did not detect any increase in silicon rates in roots, stem and leaves of coffee seedlings when doses of silicate slug were incorporated in soil used as a substrate for the formation of seedlings. Coffee plant yield from the first harvest provided a quadratic response to stainless steel slag and limestone doses (Figure 6A). According to regression equation, maximum yield (30 bags ha^{-1}) would be obtained with the application of 1.7 times the dose necessary to correct the soil acidity on the soil´s surface. Maximum yield would be 47% greater, or rather, 10 bags ha^{-1} more than that obtained in control where correction for soil acidity was not performed. Yields in treatments with 1 and 1.5 times correction requirements were respectively 38 and 46% greater than those of control.

Coffee plants are tolerant to acidity but not susceptible to Al^{3+} toxicity in the soil (Rodrigues et al., 2006). This is the reason why sometimes response of the crop to liming fails (Raij et al., 1996) or occurs in soils with high Al^{3+} and Mn^{2+} concentrations (Mendonça et al., 2007), which was not the case in current experiment. In fact, the coffee plant´s high yield response to the application of acidity correctives was unexpected. However, response may have occurred due to the cultivar (Catuaí) employed, with lower tolerance rates to soil acidity that other coffee plant varieties, such as Icatu (Rodrigues et al., 2006; Mendonça et al., 2007).

Silva et al. (2004) also registered an increase in the coffee plant (cv Catuaí) yield during the first and second harvests, with the correction of soil acidity by limestone. Treatments with stainless steel slag as a corrective for acidity averaged a yield 20% higher, or rather, 5 bags ha^{-1} more when compared to limestone corrective (Figure 6B).

Although the coffee plant is a species which does not

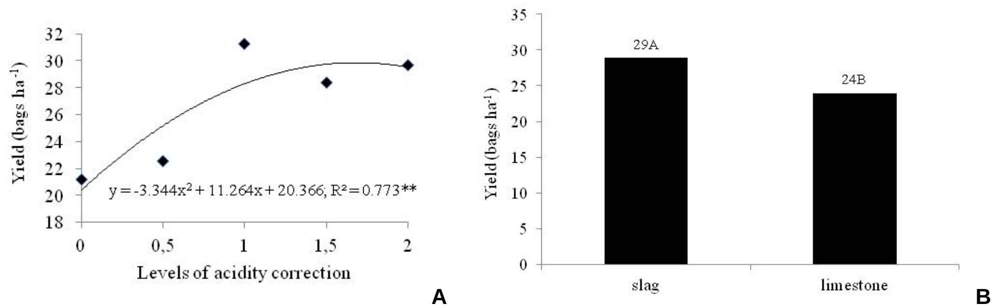

Figure 6. Mean yield of the coffee plant according to doses (A) of acidity correctives (0; 0.5; 1; 1.5 and 2 times correction requirements) and types of corrective (B) employed (stainless steel slag and limestone)

accumulate silicon (Reis et al., 2007), increase in silicon concentrations in leaves in treatments with stainless steel slag as a corrective agent against acidity may have increased the structural rigidity of the tissues and made the plants less susceptible to biotic and abiotic stress (Ribeiro et al., 2011). It may also have maintained the plants´ photosynthetic rate and stomach conductance due to a decrease in transpiration through the cuticle (Pulz et al., 2008) at drought intervals during the experiment. This may have been the cause of greater coffee yield in treatments with stainless steel slag when compared to treatments with limestone.

The concentration of some elements in high concentrations in the soil can reduce the production, so a technology to reduce the application of a higher blade is needed to dilute and percolating the excess (Valipour 2012a, 2012b; Yannopoulos et al., 2015).

CONCLUSION

Stainless steel slag has the same efficiency as limestone in correcting soil acidity at a depth of 0 to 0.1m and in providing Ca^{2+} to the coffee plant. Stainless steel slag does not correct acidic soil at depths 0.1 to 0.2 and 0.2 to 0.4m, within a 180-day period, in an area with coffee plants. Stainless steel slag increases silicon rate in the soil, in coffee leaves and increases crop yield when compared to rates by limestone.

Conflict of interests

The authors have none to declare.

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Full Length Research Paper

Bayesian discriminant analysis of plant leaf hyperspectral reflectance for identification of weeds from cabbages

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In order to spray herbicides accurately on targets, this study focused on spectral classification of weeds and crops for potential to rapidly detect weeds in crop fields. A 350 ~ 2500 nm FieldSpec-FR spectroradiometer was used to measure spectral responses of the canopies of the seedling vegetables, cabbage '8398' and cabbage 'Zhonggan 11', and weeds, Barnyard grass, green foxtail, goosegrass, crabgrass, and *Chenopodium quinoa*, at five- and seven-week growth stages (WGS). First, the characteristic wavelengths (CW) were determined using Principal Component Analysis (PCA). Then, the plants were classified using Bayesian discriminant analysis with the reflectance of the CWs. The results of spectral analysis indicated that the different growth stages of cabbages had little influence on the spectral identification of cabbages and weeds. The eight CWs determined were used as the input to the model for Bayesian discriminant analysis to classify two varieties of cabbages and five weeds with the correct classification rate of 84.3% for model testing. When the two varieties of cabbages were considered as the same category, the correct classification rate was improved to 100%. It was concluded that Bayesian discriminant analysis could be used to identify weeds from seedling cabbages using leaf hyperspectral reflectance.

Key words: Weed identification, spectrum analysis, visible and near-infrared, Bayesian discriminant, seedling weed, seedling cabbage.

INTRODUCTION

According to the research report from the United Nations Food and Agriculture Organization (FAO) in August 2009,

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weeds should be regarded as farmers' No. 1 natural enemy. It was reported that according to a leading environmental research organization, Land Care of New Zealand, weeds cause about $95 billion every year in the lost food production at global level, compared with $85 billion for pathogens, $46 billion for insects, and $2.4 billion for vertebrates (excluding humans). Of the $95 billion, $70 billion are estimated to be lost in developing countries (FAO, 2009). In China, the crop yield losses annually caused by weeds sum up to about 10% of the gross grain output (Tang, 2010). Facing the severity of the crop losses caused by weeds, it is urgent to seek highly efficient methods for effective weed control. The chemical weeding method commonly adopted at present has provoked a lot of problems, such as excessive pesticide residues, growing number of pesticide-resistant weeds, destruction of ecological environment, and lower quality and safety of agricultural products (Thompson et al., 1991). Therefore, it is critical to have a method which could not only control the growth of weeds, but also decrease the use of herbicides, and hence prevent from excessive herbicide application. In order to minimize crop damage and environmental pollution, herbicides should be sprayed accurately on targets with appropriate dose.

Rapid access to the information of spraying targets is a critical process in precision chemical application. Many approaches to weed detection and identification have been reported in literatures, such as photoelectric detection technique (Biller, 1998; Andújar et al.,, 2011), ultrasonic detection technique (Andújar et al., 2012), remote sensing detection technique (Thorp and Tian, 2004), and image processing detection technique (Weis and Sökefeld, 2010; Christensen et al., 2009; Burgos-Artizzu et al., 2009; Piron et al., 2011), X-ray weed detection technique (Haff and Slaughter, 2009), and spectral weed detection technique (Vrindts et al., 2002; Sui et al., 2008). The image processing technique can detect the target's profile and determine the coverage and amount of smart spray, but mostly this technique is still used in the laboratory instead of being used in field because of its poor stability, large amount of data processing, relatively slow response, and the high costs. In comparison, spectral detection has been widely used in real-time detection system because of its fast response, availability for non-contact detection, strong anti-interference, high reliability, low cost, simple and small configuration, and low power consumption. Many studies have focused on spectral classification of weeds and crops for potential to rapidly detect weeds in crop fields. Spectral sensors has been designed and widely used in real-time detection system in crop production, because they offer fast response, availability for non-contact detection, strong anti-interference, high reliability, low cost, simple and small configuration, and low power consumption (Wang et al., 2001; Rogalski, 2003). These sensors could be used to further study the spectral characteristics for classification of weeds and crops to realize fast and timely weed management in crop fields.

Koger et al. (2003) analyzed the hyperspectral reflectance of soybean, Ipomoea lacunosa, and soil at the two- and four-leaf stages of weed growth using wavelet analysis. For comparison, the raw spectral bands and principal components were used as discriminating features. For the two-leaf to four-leaf weed growth stage, the two features resulted in classification accuracies of 83 and 81%, respectively. Jurado-Exposito et al. (2003) distinguished sunflowers, wheat, and seven other seedling broadleaf weeds using near-infrared spectroscopy. It was found that the near infrared spectroscopy within 750 ~ 950 nm was able to identify these plants. Slaughter et al. (2004) distinguished *Solanum* weeds and tomato using the spectral reflectance in visible and near-infrared wavebands, narrow-band hyperspectral modeling, and discriminant analysis. It was found that the spectral absorbance data of weeds and tomatoes at the wavelength rang of 2120 to 2320 nm offered the best classification accuracy (100%), and narrow-band hyperspectral models of the data in the visible range also achieved good classification results (95%), while the broad-band models based on color information only provided 75% correct classification rate.

Thenkabail et al. (2004) studied how to select the optimum wavebands for classifying plants (shrubs and weeds) and crops (corn) in the range of 400 to 2500 nm waveband. It was found that 90% correct classification rate could be obtained by modeling using 13 to 22 wavebands selected from the original 168 wavebands using PCA and stepwise discriminant analysis, which accuracy was increased by 9 to 43% compared with modeling using ETM (Landsat Enhanced Thematic Mapper), plus brandband data. Piron et al. (2008) classified seven different weeds in carrot fields under artificial lighting conditions using a visible and near-infrared multispectral sensor, and found that overall correct classification rate was 72% when three optimal wavebands, 450, 550, and 700 nm were selected using the exhaust algorithm and used to establish the weed identification models. Mao et al. (2005) measured the spectral reflectance of wheat, shepherd's purse, and small quinoa in the wavelength range of 700 to 1100 nm using a Fourier transform infrared (FTIR) spectrometer, and extracted 7 characteristics wavelengths, 686, 708, 722, 795, 929, 956, and 1122 nm using stepwise discriminant analysis and achieved 97% correct identification rate through establishing the model of identifying wheat and weeds. Vrindts et al. (2002) measured the canopy reflectance of maize, sugarbeet, and seven weed species at 400 to 2000 nm. The spectral characteristics were also analyzed. Six wavelengths (555, 675, 815, 1265, 1455, and 1665 nm) at characteristic points in the spectrum were selected to derive the RVI. The STEPDISC and DISCRIM procedures in SAS were applied in the discrimination of crops (maize and sugarbeet) from weeds. The classification result showed that crop and weeds could be recognized at an accuracy of higher than 97%. More than 90% of sugar beet and weeds could be identified correctly using a line spectrograph (480 to 820 nm) in classifying the plants. With the application of the spectral technique, Sui et al. (2008) developed the Weed Seeker sensor module to detect the presence of weeds by measuring the reflectance of weeds and bare ground. The module serves as a useful tool for locating weeds.

Karimi et al. (2006) used SVMs and NNs for weed and nitrogen deficiency detection in corn with non-imaging hyperspectral reflectance data as input. In an extensive approach, they uniquely identified and classified four weed management practices and three different nitrogen rates. The classification accuracy using SVMs was higher than with NN in this research project 69.2 versus 58.3%, respectively. Lopez-Granados et al. (2008) used the hyperspectral reflectance spectrum from 400 to 900 nm for the classification of late season grass weeds and wheat plants in a field study. Their approach using linear and nonparametric functional discriminant analysis and NNs has shown that, in general, a preliminary computation of most relevant PCs improves the classification accuracy. They concluded from their study that analysis in real time of high spectrally resolved images will be adequate to map grass weed patches in wheat. For practical implementation, Moshou et al. (2002) developed a weed species spectral detector based on neural networks with local linear mappings. A self-organized map (SOM) neural network achieved fast convergence and good generalization. The proposed method classified crops and different species of weed with high accuracy. Chen et al. (2009) measured the spectral reflectance of leaves of rice, cotton, Barnyard grass and Cephalanoplos indoors in the range of 350 to 2500 nm wavelength using a spectroradiometer and determined the characteristic wavelengths (CWs) using the stepwise discriminant method, and then classified these plants using the Discrim processing, a function of discriminant analysis in SAS statistical software (SAS Institute Inc., Carrey, North Carolina, the United States).

This study found that monocotyledons, like rice and Barnyard grass, could be accurately classified using the five CWs, 375, 465, 585, 705, and 1035 nm, in which the correct identification rate reached 100%; dicotyledons, like cotton and Cephalanoplos, could also be accurately classified using the three CWs, 383, 415, and 435 nm, in which the correct identification rate also reached 100%. The spectral reflectance of cabbages and weeds were measured in the 350 to 2500 nm band and preprocessed the data with different levels to improve the operation efficiency. All kinds of plants were classified using the Soft Independent Modeling of Class Analogy (SIMCA). While the selected 23 feature wavelengths were set as the input variables, the classification rate of the modeling set and the predicting set were respectively 98.6 and 100% (Zu et al., 2013a, b).

The objects of most of the previous studies were specific to crops like corn, wheat, rice, and cotton, but few to vegetables. The vegetables, especially dicotyledonous vegetables, are important economic crops in China, which are widely cultivated throughout the country with wide cultivated area and high inputs of labors. Therefore, weed identification in vegetable fields has considerable social and economic benefits and practical significance. Additionally, few of the previous studies were on whether the possible changes of spectral characteristics caused by the changing metabolism at the different growth stages of a crop would affect the consistency of spectral identification of crops and weeds during different growth stages.

For optimal results with minimal investment, weeds should be handled at seedling stage in crop fields (Li et al., 2007). Seedling weeds are sensitive to herbicides because plants are small and the tissues are young. Therefore, the seedling stage is the time for complete weed control. In the further growth stage, weed plants become large and their tissues are strong. Consequently, with the thickening of the waxy coat, it will be difficult for herbicide agents to penetrate the weed leaves and weed herbicide tolerance will be increased accordingly. As the result, the herbicide will be hard to take effect. This study was conducted on seedling weeds in the field with seedling cabbages.

In this study, two varieties of seedling cabbages, ‘No. 8398’ and ‘Zhonggan No. 11’, and five breeds of weeds, Barnyard grass, green foxtail, goosegrass, crabgrass, and *Chenopodium quinoa*, which are commonly-seen. Annual gramineous plants in cabbage fields with strong adaptability, wide coverage, fast multiplying, and inestimable harm to crops, were selected as the representatives of plants. The spectral reflectance of the plant canopies were measured in the wavelength range of 350 to 2500 nm at two seedling growth stages of the 35th (five-week growth stage (WGS)) and 50th days (seven WGS), respectively. The objectives of this study are (1) to determine CWs at which the spectral reflectances were sensitive to plant identification using the spectral data measured, respectively at five WGS and second WGS; (2) to establish the Bayesian discriminant model to classify two varieties of cabbages and five different weeds.

MATERIALS AND METHODS

Experimental

Two varieties of cabbages used in the study were cabbage ‘No. 8398’ and cabbage ‘Zhonggan No. 11’, whose seeds were provided by the Institute of Vegetables, the Chinese Academy of Agricultural Sciences (Beijing, China). Five varieties of weeds were Barnyard grass, green foxtail, goosegrass, crabgrass, *C. quinoa*, whose seeds were provided by the College of Agronomy and Biotechnology, China Agricultural University (Beijing, China). The two varieties of cabbages and five kinds of weeds were planted in pots in a greenhouse of the Chinese National Engineering

Research Center for Information Technology in Agriculture (Beijing, China) on 23 March, 2012. Each variety of plants was grown in 30 pots; therefore, the total number of the plant samples was 210 for the seven varieties of plants.

Data acquisition

The instrument for measuring spectral data was the ASD full range FieldSpec Pro. spectroradiometer (ASD, Inc., Boulder CO., USA). The measuring range of the spectroradiometer is 350 to 2500 nm. The spectral resolution is 1.4 nm in the range of 350 to 1000 nm and 2 nm in the range of 1000 to 2500 nm. The field of view (FOV) of the measuring probe is 25°.

The spectral data of the 210 pots of plant canopies were collected in the test field of National Engineering Research Center for Information Technology in Agricultural (Beijing, China) during 10:30 am to 14:30 pm on 28 April and 13 May, 2012, respectively, corresponding to two growing stages of the plants, five WGS and seven WGS.

The white reference board was measured for spectral calibration each 10 to 15 min depending on weather conditions. After each white reference measurement, the fiber-optic probe of the FieldSpec spectroradiometer was placed vertically above the plant canopy and measured the data. In order not to affect the reflectivity of the plants, the operator should dress dark. The spectroradiometer was set in the condition that an output datum was obtained from the average of ten measurements. The measured spectral data were converted to reflectance and then to ASCII text format using the function in the ASD ViewSpectro Pro. Software provided by ASD Inc. After being imported to Microsoft EXCEL spreadsheet, the text files were transformed to matrixes which were then transferred into the Unscrambler (CAMO software AS, Oslo, Norway) and SAS software for further data processing.

For data collection on 28 April, 2012, each pot of plants was measured for three times so that the total number of the obtained spectral data was 90 for each variety of plants (30 pots for each plant) and 630 for all the 7 varieties of plants. For the measurement on 13 May, 2012, each pot was measured for five times so that the total number of the collected spectral data was 150 for each variety of plant and 1050 for all the 7 varieties of plants.

In order to reduce the random errors which are always accompanied with the spectral signal in the process of data acquisition, the spectral data were averaged for each pot of plants, which resulted in 30 averaged spectral data for each plant respectively for the measurements on 28 April and 13 May.

Principal component clustering analysis

The clustering analysis of the spectral data of cabbages and weeds was conducted using the Principal Component Analysis (PCA) method after data preprocessing. For each of the plants, 20 sample data were randomly selected as the training sample set, the other 10 data as the testing sample set. In the Unscrambler software system, the full cross validation methods in PCA and Partial Least Square (PLS) were separately used to extract the principal components to build the plant classification models. The analysis process was started by extracting 20 principal components from the spectral reflectance data. Then, the outliers were repeatedly excluded by considering the spatial aggregation conditions and spatial position of all the sample points in scoring graphs of the results based on the principle of maximization of distance between the classes and minimization of distance within a class. The appropriate principal components were determined according to the cumulative credibility of each Principal Component (PC) and the classification model was re-built with clustering all the plants (Li, 2010).

Determination of characteristic wavelengths

In order to find out the CWs needed for identification of cabbages and weeds, the score of each PC, accumulative confidence level, and loading diagrams resulting from the former PCA and the relationship between PC and original wavebands expressed through loading graph should be analyzed. According to the loading graph of wavelength variable responding to the optimum PCs obtained from the former analysis, the wavelengths greatly (positive and negative) correlating with PCs were selected as the characteristic wavelengths sensitive to the identification of various of plants and with higher correlation for establishing the identification models. The loading coefficients of the selected wavelengths were used to reflect the importance of the wavelengths to the PCs.

Bayesian classification model

Bayes' theorem (Bayes 1764)

Mathematically, Bayes' theorem gives the relationship between the probabilities of events *A* and *B*, *P*(*A*) and *P*(*B*), and the conditional probabilities of *A* given *B* and *B* given *A*, *P*(*A*|*B*) and *P*(*B*|*A*). The form of Bayesian inference is mostly expressed as follows, provided that *P*(*B*) ≠ 0.

$$P(A|B) = [P(B|A)P(A)] / P(B)$$

Probability measures a degree of belief. Bayes' theorem then links the degree of belief in a proposition before and after accounting for evidence. For example, suppose somebody proposes that a biased coin is twice as likely to land heads than tails. Degree of belief in this might initially be 50%. The coin is then flipped a number of times to collect evidence. Belief may rise to 70% if the evidence supports the proposition.

For proposition *A* and evidence *B*, *P*(*A*), the prior, is the initial degree of belief in *A*. *P*(*A*|*B*), the posterior, is the degree of belief having accounted for *B*. The quotient *P*(*B*|*A*)/*P*(*B*) represents the support *B* provides for *A*.

The event *B* is fixed in the discussion, and we wish to consider the impact of its having been observed on our belief in various possible events *A*. In such a situation, the denominator of the last expression, the probability of the given evidence *B* is fixed; what we want to vary is *A*. Bayes theorem then shows that the posterior probabilities are proportional to the numerator:

$P(A|B) \propto P(A) \cdot P(B|A)$ (proportionality over *A* for given *B*).

Further, if events *A*1, *A*2, …, are mutually exclusive and exhaustive, that is, one of them is certain to occur but no two can occur together, and we know their probabilities up to proportionality, then we can determine the proportionality constant by using the fact that their probabilities must add up to one. For instance, for a given event *A*, the event *A* itself and its complement -*A* are exclusive and exhaustive. Denoting the constant of proportionality by *c* we have:

$P(A|B) = c \cdot P(A) \cdot P(B|A)$ and $P(-A|B) = c \cdot P(-A) \cdot P(B|-A)$

Adding these two formulas, we deduce that,

$$c = \frac{1}{P(A)\Box P(B|A)+P(-A)\Box P(B|-A)}$$

For that the extended form, often, for some partition $\{A_j\}$ of the event space, the event space is given or conceptualized in

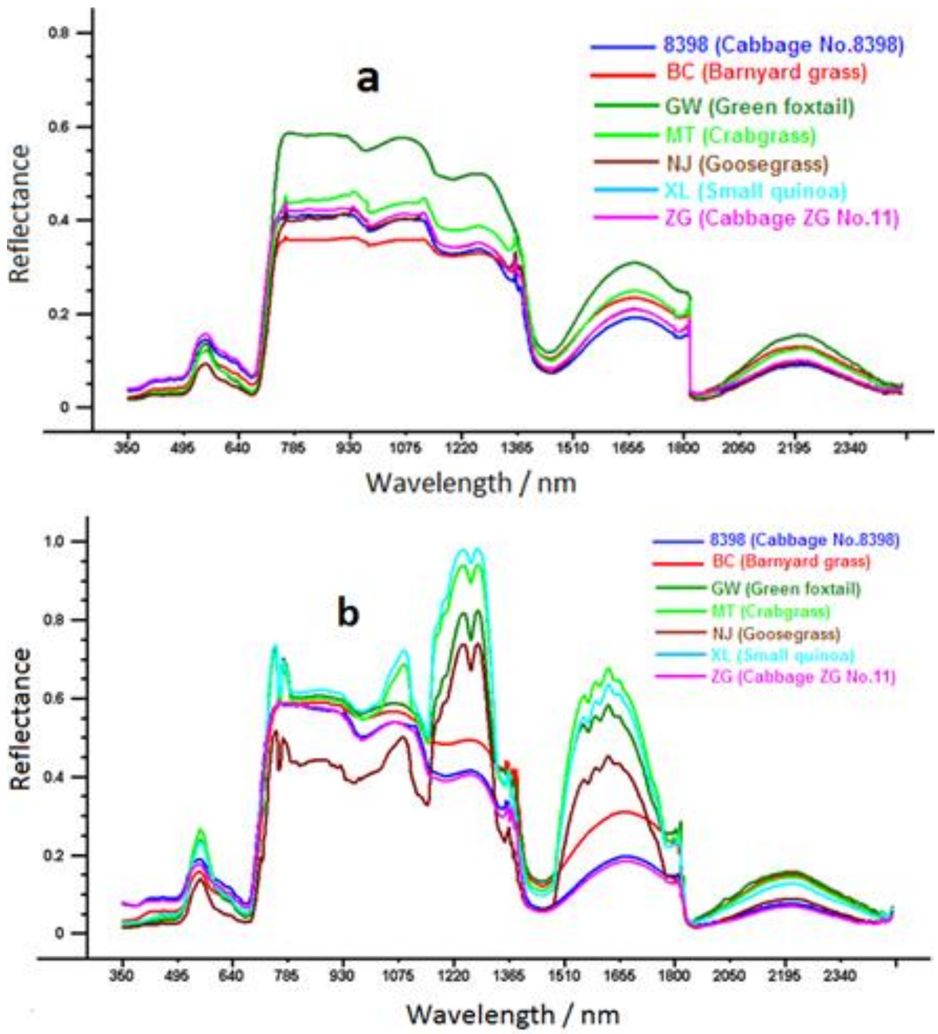

Figure 1. Curves of average spectral reflectance of seven plants. (a) Curves of average spectral reflectance at five WGS. (b) Curves of average spectral reflectance at seven WGS.

terms of $P(A_j)$ and $P(B|A_j)$. It is then useful to compute $P(B)$ using the law of total probability:

$$P(B) = \sum_j P(B|A_j)P(A_j)$$

$$\Rightarrow \quad P(A_i|B) = \frac{P(B|A_i)P(A_i)}{\sum_j P(B|A_j)P(A_j)}$$

Bayesian modeling

Using the eight CWs determined from the data at five WGS as the input variables, the discrimination model was built based on the Bayesian criterion and used to discriminate the cabbages and the weeds. In the process, 7 different plants were separately labeled using categorical variables as Y-8398 (cabbage 8398), ZG (cabbage Zhonggan 11), BC (Barnyard grass), GW (*Setaria viridis*), MT (crabgrass), NJ (*Eleusine indica*), and XL (*C. quinoa*). For each plant, two-thirds of the samples were randomly selected as the training group (140 samples) so that all the samples for the 7 plants were divided into two groups for training and testing, respectively. Then, using the data of categorical variables and 8 CWs, the discrimination model was built. In order to verify the reliability and robustness of the model, the other one-third of the samples (70 samples) were used as the testing group and the input of the model to classify the cabbage and weed samples.

RESULTS AND DISCUSSION

Data observation

Further, the 30 averaged data were averaged for each variety of the plants. Figure 1 shows the averaged spectral reflectance curves for each of the plants. It can be seen that the curves are all the same as the typical healthy plant spectral reflectance curves. In the vicinity of

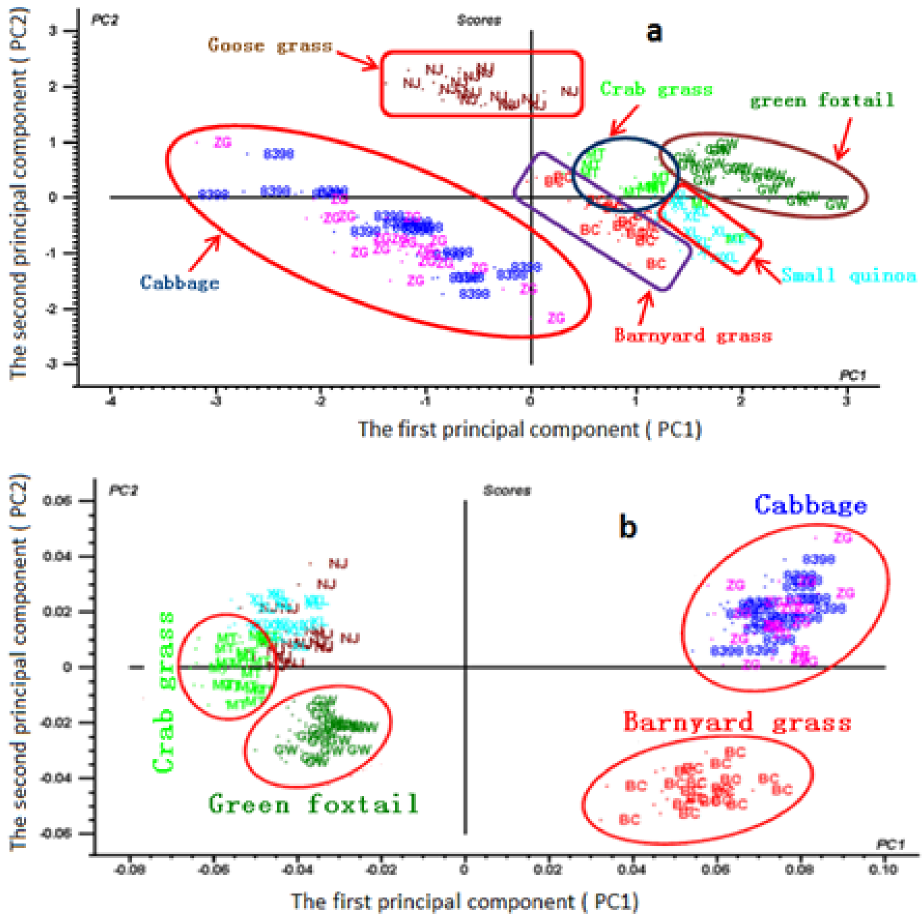

Figure 2. The clustering graphs of PCs obtained after preprocessing. (a) The clustering graph of the plants and weeds at five WGS. (b) The clustering graph of the plants and weeds at seven WGS.

450 and 650 nm, the light of blue and red bands is absorbed by chlorophylls for photosynthesis, leading to two distinct absorption valleys. At 550 nm, the light of green light is partly absorbed by chlorophylls and partly reflected, forming a reflection peak. A steep slope at 700 to 800 nm demonstrates a sharp increase of reflectivity to form a high reflection platform. In the range of 800 to 1300 nm, the porous parenchyma tissue (spongy tissue) of plant leaves have always a very strong reflection to near-infrared light, creating a peak area of reflectance on spectral curves with the reflectance up to 40%. At about 1450 and 1950 nm, an apparent absorption valley is formed due to the cell sap, cell membranes, and absorbed vapor of the plant leaves.

Particularly, it is shown in Figure 3 that for the spectral reflectance curves at the first WGS, the spectral reflectivity of green foxtail in the range of 700 to 1800 nm is obviously higher than other plants, while the spectral reflectivity of crabgrass comes to the next. In the range of 750 to 1100 nm, the reflectance of Barnyard grass is lower than other plants, while the spectral reflectivity of cabbages is modest and the spectral curves of two cabbages are almost superimpose. For the spectral curves at the seven WGS, the spectral reflectance curve of goosegrass is obviously distinct from other plants. It is seen that the curves of cabbages are relatively stable while the curves of weeds fluctuate dramatically, which could be a characteristic used to differentiate cabbages from weeds. In overall, there are some differences between the spectral curves of cabbages and weeds, but the spatial distributions of some samples overlap, which make it difficult to exactly distinguish the variety of each sample. In order to accurately classify cabbages and weeds, quantitative discriminant models should be established.

Clustering based on PCA

In the case of optimum preprocessing, the score plot of PC 1 and PC 2 of the training set is shown in Figure 2, in which the horizontal axis presents the score value of the

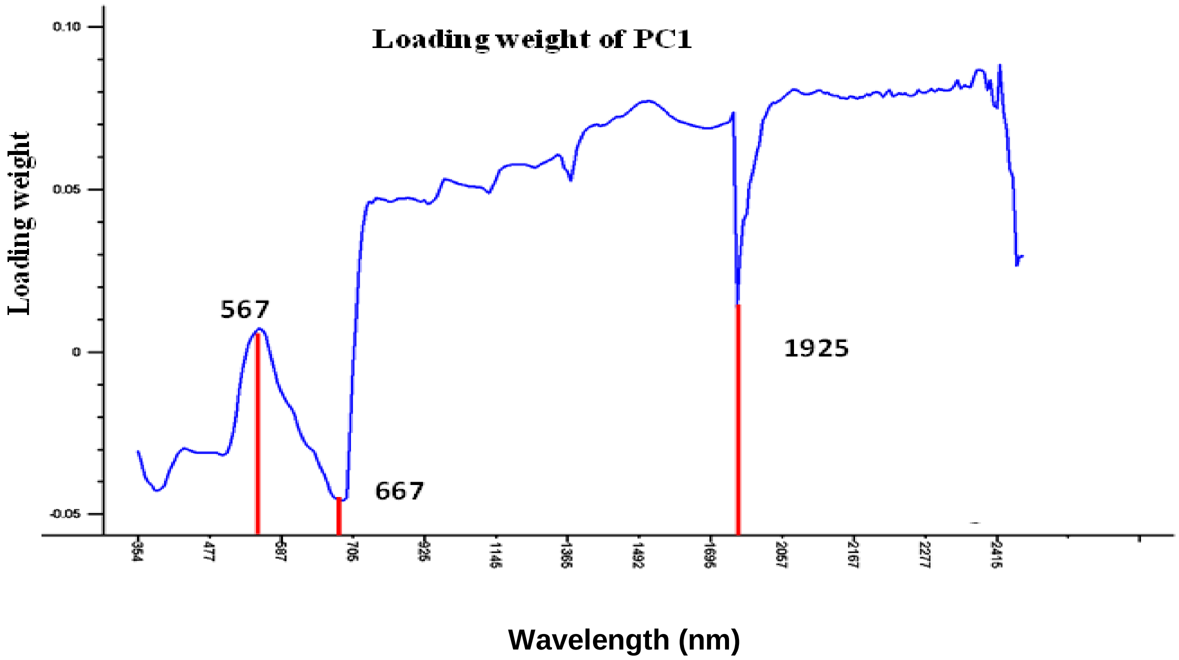

Figure 3. Loading graph corresponding to the PC1 in modeling the data at five WGS.

first PC and the vertical axis is the score value of the second PC. It can be seen from Figure 2a that the data samples of cabbages mainly concentrate in the second and third quadrant, goosegrass samples mainly in the upper area of the second quadrant, crabgrass and green foxtail samples in upper area of the first quadrant, Barnyard grass and *C. quinoa* principally around the horizontal axis in the fourth quadrant. It can be found from Figure 2b that cabbage samples closely distributing in the first quadrant show a good degree of aggregation which indicates that the two varieties of cabbages can be regarded as the same category. As well in a good degree of aggregation, all the Barnyard grass samples closely gather in the fourth quadrant and all the green foxtail in third quadrant. Although crabgrass samples distribute in both the second and third quadrant, the aggregating degree is still high. The samples of *C.quinoa* and goosegrass loosely gather in the second quadrant. Therefore, it illustrates that PC1 and PC2 have better contribution to clustering cabbages and weeds. The synthetic method of PCA and clustering analysis can not only to a large extent reduce the data dimension but also greatly express the features of original data without losing the effective information.

Determining CWs

The loading diagrams corresponding to the optimum PCs obtained from spectral data processing at five and seven WGS are respectively shown in Figures 3 and 4. In the diagram, only the first PC is shown. In the loading diagrams, the horizontal coordinate represents the wavelength and the vertical coordinate is the load factor (that is, the correlation between wavelength and plant species) of each wavelength, wherein, the larger the absolute value of the corresponding load factor of a wavelength variable is, the stronger the correlation between the PC and the corresponding load factor is, and the more sensitive to the discrimination of the plant species.

It could be found from the loading diagrams that obvious crests and troughs present at some wavelengths and the rates of change of corresponding load factors appear as local maximum/minimum. These wavelengths are likely to play a decisive role in the identification of cabbages and weeds (Piron et al., 2011). Whereby, the corresponding CWs selected from the loading diagrams were 552, 567, 602, 607, 667, 715, 725, 1345, 1402, 1447, 1725, 1925, 1945, 1955, 2015, and 2072 for the five WGS plants and 425, 567, 667, 685, 745, 755, 1095, 1135, 1155, 1235, 1315, 1345, 1385, 1402, 1435, 1535, 1545, 1625, 1725, 1805, 1815, 1925, and 2030 for the seven WGS plants. The number of the CWs selected from the spectral data in the five and seven WGS was respectively 16 and 23.

Although the dimension of the data was already greatly reduced relative to the original data, the number of the band data is still relatively large for a practical instrumental design and development for agricultural use. Therefore, the selected CWs needed to be further optimized. The optimization process was to start with the

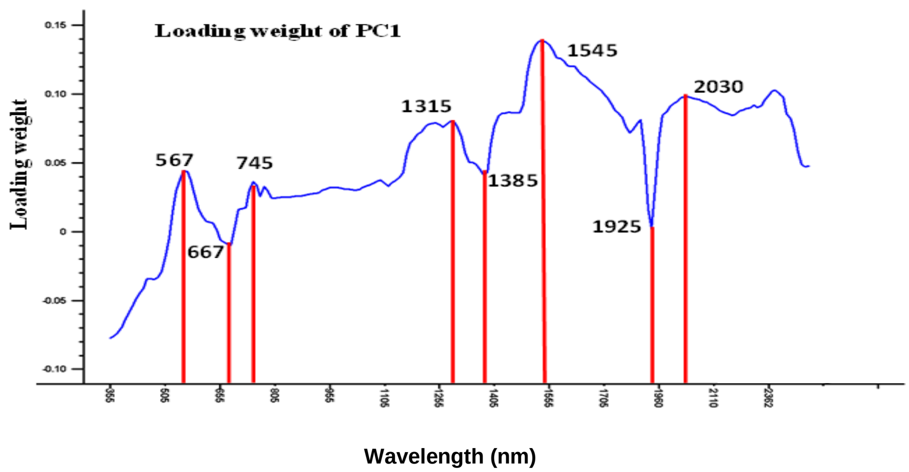

Figure 4. The corresponding loading diagram of PC1 in modeling the data at seven WGS.

first PC by sorting of wavelengths in terms of the absolute value of the corresponding load factors. Then, the wavelengths were further selected at which the absolute value of load was large and obvious crests and troughs were present in the loading diagrams. As the result, the selected CWs were 567, 667, 715, 1345, 1402, 1725, 1925, and 2015 nm for five WGS and 567, 667, 745, 1345, 1402, 1545, 1725, and 1925 nm at seven WGS (Table 1). In order to evaluate the effect of the selected CWs, the identification models were built using these CWs.

Among the each 8-CW set further determined respectively at two growth stages, just two of them were different as highlighted in bold in Table 1, which indicated that the change of the growth stage of cabbages and weeds had limited influence on the spectral features.

Bayesian classification

Based on the method mentioned in earlier, the discriminant functions of the classification models were obtained as follows in Equation 1, in which, the input variables (x1, x2, …, x8) are the eight CWs extracted from the data at the five WGS through PCA method.

$$BC = -49.89 + 75.11x_1 + 976.62x_2 - 247.88x_3 + 8.52x_4 + 184.98x_5 + 360.82x_6 + 115.39x_7 - 464.08x_8$$
$$GW = -68.91 + 1116x_1 + 745.44x_2 - 1112x_3 + 677.47x_4 - 436.09x_5 + 222.38x_6 + 44.97x_7 - 216.67x_8$$
$$MT = -45.98 + 213.48x_1 + 668.17x_2 - 309.73x_3 + 300.99x_4 + 149.24x_5 - 24.16x_6 + 114.15x_7 - 285.32x_8$$
$$NJ = -41.12 + 187.37x_1 + 725.07x_2 - 422.14x_3 + 663.92x_4 - 98.88x_5 - 338.86x_6 + 127.71x_7 - 76.97x_8 \quad (1)$$
$$XL = -93.59 - 3026x_1 + 1839x_2 + 1459x_3 - 329.18x_4 + 78.99x_5 + 600.50x_6 - 3.27x_7 - 331.96x_8$$
$$Y\text{-}8398 = -83.34 - 1803x_1 + 1380x_2 + 1344x_3 + 39.46x_4 - 148.77x_5 - 358.52x_6 + 87.37x_7 + 218.22x_8$$
$$ZG = -88.29 - 1874x_1 + 1398x_2 + 1432x_3 - 118.03x_4 - 87.21x_5 - 211.36x_6 + 54.09x_7 + 172.79x_8$$

The frequency numbers of each training sample and the misclassified rates of the plants for 7 different plants discriminated into various categories are exhibited in Table 2.

In training data classification, five Cabbage ‘8398’ samples were misclassified as Cabbage ‘Zhonggan No.11’ and four ‘Zhonggan No.11’ as ‘ 8398’, which was because they are all cabbages with the identical internal structure and the similar pigment and appearance. Therefore, it is apparent that different varieties of cabbages can be considered in the same category. In addition, one Barnyard grass was misclassified as crabgrass, one crabgrass was misclassified as goosegrass, and two crabgrasses were misclassified as crabgrass, which is perhaps because they are all monocotyledonous weeds with similar internal structure and composition. Total of 13 samples in the training set were falsely classified and the misclassified rate is 0.0929, which is translated to 90.7% of the overall correct classification rate.

The classification results of the testing set showed that three Cabbage ‘8398’ were misclassified as Cabbage ‘Zhonggan No.11’ and six Cabbage ‘Zhonggan No.11’ were misclassified as ‘8398’. Moreover, one crabgrass was misclassified as goosegrass and one crabgrass was misclassified as Barnyard grass. Total of 11 samples were misclassified, therefore the misclassified rate is 0.1571. Then, the correct classification rate is 84.3%.

In order to verify the similarity of the spectral characteristics of different varieties of cabbages, cabbage ‘8398’ and ‘Zhonggan No.11’ were combined into one category. The 8 CWs which had been used earlier were still used as the input variables. All varieties of plants

Table 1. The CWs selected from the loading diagrams of PC at the first and second selection.

Selection	Testing stage	Characteristic wavelengths (CWs) / (nm)
First selection	Five WGS	552, 567, 602, 607, 667, 715, 725, 1345, 1402, 1447, 1725, 1925, 1945, 1955, 2015, and 2072
	Seven WGS	425, 567, 667, 685, 745, 755, 1095, 1135, 1155, 1235, 1315, 1345, 1385, 1402, 1435, 1535, 1545, 1625, 1725, 1805, 1815, 1925, and 2030
Second selection	Five WGS	567, 667, **715**, 1345, 1402, 1725, 1925, **2015**
	Seven WGS	567, 667, **745**, 1345, 1402, **1545**, 1725, 1925

Table 2. Frequency numbers of samples classified into seven categories and rates of misclassification in Bayesian analysis.

Sample		Categories							
		Barnyard grass	Green foxtail	Crabgrass	Goosegrass	*Chenopodium quinoa*	Cabbage '8398'	Cabbage 'zhonggan 11'	Overall samples
Training samples	Barnyard grass	19	0	1	0	0	0	0	-
	Green foxtial	0	20	0	0	0	0	0	-
	Crabgrass	0	0	19	1	0	0	0	-
	Goosegrass	0	0	2	18	0	0	0	-
	Chenopodium quinoa	0	0	0	0	20	0	0	-
	Cabbage '8398'	0	0	0	0	0	15	5	-
	Cabbage 'zhonggan 11'	0	0	0	0	0	4	16	-
	Overall samples	19	20	22	19	20	19	21	-
Testing samples	Barnyard grass	10	0	0	0	0	0	0	-
	Green foxtial	0	10	0	0	0	0	0	-
	Crabgrass	1	0	8	1	0	0	0	-
	Goosegrass	0	0	0	10	0	0	0	-
	Chenopodium quinoa	0	0	0	0	10	0	0	-
	Cabbage '8398'	0	0	0	0	0	7	3	-
	Cabbage 'zhonggan 11'	0	0	0	0	0	6	4	-
	Overall samples	11	10	8	11	10	13	7	-
Rates of misclassification	Prior probability	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	0.1429	1.0000
	Rates of misclassification of the training sample set	0.0500	0.0000	0.0500	0.1000	0.0000	0.2500	0.2000	0.0929
	Rates of misclassification of the testing sample set	0.0000	0.0000	0.2000	0.0000	0.0000	0.3000	0.6000	0.1571

Table 3. Frequency numbers of samples classified into six categories and rates of misclassification in Bayesian analysis.

Sample		Categories						
		Barnyard grass	Green foxtail	Crabgrass	Goosegrass	*Chenopodium quinoa*	Cabbage	Overall samples
Training samples	Barnyard grass	20	0	0	0	0	0	
	Green foxtial	0	18	1	1	0	0	
	Crabgrass	1	0	16	3	0	0	
	Goosegrass	1	0	0	19	0	0	
	Chenopodium quinoa	0	0	0	0	20	0	
	Cabbage	0	0	0	0	0	40	
	Overall samples	22	18	17	23	20	40	
Testing samples	Barnyard grass	10	0	0	0	0	0	
	Green foxtial	0	10	0	0	0	0	
	Crabgrass	0	0	10	0	0	0	
	Goosegrass	0	0	0	10	0	0	
	Chenopodium quinoa	0	0	0	0	10	0	
	Cabbage	0	0	0	0	0	20	
	Overall samples	10	10	10	10	10	20	
Rates of misclassification	prior probability	0.1429	0.1429	0.1429	0.1429	0.1429	0.2857	1.0000
	Rates of misclassification of the training sample set	0.0000	0.1000	0.2000	0.0500	0.0000	0.0000	0.0500
	Rates of misclassification of the testing sample set	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

were labeled by categorical variables as GL (cabbage), BC (Barnyard grass), GW (*S. viridis*), MT (crabgrass), NJ (*E. indica*) and XL (*C. quinoa*). By repeating the previous process, the discriminant functions were obtained and shown as in Equation 2 and the classification results are shown in Table 3.

$$BC = -50.96 + 3412x_1 - 3703x_2 - 1259x_3 + 1986x_4 + 301.55x_5 - 400.99x_6 + 341.52x_7 - 79.76x_8$$
$$GW = -74.97 + 626.77x_1 - 2181x_2 - 1144x_3 + 1988x_4 + 246x_5 - 27.37x_6 + 89.15x_7 - 30.93x_8$$
$$MT = -53.05 + 2481x_1 - 3611x_2 - 906.51x_3 + 1878x_4 + 356.56x_5 - 300.68x_6 + 176.24x_7 - 27x_8 \quad (2)$$
$$NJ = -42.19 + 3054x_1 - 3533x_2 - 1284x_3 + 1688x_4 + 280.05x_5 - 146.62x_6 + 75.17x_7 - 1.76x_8$$
$$XL = -72.26 - 5909x_1 + 7404x_2 - 1905x_3 + 585.01x_4 + 241.69x_5 - 821.22x_6 + 1190x_7 - 356.42x_8$$
$$GL = -73.44 + 4979x_1 - 5095x_2 - 744.15x_3 + 2056x_4 + 59.29x_5 + 981.29x_6 - 1335x_7 + 374.43x_8$$

From the results of the training set, for green foxtails, one was misclassified as crabgrass and one other as goosegrass; one crabgrass was misclassified as Barnyard grass and three were misclassified as goosegrass; one goosegrass was misclassified as Barnyard grass. Overall, the misclassified rate is 0.05, that is, the correct classification rate was 95%.

From the results of the testing set, all the samples were correctly classified therefore its correct classification rate was 100%. Compared with the previous correct classification rate from which the two varieties of cabbages were considered as two separate categories, the current correct classification rate had been greatly raised.

Conclusion

Using the ASD 350 to 2500 nm FieldSpec-FR spectroradiometer, the canopies of the seedling plants, cabbage '8398, cabbage 'zhonggan', Barnyard grass, green foxtail, goosegrass, crabgrass, and small quinoa, at five- and seven-week growth stages were measured. The results were concluded as follows:

(1) In terms of the load factors and the changing rate of the PCs, eight CWs which were sensitive to plant identification, were determined, respectively for the first growth stage of cabbages (five WGS) and the second growth stage (seven WGS). Among the 8 CWs for each growth stage, only two of them were different, which indicates that different growth stages of the cabbages have limited impact on the plant spectral characteristics for identification of cabbages and weeds.

(2) The corresponding spectral data of the 8 CWs determined from the data at the five WGS were used as the input variables of the Bayesian discriminant model to classify two varieties of cabbages and five different weeds. The correct classification rates for the training and testing sets were 90.7 and 84.3%, respectively. When the two varieties of cabbages were combined into the same category, the correct classification rates of the training and testing sets were improved to 95 and 100%, respectively, which indicates that different varieties of cabbages have similar spectral features to limit weed classification. Therefore, combining different varieties of cabbages as the same category could be effective to greatly improve the correct classification rates of weeds compared with the condition in which two varieties of cabbages were treated as different categories.

(3) The study results showed that Bayesian discriminant analysis could be used to identify weeds from seedling cabbages using leaf hyperspectral reflectance.

Conflict of Interests

The authors have not declared any conflict of interests

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Root system and yield of sugarcane cultivated under different amounts of straw in southern Brazil

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The amount of straw of sugarcane needed to remain in field for sustainability of the production system and quantity that could be used in sectors such as cogeneration and production of bioethanol for optimization of power generation by the sector are unclear issues. The aim of this study was to evaluate the effect of different amounts of straw on the development of the sugarcane root system and yield using the variety SP 801816 in a Rhodic Eutrudox in southern Brazil. Six treatments were evaluated: 0 (no straw), 25, 50, 75 and 100% (20 Mg ha^{-1}) of straw and straw burned at 60, 180 and 270 days after planting in 150 m^2 plots. Root samples were collected at 0.45 and 0.75 m from the planting line at depths of 0-0.10, 0.10-0.20, 0.20-0.40 and 0.40 to 0.60 m at harvest, and the stems of the plots were weighed to measure yield. In water stress period, the 50, 75 and 100% straw treatments promoted a greater root mass to 0.20 m deep, which was also reflected in the yield. The 50 and 75% straw treatments resulted in 25% greater yield than the 0 and 25% straw and straw burned, resulting in 28 Mg ha^{-1} more. The amount, 50% straw retention in the field is sufficient to increase the mass of the roots and, in turn, productivity, which is possible to remove the 50% surplus from the field for industrial processes for the production of energy, without the occurrence of damage to the crop.

Key words: Green cane, biomass, mechanized harvesting, agricultural waste, *Saccharum* spp.

INTRODUCTION

Brazil supplies over 50% of the sugar sold globally and is the largest producer of sugar and sugarcane ethanol. The mechanized harvest of sugarcane, without straw removal by burning, is currently practiced in the main sugarcane production areas in Brazil, and this practice is increasing in current production areas (Viana et al., 2008). According to Oliveira et al. (1999), the straw that remains on the soil after harvest may range from 8-30 t ha^{-1} due to the variety and age of the plantation. This residue layer generates physical, chemical and biological changes in

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the agricultural environment which may interfere with rooting and, in turn, influence the final yield (Souza et al., 2005a; Costa et al., 2011).

Changes in the agricultural environment caused by the residue layer include the increase and stabilization of moisture and soil temperature, elevated levels of organic matter, improved fertility, greater efficiency in erosion control, and interference with light interception by the soil surface (Christoffoleti et al., 2007; Cavenaghi et al., 2007; Garcia et al., 2007; Guimarães et al., 2008, Panosso et al., 2010;, Shukla et al., 2013; Awe et al., 2014).

Despite the fact that root system of sugarcane play a vital role in the regeneration of ratoons after harvest, the root system has often been neglected in research, mainly due to the difficulty of observation, especially in field evaluations. The roots directly influence the efficiency of the absorption of nutrients by the plant, which affects drought resistance and tolerance to soil pests. These impacts are reflected in both the development of the culture and the final yield. According to Smith et al. (2005), root growth is dependent on the soil environment, which influences the shape and size of the root system, and the greater the mass of the roots, the higher the water and nutrient holding capacities.

Vasconcelos and Garcia (2005) states that death or renewal of the root system does not follow cane cutting but rather the water conditions to which the culture is exposed in a given period of development. In this way, the microclimate created by surface residue, characterized by high relative humidity, restriction of soil water loss and temperature stability, provides greater water availability than is found in bare soil. This can change the behavior of the roots and help minimize the decline from one production cycle to another, particularly during periods of water deficit.

Ball-Coelho et al. (1993) reported the positive effects of straw on the productivity of sugarcane under low or irregular rainfall, showing an increase of 43% in dry matter production of sugarcane in soil under straw.

Several authors describe the benefits of retaining sugarcane straw on the soil; however, the amount that is sufficient to promote such benefits and the effects of retaining smaller amounts, has not yet been investigated. Determining the minimum amount of straw to leave in the field is paramount to the sustainability of the sugarcane production system. This information also affects the energy generation sector because excess straw can be used for producing bioethanol and/or bioelectricity, sectors that have high demand for this material. (Azad et al., 2014). It is estimated that the use of straw and bagasse could triple Brazilian ethanol production (without increasing the plantation area) and this would produce the equivalent of 15% of the total energy consumed in Brazil by 2020 (Lima and Natalense, 2010).

Given the importance of this information and the lack of current literature, the aim of this study was to evaluate the effect of different amounts of straw on the sugarcane root system and its productivity in the first crop cycle (plant cane) using the variety SP801816 in a Rhodic Eutrudox soil.

MATERIALS AND METHODS

This experiment was conducted at the Sugar and Alcohol Plant Bandeirantes, in the municipality of Bandeirantes, PR, at latitude 23° 06 'S and 50° 21' W 440 m. The climate in the region is Cfa (Koeppen climate classification), with annual rainfall of 1300 mm (average of 30 mm in the driest month).

The climatic water balance (Figure 1) was calculated according to Thornthwaite and Mather (1955). Monthly average temperature and total monthly rainfall data from the weather station network of the Agronomic Institute of Paraná (IAPAR), located in Bandeirantes-PR, three kilometers from the experimental site, were used. For the available water capacity (CAD), 100 mm was used. The soil is classified as Rhodic Eutrudox (Santos et al., 2013) with a clayey texture. A particle size analysis showed that this soil was 61% clay, 2% silt and 37% sand.

The apparent density and the soil chemical analyzes were performed in layers from 0-0.10, 0.10-0.20, 0.20-0.40 and 0.40-0.60 m deep in the soil profile before the initiation of the experiment, both according to methodology described by the EMBRAPA (1997). The apparent density of soil was evaluated using the volumetric ring method (internal volume of 50 cm^3) to verify the physical existence impediment to the development of the roots. The values of apparent density of soil in the layers were respectively, 1.33, 1.30, 1.30, 1.29 (g cm^{-3} of the soil).

The soil chemical analyzes results are described in Table 1. There was no need for chemical fertilizers. Prior to planting, 70 Mg ha^{-1} of filter cake was applied across the entire area after harvest to replenish the potassium extracted by the crop. The soil was prepared with a light harrowing, using a disk harrow.

In the experimental area, sugar cane has been grown for 65 years. During this period, a manual harvesting method with straw removal by burning was used, and in 2010, the plant adopted a mechanized harvesting system and an on-site test was conducted. The experiment was installed in August 2010 and conducted over a crop cycle (plant cane) in a randomized block design with four replications. Each plot consisted of 10 rows of sugarcane (variety SP 80-1816) that were 10 m long (10 x 10 m, 100 linear meters) with a 1.5 m spacing between rows. The data were collected on the six central lines, subtracting 0.50 m from each end. The harvest occurred in September 2011. The authors evaluated six treatments: 0 (no straw), 25 (5 Mg ha^{-1}), 50 (10 Mg ha^{-1}), 75 (15 Mg ha^{-1}), 100% (20 Mg ha^{-1}) and straw burned (20 Mg ha^{-1} of the straw was burned) on the root system of sugarcane at 60, 180, 270 days after planting (DAP) and on yield at 390 DAP.

The straw used was collected after mechanical harvesting in a cultivation area with the same variety of cane, which were demarcated in plots with the same measures as the experimental area. The amount of residue produced by this variety was estimated from the weight of the dry matter collected at each site. After weighing, the straw was evenly distributed over the experimental site, immediately after planting, according to the percentage required for each treatment.

To evaluate the root system, small trenches were opened between the rows (dimensions of 0.80 × 1.00 × 0.80 m, width, length and height, respectively) and metal cylinders (0.074 m diameter and 0.10 m height) were used for sampling, resulting in a volume of 0.00043 m^3 ring (Azevedo et al., 2011). These were spiked with the aid of a hydraulic tensioner in the trench

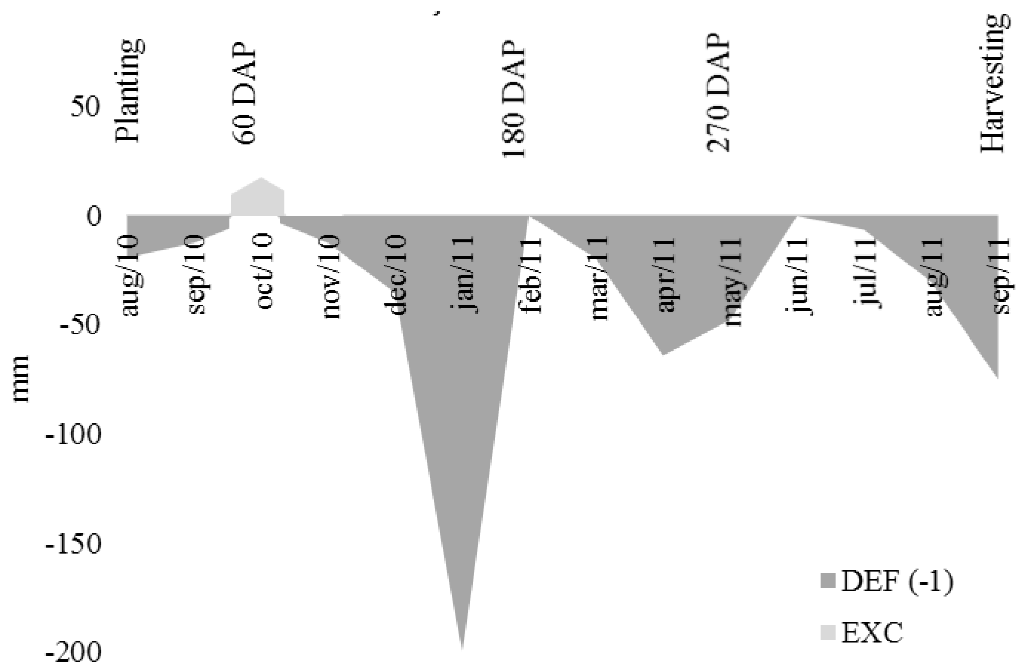

Figure 1. Extract of the monthly water balance during the experimental period. *DAP: Days after planting.

Table 1. Results of the chemical analysis of soil Rhodic Eutrudox at depths of 0 to 0.60 m, Municipality Bandeirantes - PR, 2010.

Prof.	M.O	pH	P*	K	Ca	Mg	H+Al	CTC	K	Ca	Mg
(m)	g kg^{-1}	$CaCl_2$	mg dm^{-3}			Cmolc dm^{-3}				% Saturation	
0–0.10	26.8	5.4	8.6	2.50	7.8	1.7	3.1	15.1	16	52	11
0.10–0.20	41.6	5.9	71.3	3.60	7.9	1.9	2.9	16.3	22	49	12
0.20–0.30	34.9	6.1	31.0	3.70	8.0	2.1	3.0	16.8	22	48	12
0.30-0.40	30.9	6.2	5.1	4.60	8.1	2.1	2.2	17.0	27	48	12
0.40–0.50	37.6	6.3	9.0	4.20	7.3	2.0	2.4	15.9	26	46	13
0.50–0.60	28.2	6.3	5.3	3.20	6.1	2.1	2.4	13.8	23	44	15

Methodology Embrapa (1997). *Used Melich extractor.

perpendicular to the seed row.

The volume of roots was evaluated horizontally, at a distance of 0.45 and 0.75 m from the planting line, at depths from 0 to 0.10, 0.10 to 0.20, 0.20 to 0.40 and 0.40 to 0.60 m, with four replicates per treatment (Figure 2). Each repetition consisted of three surveys conducted in each plot, to provide representation results. Subsequently, samples were taken to the Roots Study Laboratory, Department of Agriculture, Universidade Estadual de Londrina. Each sample was placed in a plastic bucket with water and stirred manually, then the water and roots in suspension were poured through a 1.0 mm mesh sieve until no soil remained.

All roots retained in the sieves were collected and held in a greenhouse at 65°C until they reached a constant weight. After drying, the roots were weighed on a precision balance, and the results are reported as roots mg per cm3 of soil at each depth.

The fresh mass of stems in milligrams of cane per hectare (Mg ha-1) was evaluated at 390 DAP (September 2011) by collecting all stems contained in the useful area of the plots. Green leaves were dried, tip clipped and then weighed.

The data were subjected to an analysis of variance (ANOVA) and means were compared using Tukey's test at 1 and 5% significance levels. The software Sisvar 5.3 (Ferreira, 2010) was used for the analyses.

RESULTS AND DISCUSSION

According to Tomé Jr. (1997), fertile soil with a good nutritional status has the following: 3 to 5% K, 10 to 15% Mg and 50 to 70% Ca. At a depth of 0.60 m, it was observed that the Ca content was very close to the range considered appropriate for that nutrient, and the Mg

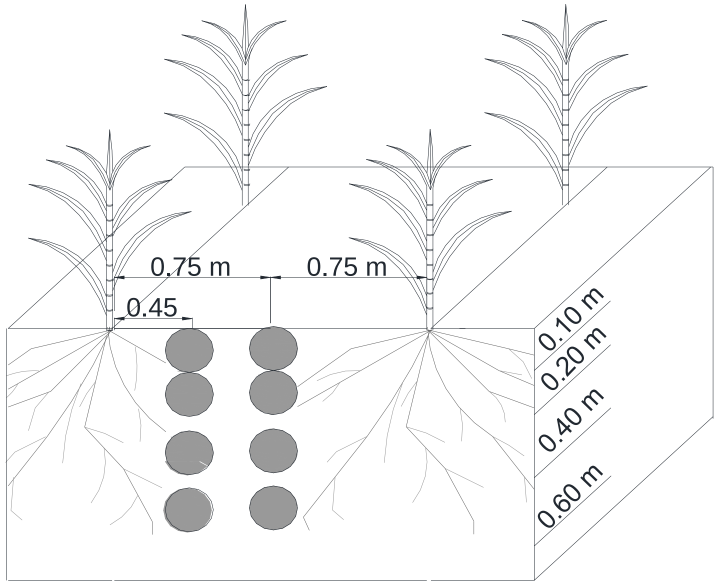

Figure 2. Schematic drawing showing the planting line distances (0.45 and 0.75 m) and depths (0-0.10; 0.10-0.20; 0.20-0.40 and 0.40 to 0 60 m) for rings used to sample the roots.

content was at the proper range for all measured depths (Table 1).

K showed a high saturation (above 20%), which may be because this nutrient is not connected to any organic constituent, is easily leached, and the concentration will decrease to the proper range during the rainy season because there were no new vinasse or mineral fertilizer applications.

Phosphorus (Table 1) showed adequate levels in the 0.30 to 0.40 and 0.50 to 0.60 m layers but was high in the other layers (Sousa and Lobato, 2004). Notably, the soil did not show any chemical (Table 1) or physical impediments to root growth. At 60 DAP, there were no roots at the 0.45 to 0.75 m distance from the planting line. At 60 DAP, cane plants had less roots than soca cane because the cane root system begins to develop at planting. In addition, the water deficit experienced during the months of August and September (Figure 1) may have contributed to the absence of roots in this period (Vasconcelos and Garcia, 2005). Water stress is one of the main limiting factors for sprout and root growth, and also reduces the total mass of the root system.

At 0.45 m from the planting line (Figure 3), there was effect of straw on the root system to a depth of 0.20 m. At both 180 and 270 DAP, there was a greater mean root mass in the treatments with 50, 75 and 100% straw, which was higher than for the other treatments, and these treatments did not significantly differ from each other. The 25% straw treatment was insufficient to make changes at any depth, and did not differ from the treatments with 0% straw and burned cane. At 0.75 m from the planting line (Figure 4), the same was observed at 0.45 m, indicating that the straw influenced the root system to the middle of the spacing.

Comparing the dry mass of roots (mg cm^{-3} soil) in both periods, we observed an increase in the amount of roots at 270 DAP at 0.20 to 0.40 m and at 0.40 to 0.60 m depth, both at 0.45 and 0.75 m from the planting line (Figures 3 and 4, respectively) for all treatments. This indicates a greater depth of the root system. These results confirm those of Vasconcelos and Garcia (2005), who found that under water deficit conditions, there is an increase in roots in the deeper soil layers because humidity is maintained for a longer time in these layers and this provides less resistance to new root penetration. The significant effect of straw in the first year of cultivation may be due to the prolonged drought that occurred, with rainfall below the historical average, resulting in high water stress (up to 200 mm (Figure 1)). This drought caused low sugarcane yields throughout south-central Brazil, representing a decrease of 11.20% (CONAB, 2015). The water deficit was especially apparent in the early stages of crop development (up to 180 DAP) (Figure 1). Water deficit has a direct influence on the development of the root system. However, the results of this study show that the 50% straw treatment mitigated this effect, allowing a greater mass of roots.

The death or renewal of the roots is directly related to water availability and soil temperature. Water deficit results in a high expenditure of energy for the formation

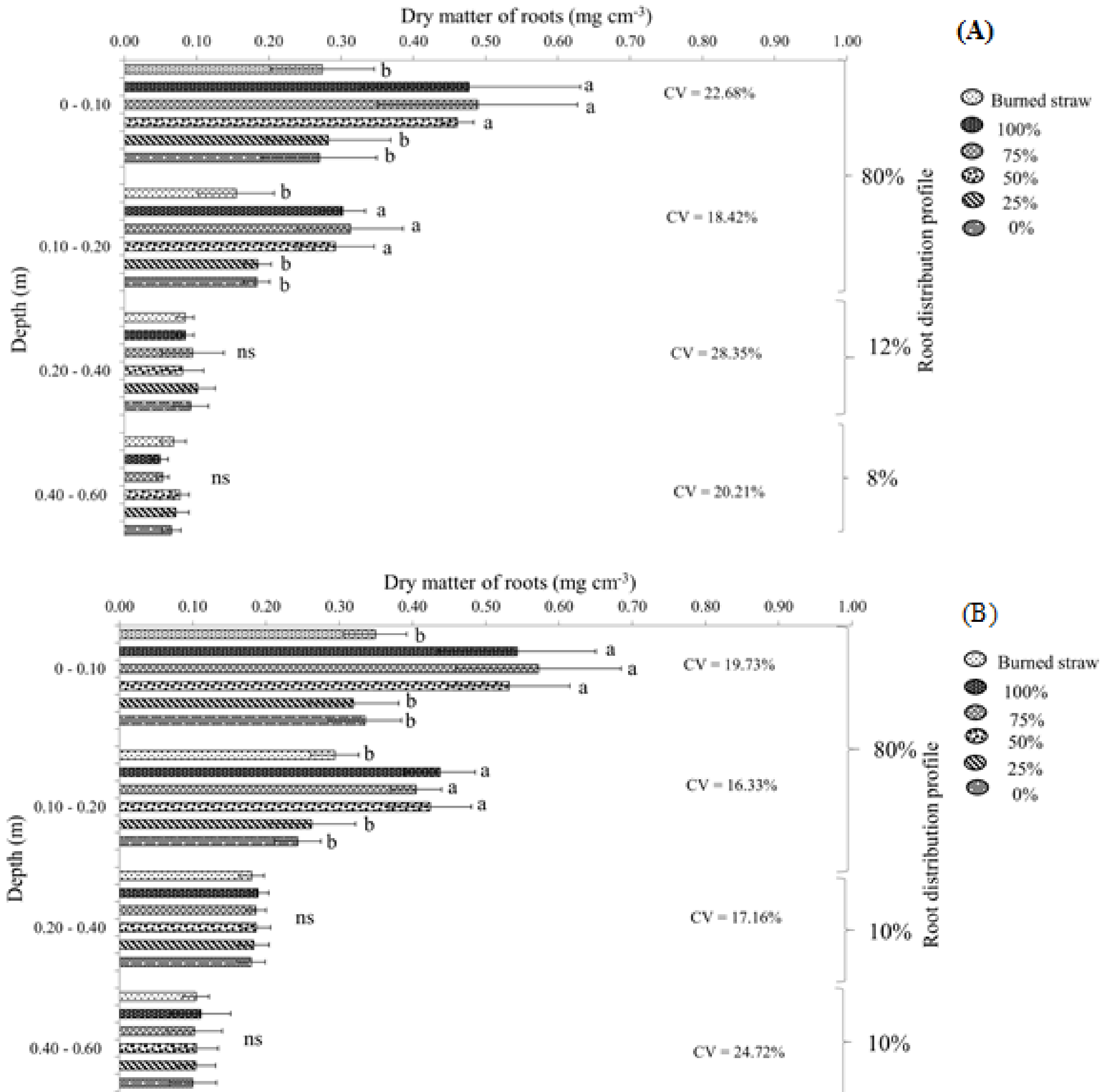

Figure 3. Dry root weight (mg) per cm^3 of soil at 0.45 m from the planting line on days 180 (a) and 270 (b) after planting (depths 0-0.10; 0.10-0.20; 0.20-0.40 and 0.40-0.60 m) and mean percentage of root distribution in the evaluated profile. Means followed by the same letter are not significantly different according to Tukey's test at the 5% significance level. ns = not significant.

of new roots, which can vary according to the time of exposure to the deficiency (Vasconcelos and Garcia, 2005), and this also impacts productivity (Tavares et al., 2010 and Costa et al., 2014).

Thus, retaining sugarcane straw residue results in the highest rate of water infiltration and retention in the soil and lowers temperatures on the soil surface (Souza et al., 2005b; Awe et al., 2015), which are important benefits for the crop, especially in periods with water stress or irregular rainfall. Others studies have reported an approximately 70% reduction in soil water loss when planting under straw (Braunbeck and Magalhães, 2010).

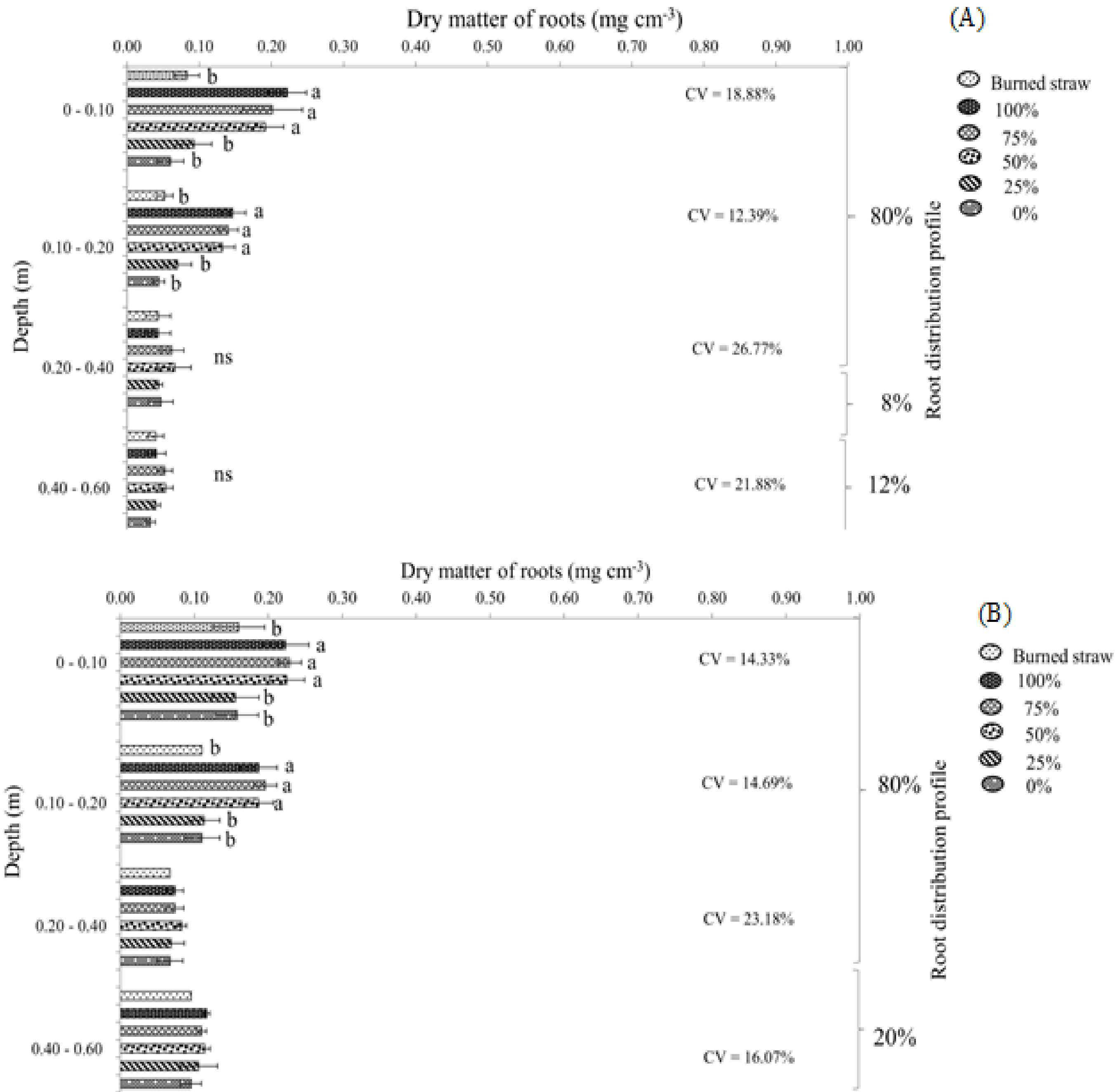

Figure 4. Dry root weight (mg) per cm^3 of soil at 0.75 m from the planting line on days 180 (a) and 270 (b) after planting (depths 0-0.10; 0.10-0.20; 0.20-0.40 and 0.40-0.60 m) and mean percentage of root distribution in the evaluated profile. Means followed by the same letter are not significantly different according to Tukey's test at the 5% significance level. ns = not significant.

In addition to the benefits gained by increased humidity, several authors (Oliveira, 1999; Resende et al., 2006) have found that as the straw decomposes, it releases nutrients into the soil, contributing to enhanced soil fertility and better rooting.

Soares et al. (2004) reported that periods of water stress can occur throughout the crop cycle, but damage to the plant and final stalk yield varies, greatly depending on the interaction between the time of the year in which the stress occurs and the plant's phenological phase. They also suggest that water stress has a greater influence on sugarcane yield when it occurs in the early

Table 2. Yield of sugarcane (Mg ha^{-1}) in relation to the amount of surface straw (%). 2010/11 Crop, Municipality of Bandeirantes, PR.

Treatment (% Straw)	Yield (Mg ha^{-1})
0	86.28 [b]
25	82.73 [b]
50	112.28 [a]
75	112.78 [a]
100	96.88 [ab]
Straw burned	89. 05 [b]
CV	6%

Means followed by the same letter are not significantly different according to Tukey's test at the 1% significance level.

stages of culture and may hinder or delay the development of the root system and aerial parts, which agrees with the results obtained in the present study. According to Soares et al. (2004), when water stress occurs in other phenological phases, yield is rarely affected.

Alvarez et al. (2000) evaluated the effects of the management of raw cane and burned cane on rooting in a Red Latosol dystrophic. They found no significant differences in the first and second years of cultivation, to a depth of 0.60 m, which differs from the results of the present study. This lack of effect of the straw may be due to differences in genotype, age and the production environment of the evaluations. Alvarez et al. (2000) reported that there were practically no adverse weather events in either year of their study. Under relatively stress-free climatic conditions, it is likely that the effect of straw is not immediate, and the effects differ across regions or periods that have less favorable conditions, such as was found in the present study.

Vasconcelos and Garcia (2005), working with six varieties of cane over two years, evaluated the root dry matter in raw cane and burned cane at 0-0.20, 0.20-0.40, 0.40 to 0.60 and 0.60 to 0.80 m soil layers. Greater root development of the harvested green cane was found in only the 0-0.20 m layer, and this is in agreement with the results of our study. Vasconcelos and Garcia (2005) attributed this difference between treatments to greater soil moisture under the straw in the dry season, a higher calcium content from the decomposition of the straw on the soil surface, and a higher content of organic matter from microbial activity on the straw.

The distribution of the roots (Figures 3 and 4) on the assessed profile (up to 0.60 m depth) was similar to that of other tropical grasses, with an exponential decline in the biomass function with depth and a variability in their distribution (Smith et al., 2005).

The actual depth was 0.20 m for the distance of 0.45 m (Figure 3) from the planting line at 180 DAP. After the new water deficit period (April and May), the depth was 0.28 m at 270 DAP. For the distance of 0.75 m (Figure 4), the effective depth was 0.34 at 180 DAP and 0.40 m at 270 DAP, confirming the results obtained by Vasconcelos and Garcia (2005). This is a characteristic of the root system of the cane plant, which explores beyond superficial soil layers, in contrast with that of ratoon (Vasconcelos and Garcia, 2005). The greatest water infiltration, low humidity and temperature in the soil were provided by the straw in the surface layers in 0 to 0.20 m. This finding is important because it allows for the development and maintenance of roots during periods of lower water availability and high temperatures, precisely at the depth where the highest concentration of roots occurs.

Medina et al. (2002) found similar results when evaluating roots of the RB 785148 variety in a Rhodic, to a depth of 0.50 m. They found that there was a higher concentration of roots in the 0 to 0.25 m layer. Costa et al. (2007) evaluated the vertical distributions of RB83-5486 and RB83-5089 cultivar roots in an Oxisol and found that there was a greater root length in the first 0.18 m of soil. The root lengths declined from a 0- to 0.18- m depth to a 0.18 to 0.36-m depth.

Straw coverage had a significant effect on final yield (Mg ha^{-1}). The 50 and 75% treatments did not differ (112 Mg ha^{-1}) and showed an average yield that was 23% higher than the 0, 25% straw and burned cane (86, 82 and 89 Mg ha^{-1}, respectively) treatments, representing an increase of 26 Mg ha^{-1} (Table 2).

It was observed that the treatments influenced the root system to 0.20 m deep, resulting in a greater mass dry root (50, 75 and 100% straw treatments) and resulting in higher yield of sugarcane.

A natural characteristic of sugarcane is that it has the highest concentration of roots in the 0- to 0.20 m layer. This layer, being superficial, is vulnerable to climatic conditions, directly influencing the root system and causing a sharp drop in production under unfavorable environmental situations. Thus, the use of a management practice that provides a greater stability in this layer will result in a more developed root system, which consequently helps mitigate yield declines in sugarcane exposed to adverse weather conditions.

Resende et al. (2006) evaluated the effect of harvesting with and without straw burning after 16 years of cultivation. They found a 15% increase in yield of sugarcane under straw when compared with burned cane in the evaluated ratoons from 1988 to 1992. From 1992 to 1999 (after the renewal of the sugarcane culture), these values reached 59 and 12 to 28% in harvest ratoons. Resende et al. (2006) also stressed that the greatest differences occurred mainly in years with a lower rainfall, indicating that the presence of straw in the field was beneficial in conserving soil moisture. These results agree with those obtained by Oliveira et al. (1999) and those of this study.

Despite the benefits obtained with straw retention in this study and those described by these authors, there are others who reported disadvantages in using 100% straw for raw cane (Campos et al., 2008; Campos, 2010). Notably, the negative results described have typically been found in 100% straw retention; therefore, it is not possible to determine whether the same effect would occur with smaller amounts of this material. We observed that different amounts of residue retained in the field have different effects. This is particularly important if we consider that recently, the use of this waste as a feedstock for second generation ethanol and bioelectricity production has been one of the main alternatives to supply the world's growing energy demand, and we must determine how much straw retention is required to guarantee the sustainability of the production system.

Overall, 50% (10 Mg ha^{-1}) straw retention provided enough residue to promote improvements in the root system and yield of sugarcane. Above 50%, there were no statistically significant responses. The withdraw of the 50% surplus straw from the field for use in industrial processes did not cause damage to the crop yield (Figures 3, 4 and Table 2).

Conclusions

1. The 50, 75 and 100% straw treatments promoted a greater root mass to a depth of 0.20 m.
2. The effective depth for the 0.45 m distance from the planting line was 0.28 m and was 0.40 m for 0.75 m at 270 DAP.
3. The harvesting with straw burning, the total removal of straw from the field or the 25% straw maintenance reduced crop yield of sugarcane in periods with a water deficit.
4. Retaining of the 50% straw on the field is sufficient to increase the mass of roots and yield of sugarcane, even in periods of water stress.

Conflict of Interests

The authors have not declared any conflict of interests.

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Full Length Research Paper

Nitrogenous compounds in hog plum plants (*Spondia mombin* L.) under water deficit

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The hog plum tree is a species exploited extractively, but this information is not included in official statistics, despite the socioeconomic relevance of the species in the North and Northeast of Brazil. The present study aimed to analyze physiological and biochemical processes in *Spondia mombin* L. plants under two water regimes. The experiment was conducted in a greenhouse at the Federal Rural University of the Amazon, Belém, PA. The experimental design was completely randomized with two water conditions: control and water deficit, with 20 repetitions totaling 40 experimental units, where each experimental unit consisted of one (1) plant/pot. Moderate/severe water deficit was simulated by suspending irrigation of the seedlings, respectively, for a 15-day period. There were reductions in the levels of water potential, nitrate, nitrate reductase and proteins, while the values for ammonium, glutamine synthetase, amino acids, proline and glycine betaine had a significant increase in plants under water stress compared with control plants. Young hog plum plants under water deficit undergo changes in nitrogen metabolic pathways. These changes are indicative of intolerance to extremely dry environments.

Key words: Nitrate content, osmoregulator, tolerance, amino acid.

INTRODUCTION

The hog plum tree (*Spondias mombin* L.) is a fruit species, native to tropical America, belonging to the Anacardiaceae family, common in the Amazon region, where it is a wild species. Its fruits are commercialized fresh and can be consumed in the form of juice, ice cream, popsicles, custard and mousse. Important species

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of the genus *Spondias* include the hog plum (*S. mombin* L.), the green mombin (*S. tuberosa* Arruda), and the golden apple (*S. dulcis* Parkinson). These species are exploited extractively or in domestic orchards, but this information is not included in official statistics, despite their socioeconomic relevance in the North and Northeast of Brazil (Quadros, 2013).

Hog plums are considered to have good nutritional quality; the fruit has a pleasant aroma and a juicy pulp, as well as a distinctive bittersweet flavor (Silva et al., 2007). In addition, the fruit is composed of compounds such as carotenoids and tannins, representing a good source of this component and playing its most important nutritional role, that is, its activity as provitamin A, thus gaining prominence as a probable natural antioxidant.

More than any other environmental stress, soil water deficit is a serious global problem (Carlin and Santos, 2009). One of the great challenges currently faced by agriculture, therefore, is to increase crop yields in regions that are likely to be under water deficit. In response to the lack of water, plants perform various physiological events; the most frequent one is osmotic adjustment, whereby they adapt to keep water potential and cell turgor at more appropriate levels. Water participates as a reagent in numerous metabolic reactions; lack of water affects all aspects of plant growth and development (Pereira et al., 2012).

Various physiological and biochemical processes, such as gas exchanges between the inner leaf and the atmosphere, photosynthesis and metabolism of carbohydrates, proteins, amino acids and other organic compounds, are modified by water deficit (Silva, 2008). In this context, the aim of this study was to evaluate the metabolism of nitrogenous compounds in young hog plum plants (*S. mombin* L.) under water deficit conditions.

MATERIALS AND METHODS

Experimental setup and location

The experiment was conducted in a greenhouse at the Institute of Agricultural Sciences (ICA) of the Federal Rural University of the Amazon (UFRA), in Belém, PA, Brazil (01° 27' S and 48° 26' W). Before the start of treatment, all plants were placed under 50% shade cloth, irrigated daily for a month to keep them at field capacity and acclimatization (Fernandez and Sykes, 1968).

Plants

Young hog plum plants grown from seeds were supplied by AIMEX (Federation of Timber Export Industries from the State of Pará). Hog plum seedlings were transplanted to 10 kg pots with substrate containing a mixture composed of black soil, manure and earthworm humus at a ratio of 3:1:1 (v:v:v), respectively, on a 0.02 m layer of crushed stones to facilitate soil drainage. Before transplanting, tests were made to check the field capacity of the pots; liming was performed to correct soil pH, and macro and micronutrients were supplemented, based on chemical soil analysis, by applying 600 ml of the nutrient solution of Hoagland and Arnon (1950), modified at the Laboratory of Biodiversity Studies on Higher Plants (EBPS), UFRA.

Experimental design

The experimental design was completely randomized with two water conditions: control and water deficit, with 20 repetitions totaling 40 experimental units, where each experimental unit consisted of one (1) plant/pot.

Statistics

Analysis of variance was applied to the results and when there was significant difference, the means were compared by Tukey's test at 5% significance level. Moreover, standard deviations were calculated for each treatment, and statistical analyses were performed with the software program (SAS-Institute, 1996).

Plant training

A preliminary experiment was performed to simulate moderate/ severe water deficit by suspending irrigation on the seedlings, respectively, for 15 days. During the experimental period, the control plants were watered daily to replace water loss. Watering was performed individually for each pot, taking into account daily weighings, forming a set (pot + plant + soil); weed control was also made, weed from manual weeding without causing nutritional deficiency, pests and pathogens. The soil was sieved. Then pots were filled and the average weight of the vessels determined when the soil was at field capacity. The average weight of the plants in clod was also made from each treatment. So when planting each seedling in a respective vessel, the average weight of each pot at field capacity was known. The vessels were weighed at every turn of irrigation, and the average weight determined with the soil in the current humidity. Following irrigation, the weight of a vase with irrigated soil was made to be the same, thus maintaining the field capacity. This procedure was determined following the recommendations of Melo et al., (1998).

Preedawn water potential

Predawn water potential (Ψam) was determined between 4:30 and 5:30 am, by means of a pressure pump type Scholander (M670, PMS Instrument Co., Albany, USA) as described by Pinheiro et al., (2007).

Determination of gas exchange

The stomatal condutance to water vapor (gs) and the transpiration (E) were determined by a portable porometer of dynamics balance (mod. Li 1600, LiCor, Nebraska, USA). The measurements were made at 9:00 a.m. As samples, mature leaflets, completely expanded, were selected from leaves of second or third pair counted starting from the apex. After gas exchange, leaf samples were collected and immediately taken to a forced air circulation glasshouse at 65°C until drought for the flour preparation.

Determination of the biochemical variables

Determination of the concentrations of nitrate

Fifty (50 mg) were weighed of previously lyophilized leaves, adding

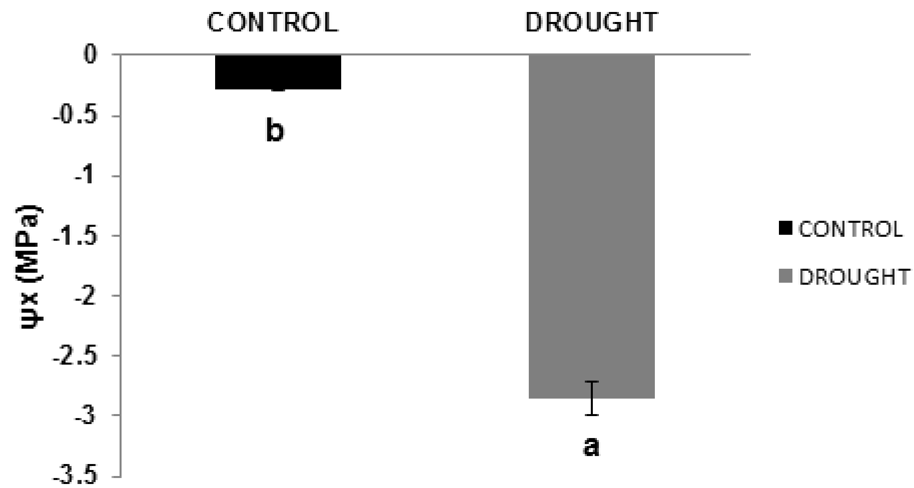

Figure 1. Water potential in young plants of *S.mombin* under drought. The letters a and b show statistically significant differences between treatments were compared by Tukey test at 5% probability. The bars represent the standard deviations of the mean.

total extract, salicylic acid 5% solution in concentrated sulfuric acid. The concentration of nitrate was obtained from a standard curve with increasing concentrations of NO_3^- (0, 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0 μmol ml^{-1}) according the method described by Cataldo et al., (1975).

Determination of nitrate reductase activity

200 mg were weighed of leaf disks of 0.5 cm diameter placing the samples in test tubes containing phosphate buffer isopropanol from a standard curve obtained with KNO_2 p.a. (Sigma) according the method *in vivo* recommended by Hageman and Hucklesby (1971).

Free ammonium concentrations

Fifty (50 mg) were weighed of lyophilised leaves previously, adding in the test tubes the total extract, solution A and solution B after shaking. The free ammonium concentrations were estimated from the standard curve constructed with $(NH_4)2SO_4$ p.a. (Sigma) according to the method described by Weatherburn (1967).

Total soluble amino acid concentrations

Fifty (50 mg) were weighed of previously lyophilised leaves, by adding the total extract, buffered solution and reagent ninhydrin. The total free amino acid levels were determined based on a standard curve adjusted from increasing concentrations of a standard mixture of L-glutamine according to the method described by Peoples et al., (1989).

Determination of proline levels

Fifty (50 mg) were weighed of lyophilised leaves previously by adding in the test tubes total extract, ninhydrin acid and glacial acetic acid. It was determined through a calibration curve proline and proline results expressed in mmol g^{-1} dry matter (DM) were determined according to Bates et al., (1973).

Glycine betaine content determination

Twenty five (25 mg) were weighed of lyophilised leaves previously by adding H_2SO_4 2 N test tubes and $KI\text{-}I_2$ iced. A standard curve was used and Glycine – Betaine was determined by the method described by Grieve and Grattan (1983).

Glutamine synthetase activity

It was determined by the *"in vitro"* method of Kamachi et al., (1991). The results were expressed in mmol of γ-glutamyl-hydroxamate kg^{1-} DM of tissue h^{-1}.

Determination of total soluble proteins concentration

The concentrations of total soluble proteins were determined by method of Bradford (1976). The results were expressed in mg protein g^{-1} DM.

RESULTS AND DISCUSSION

Water potential

The results showed significant reduction in water potential (Ψw); the results ranged from -0.28 MPa (control plants) to -2.855 MPa (plants under water deficit) (Figure 1). This represents a decrease of 919% of the water potential compared with control plants. Water potential was decreased in plants under water stress and this may be due to biochemical changes that lead to changes in cell juice concentration. However, it may also have resulted from the decrease in leaf cell volume by increasing water deficit in the soil, which prevents water supply to plants (Pallardy, 2008). This may also have occurred because the leaf transpiration rate is greater than the absorption

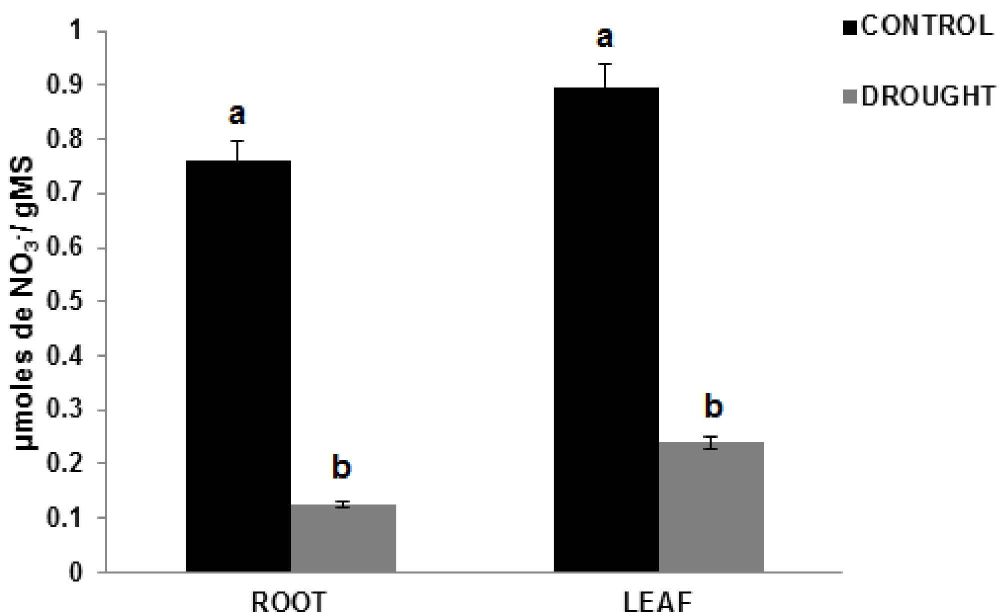

Figure 2. Nitrate concentration in Young plants of *S. mombin* under drought. The letters a and b show statistically significant differences between treatments were compared by Tukey test at 5% probability. The bars represent the standard deviations of the mean.

capacity (roots) or greater than the transportation capacity throughout the trunk and branches of trees (Marenco et al., 2014). Similarly, Fernandes et al., (2015) found -2.2 MPa when working with eucalyptus plants grown in a greenhouse under water stress. Lima et al., (2015), during a 25-day experiment, found that water deficit caused a significant reduction in water potential in andiroba plants, reaching levels near -2.00 MPa, while the irrigated plants obtained values of - 0.08 MPa during the experiment.

Nitrate concentration

The results obtained in hog plum plants revealed that there was a significant reduction in nitrate concentration in the roots and leaves under irrigation suspension (Figure 2). For the roots, the values ranged between 0.76 and 0.12 µmoles NO_3^-/g DM for control plants and plants under water deficit, accounting for a decrease by 83.64%. By contrast, the values were 0.89 and 0.24 µmoles NO_3^-/g DM in the leaves of control plants and plants under water deficit, with a decrease by 73.25%, respectively.

Ammonium and nitrate are the main forms of nitrogen available to plants. In the processes of reduction and assimilation, nitrogen can be absorbed both in the leaves and in the roots simultaneously or between these organs. They are, therefore, essential processes for plants because they control their growth and development (Shan et al., 2012). Thus, nitrate is not only a source of nitrogen supply, but also a marker for various cellular processes (Lemos et al., 2008).

For nitrate to be taken up by the roots, it has to be diluted with water present in the soil. However, nitrate concentration was reduced during water deficit, as a possible response to low absorption of nitrate and due to high retention of the soil solution caused by water deficit as well as low concentration of NO_3^- in the soil (Nobre et al., 2010). Entry of nitrate into the plant is a process involving multiple biochemical reactions, and it consumes high amounts of energy. Water deficiency decreased nutrient absorption, which provides the lowest root to shoot transport, because osmotic adjustment in the leaves occurs more slowly (Suassuna et al., 2012). As a result, there is a low shoot growth, that is, cell division was inhibited by stomatal closure, thus reducing perspiration and consequently affecting the process of photosynthesis (Galon et al., 2010).

A study conducted by Ananthi and Vijayaraghavan (2012) on cotton under water deficit, showed that the latter caused a reduction in the activity of the nitrate reductase enzyme (Figure 3), which leads to low nitrate concentration; thus, productivity was remarkably reduced when water stress was imposed, with flowering being the most sensitive stage in this process.

Nitrate reductase activity

The results obtained in hog plum plants revealed that the activity of the nitrate reductase enzyme was significantly reduced in the roots and the leaves under water deficit

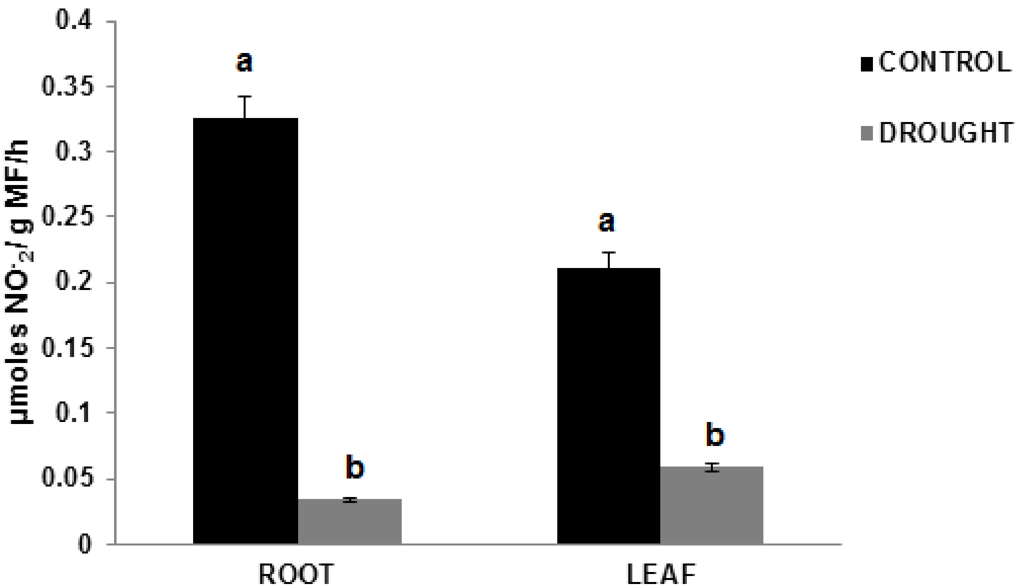

Figure 3. Nitrate reductase activity in Young plantas of *S. mombin* under drought. The letters a and b show statistically significant differences between treatments were compared by Tukey test at 5% probability. The bars represent the standard deviations of the mean.

(Figure 3). For the root, the values were 0.33 and 0.03 µmoles NO_2^-/g MF/h for control plants and plants under water deficit, which represents a decrease by 89.51%. For the leaves, the values were 0.21 and 0.06 µmoles NO_2^-/g MF/h control plants and plants under water stress, that is, a decrease by 72.17%, respectively.

Nitrate is the main form of nitrogen assimilated by plants and its absence is the major factor limiting plant growth. For this nutrient to be absorbed by plants, an enzyme goes into action; particularly, nitrate reductase, which is a physiological indicator of the effect of the association between them in an environment under water stress (Rhein et al., 2011).

According to Valduga and Finzer (2010), when a plant has more limited access to water available in the soil for its physiological activities, there is a control in stomatal closure that will occur according to the current amount of water. In other words, if there is little water available, guard cells will not be turgid; there will be lower water potential, thereby leading to a low release of water to the environment. With this mechanism, the plant can use water more efficiently. However, as water becomes a limiting factor in stomatal closure, there is a decrease in photosynthesis and in the nitrate reductase enzyme (Marenco et al., 2014). When there are small decreases in water potential, water tends to respond quickly and decrease dramatically. A previous study by Castro et al., (2008) reported a decrease in nitrate reductase activity as a result of water deficit in Teak plants.

Another possible inhibition is the occurrence of a high synthesis-degradation ratio that, in turn, is highly dependent on its substrate, since the enzyme was induced by it (Oliveira et al., 2011). Another explanation for this reduction is the high amount of energy required by the process; as photosynthesis is consequently reduced, the energy resulting from this process will be reduced, causing this enzyme to restrict its activities (Soares et al., 2011).

A study carried out by Souza et al. (2008) showed data on hog plum plants, indicating that the nitrate reductase enzyme had lower activity in the leaves. This may have been a strategy used by the plants to lose their leaves during the dry season or during water stress. A similar result was found by Melo et al., (2014) on *Coffea arabica* seedlings, where nitrate reductase activity was reduced in the leaves under water deficit. Similar results were observed in another study with Açai; results indicated that, nitrate reductase activity was decreased under water deficit conditions (Freitas et al., 2008). On the contrary, Oliveira et al. (2005) found that the peach palm species showed greater reductase activity in the leaves.

Ammonium

In plants under water deficit, free ammonium concentration was increased by 15.48 mmol NH_4^+/kg DM and 8.98 mmol NH_4^+/kg DM compared to control plants -12.37 mmol NH_4^+/kg DM and 5.38 mmol NH_4^+/kg DM - for the root and leaf tissues, corresponding to a percentage of 25.14 and 66.91%, respectively (Figure 4). This accumulation of ammonium either in the root and in the leaves may stem from protein degradation, as can be seen in Figure 5. The high ammonium concentration may

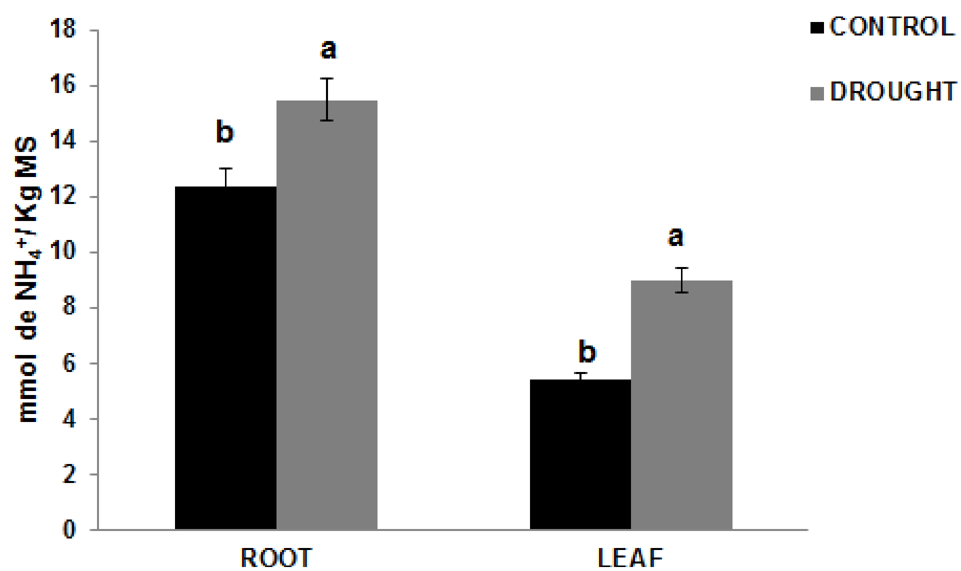

Figure 4. Ammonium concentration in Young plants of *S. mombin* under drought. The letters a and b show statistically significant differences between treatments were compared by Tukey test at 5% probability. The bars represent the standard deviations of the mean.

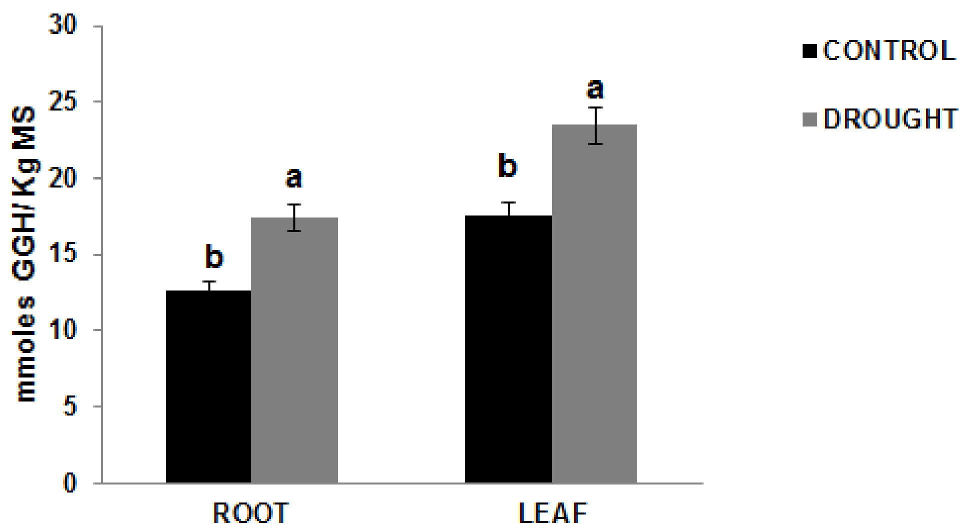

Figure 5. Activity of Glutamine synthetase in young plants of *S. mombin* under drought. The letters a and b show statistically significant differences between treatments were compared by Tukey test at 5% probability. The bars represent the standard deviations of the mean.

have lowered regeneration as a result of its toxic effect. The toxic effect of ammonium on tissues can be due to pH changes and acidification of the environment or toxic effect of free ammonium levels (Mukeshimana and Kelly, 2013).

Ammonium is assimilated by the enzymes glutamine synthetase (GS) and glutamate 2-oxoglutarate aminotransferase (GOGAT), which form the GS/GOGAT cycle, or by the enzyme glutamate dehydrogenase (GDH), which participates in an alternative pathway and performs reversible catalysis for the amination of glutamate (Masclaux-Daubresse et al., 2006). Glutamate dehydrogenase (GDH) can also metabolize ammonium, especially under conditions where there is excess ammonium. However, some authors reported that this enzyme is less important than GS, and GOGAT

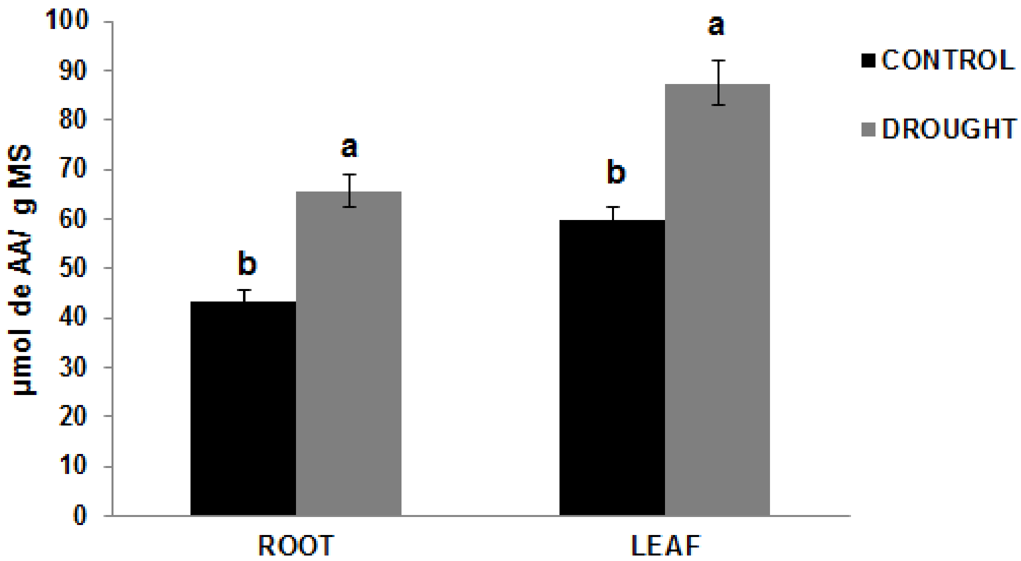

Figure 6. Soluble aminoacids concentrations in young plants of *S. mombin* under drought. The letters a and b show statistically significant differences between treatments were compared by Tukey test at 5% probability. The bars represent the standard deviations of the mean.

(Shridhar, 2012).

Genetic breeding studies are focused on finding cultivars and varieties that are more resistant to environmental adversities, through genotypes with lower free ammonium accumulation in the tissue and a higher activity of the glutamine synthetase enzyme, thereby avoiding the toxicity of this ion.

Glutamine synthetase

Fifteen days after the beginning of the experiment, there was an increase in the activity of the glutamine synthetase enzyme in the range of 17.46 and 23.48 mmol GGH/kg DM in plants under water stress when compared to control plants -12.58 and 17.49 GGH mmol/kg DM for root and leaves, respectively (Figure 5). It can be seen that, even under water stress, the plants maintained the activity of this enzyme, then moving onto free ammonium incorporation in the formation of amino acids, as evidenced by the information in Figure 6. A glutamine synthetase (GS) converts ammonium into amino acids, thereby preventing its excessive accumulation, which could lead to toxicity and inhibition of biological nitrogen fixation (Prell and Poole, 2006; Bernard and Habash, 2009). This can be observed through ammonium accumulation and high GS activity in the present study.

In order to keep nitrogen balance, glutamine synthetase may be located in tissues and organs involved in the generation and transport of reduced nitrogen (Miflin and Habash, 2002). The substrate used for GOGAT, glutamine, did not limit the reaction, because there is still a high GS activity even in plants under water stress.

In the present study, and also in the study by Masclaux-Daubresse et al., (2006), who worked with tobacco plants, GS activity was higher in the leaves than in the roots, which is probably associated with primary and secondary N assimilation. By contrast, Oliveira Neto et al. (2009) found different results when working with sorghum plants under water stress.

Amino acids

The total soluble amino acid concentrations showed a significant increase. The values were 43.38 and 59.59 µmol $AA.g^{-1}$ M in roots and leaves, respectively (Figure 6) for the control plants and 65.65 and 87.49 µmol $AA.g^{-1}$ M in roots and leaves, respectively, for plants under water stress. The total soluble amino acid content was increased by 51.34% in the roots and 46.82% in the leaves when under water stress for 15 days. In the present study, the amino acid accumulation recorded can be explained by the possible inactivation of protein synthesis. Another factor that may be considered for the results is the fact that proteolytic enzymes degrade proteins by breaking peptide bonds, thus increasing free amino acid content (Sousa et al., 2015). These results are in agreement with those obtained by Rivas et al. (2013) who found a significant increase in amino acid levels when working with *Moringa oleifera* plants under water deficit for 10 days. Moura (2010) who studied *Jatropha curcas* plants, found opposite results for total soluble amino acid content when the plants were under water deficit when such stress was more intense.

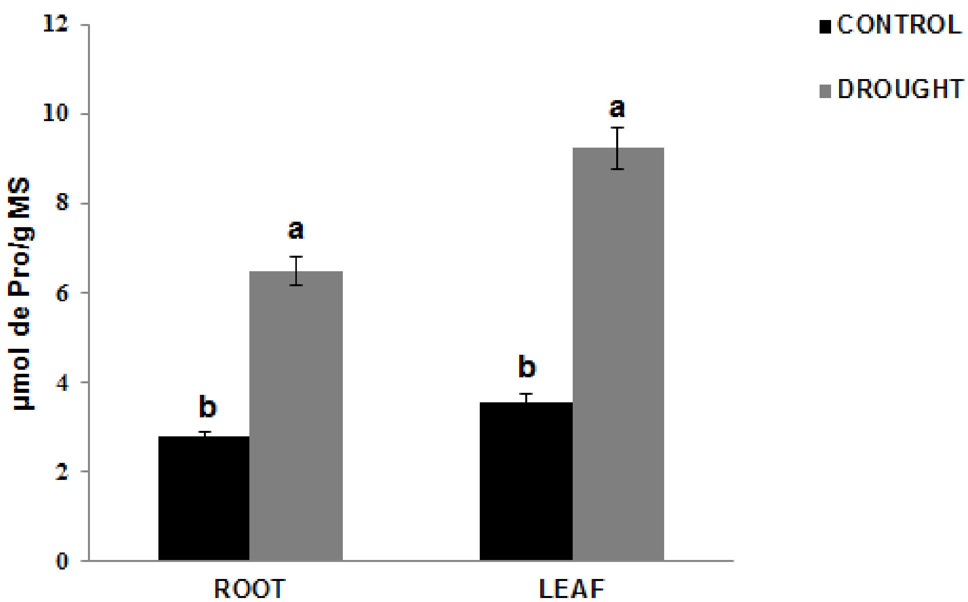

Figure 7. Proline concentrations in young plants of *S. mombin* under drought. The letters a and b show statistically significant differences between treatments were compared by Tukey test at 5% probability. The bars represent the standard deviations of the mean.

Proline

There was a significant increase in proline levels (Figure 7), which were 2.76 µmol pro/g DM in the roots and 3.56 µmol pro/g DM in the leaves for control plants, while the values for the plants under water stress were 6.47 µmol pro/g DM in the roots and 9.23 µmol pro/g DM in the leaves. There was an increase in proline content by 134.42% in the roots and 159.27% in the leaves when the plants were under water deficit. Lisar et al., (2012) showed that proline accumulation cannot be considered as a resistance factor but an indicator of tolerance as a result of osmotic adjustment by the plant when exposed to water stress. However, proline accumulation brings several advantages in addition to osmotic adjustment. This molecule can avoid damage to cell membranes and prevent protein denaturation by forming some types of reactive oxygen species (ROS), especially hydroxyl radicals (Verbruggen and Hermans, 2008). This is due to the fact that NADPH is used during proline synthesis (Jortzik et al., 2010). This finding was confirmed by Amorim et al., (2011) who researched proline content in *Anacardium occidentale* leaves under water deficit, and found an increase in this solute in response to such stress. Husen (2010), when working with two different teak clones, found significant increase in proline content by 82.09 and 87.09% after 20 days under water deficit.

Glycine betaine

The reported amounts of glycine betaine (Figure 8) in the leaves of plants under water stress were 12.48 mg/g DM, which represents an increase of 171.8% compared to the irrigated plants (4.59 mg/g DM), while the values found in non-irrigated roots were 10.76 mg/g DM, which accounts for 198.8% compared to the control treatment (3.6 mg/g DM). The increased levels of glycine betaine are associated with the fact that it is an effective osmotic adjuster in plant species. It is tolerant to various types of abiotic stress and its properties suggest promising strategies for developing stress-tolerant plants (Wani et al., 2013). Glycine betaine is involved in osmotic adjustment, protection of cellular structures and antioxidant protection (Silva et al., 2010). Therefore, the accumulation of this solute may have contributed to the protection of plants in the harsh conditions of osmotic potential in soil; it can act as an osmolyte and maintain water balance between the plant cell and the environment. This increase in glycine concentration was observed in *Jatropha curcas* plants in the treatments with irrigation and non-irrigation after 35 days of water stress (Sousa et al., 2012). However, there was no significant change in glycine betaine concentration in young plants of *Khaya ivorensis* A. Chev. under water deficit (Albuquerque et al., 2013).

Proteins

The values for total soluble protein levels (Figure 9) in plants under water stress were 0.031 mg protein/g DM in the roots and 0.0948 mg protein/g DM in the leaves, with a considerable decrease compared to control plants,

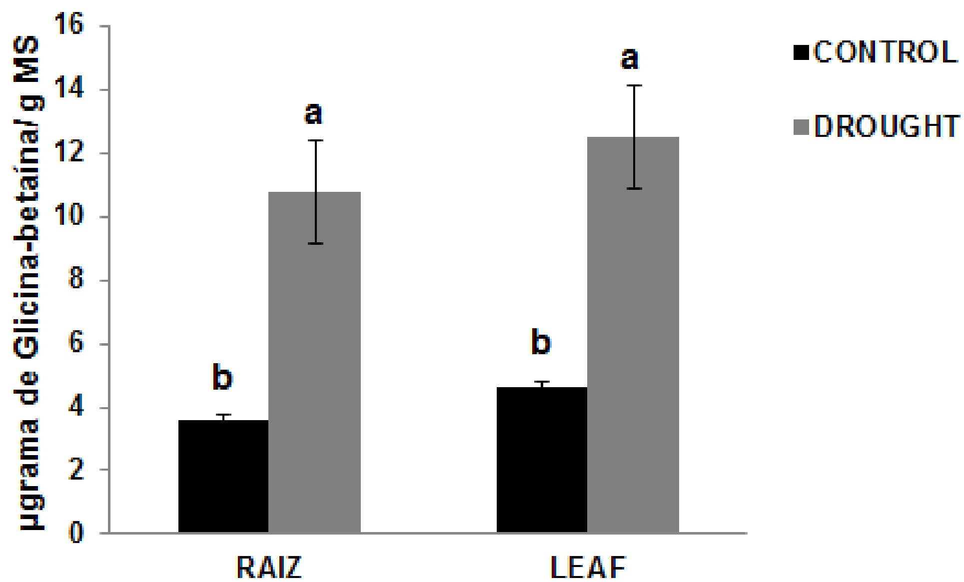

Figure 8. Glycine betaine concentrations in young plants of *S. mombin* under drought. The letters a and b show statistically significant differences between treatments were compared by Tukey test at 5% probability. The bars represent the standard deviations of the mean.

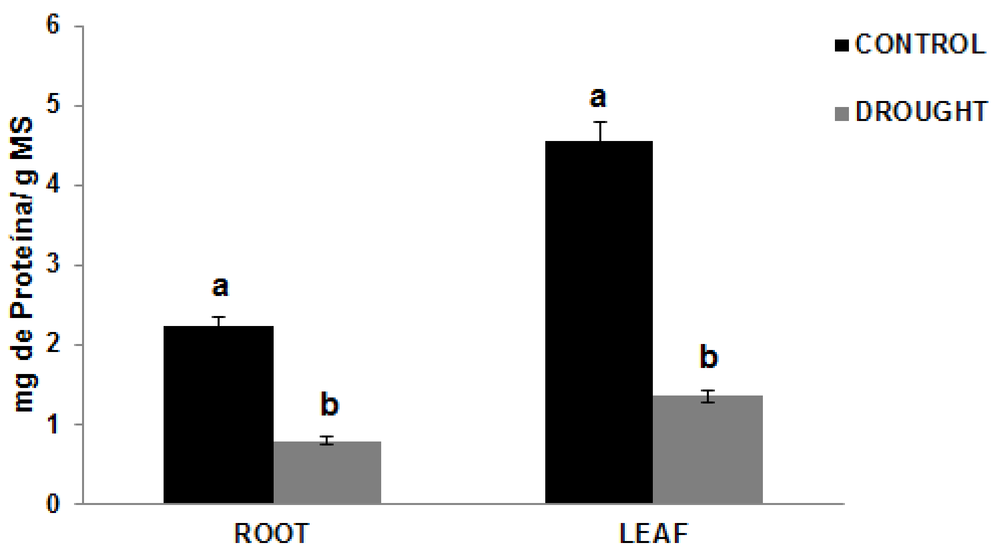

Figure 9. Total Soluble Protein Concentrations in young plants of *S.mombin* under drought. The letters a and b show statistically significant differences between treatments were compared by Tukey test at 5% probability. The bars represent the standard deviations of the mean.

whose values were 0.06767 mg protein/g DM in the roots and 0.2135 mg protein/g DM in the leaves. Thus, there was a decrease of 45.81% in the roots and 44.03% in the leaves. According to Maraghni et al., (2011), protein metabolism was significantly affected by water deficit, yet protein biosynthesis is one of the first metabolic events paralyzed after the perception of stress. Proteolysis then starts; it is an event that promotes an increase in soluble amino acid content, with consequent reduction of protein concentration (Brito et al., 2008). These results corroborate those found by Lechinoski et al. (2007) while working with Teak plants; therefore, water deficit reduces total soluble protein concentrations in the tissues of hog plum plants, probably as a result of increased activity of proteolytic enzymes that break down reserve proteins while reducing their synthesis. Opposite results were reported by Viana et al., (2014) when working with *Eucalyptus urophylla* plants after 20-day exposure to water stress.

Conclusion

The metabolismo of taperebá plants altered nitrogen metabolism when subjected to drought, reducing the water potential, nitrate concentration, and protein concentration of nitrate reductase activity, and increasing concentration of proline, glycine betaine, amino acids, ammonium and glutamine synthetase activity. There is still a need for further research to precede this study, especially as concerns the use of more varieties of this species, the genre Spondia, which are diverse. Therefore, studies that address the physiology, biochemistry and antioxidant enzymes in such species, to indicate varieties more resistant or tolerant to water stress are necessary.

Conflict of Interests

The authors have not declared any conflict of interests.

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Full Length Research Paper

Adoption of Bambara groundnut production and its effects on farmers' welfare in Northern Ghana

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With the growing concerns about the likely implications of climate change, the long term sustainability of conventional agricultural approaches and biodiversity loss have contributed to a growing interest in the potential of the so-called underutilised crops to address food, nutritional, and income security challenges. In support of their wider use, advocates of underutilised crops associate a number of benefits with them. These include agronomic and nutritional benefits such as drought tolerance and micro-nutrient content and the perceived socio-economic benefits of their wider use. It is widely suggested that the adoption of such crops can generate improved agricultural resilience and support nutrition, food and income security. Simultaneously, the adoption of underutilised crops is seen as a means of conserving biodiversity. However, scientific evidence concerning the use of such crops remains extremely limited. Crucially, little research has been undertaken concerning the contribution of such crops to the welfare of producers. This study investigates the socio-economic factors characterising the production of Bambara groundnut (*Vigna subterrana* (L.) Verdc.) in Northern Ghana and the impact of its production on farmers' welfare. Primary data was collected based on the 2013 farming season, 240 farmers were selected using a multi-stage sampling technique. A treatment effect model, comprising an adoption and a welfare model was estimated. The probability of adopting Bambara groundnut was found to be greater for: unmarried farmers; farmers in larger households; farmers with little or no formal education; and farmers who had no access to credit. The production of Bambara groundnut led to increased household welfare, as measured by the level of household per capita expenditure/consumption. Results suggest that while further research and support for Bambara groundnut production could contribute to addressing high poverty levels in the region, many of the basic assumptions underlying current advocacy of underutilised crops need rigorous empirical verification.

Key words: Adoption, underutilised crops, Bambara groundnut, Northern Ghana, treatment effect model, welfare.

INTRODUCTION

While global levels of chronic under nutrition have been on a decline since 1990, it is still estimated that a total of 805 million people (11.3%) were chronically undernourished during the period of 2012 to 2014 (FAO, 2014). Many of these people are located in the rural areas of developing nations. This raises questions as to the extent to which existing agricultural practices are capable of addressing the needs of marginalised groups in such areas. Multiple sources point to the relatively narrow range of crops upon which human food supply depends (Williams and Haq, 2002). While estimates vary, FAO (2001) suggests that less than 20 crop species constitute the main sources of human food. Equally, numerous sources suggest that the world's food supply is further concentrated with up to 60% of food supply coming from maize, rice, and wheat (Williams and Haq, 2002; Azam-Ali, 2007; Loftas and Ross, 1995). Not unsurprisingly, this has resulted in the concentration of agricultural research and development efforts on major crops leading to the further marginalization of a large number of species which have historically been cultivated in a range of different cropping systems and locations (Azam-Ali et al., 2001). This has led to their characterisation as "orphan", "indigenous", "traditional" or "neglected" crops, among other terms. While by no means universally accepted or clearly defined, the term "underutilised" is widely applied to these lesser used crops (Padulosi and Hoseschle-Zeledon, 2004; Padulosi et al., 2001). These crops are often noted as having an important role as subsistence or "famine crops" which are in many cases cultivated by small-scale farmers in tropical environments. In particular, numerous local studies have linked the cultivation of such crops with gendered agricultural systems where they are viewed as women's crops (Adu-Dapaah and Sangwan, 2004). Furthermore, specific agronomic benefits are linked to such crops, most critically that they are viewed as requiring less inputs of, for example, water, fertiliser and agrochemicals and can be grown employing local techniques with minimal external expertise. Finally, in many cases such crops are regarded as being good sources of a wide range of nutrients. Considering perceptions concerning the importance of underutilised crops to smallholder farmers in developing countries, their suitability to hostile environments, low input requirements and nutritional benefits, it is scarcely surprising that such crops have gained significant attention as a potentially important avenue for addressing global poverty and improving food security. Alongside perceptions that underutilised crops have an important role in development, such crops are also seen as an important subset of biodiversity which is threatened by modern approaches to farming, thus resulting in calls for conservation both in their own right and as a future genetic resource for agricultural growth in the future. In this context, calls for the promotion of underutilised crops are proposed as a means of simultaneously meeting development goals and supporting the "*in-situ*" conservation of biodiversity.

However, while the benefits of these crops have been much vaunted by their advocates, such crops continue to attract a very small portion of global research budgets. In this context, many of the claims made about these crops rely on relatively small scale studies or remain speculative. If the actual potential of such crops is to be fully understood and realised, then some consideration needs to be given to how the claims made for them bear up to empirical observation. Critically, little effort has been made to empirically assess the contribution to welfare of such crops within large populations. This study draws on empirical research to examine the impact of the adoption of an underutilised crop, Bambara groundnut, on the welfare of current cultivators.

While regularly described as underutilized, Bambara groundnut is a widely grown indigenous African legume native to Western Nigeria and Eastern Sudan (Begemann, 1988; Pasquet, 2003). While Bambara groundnut is mostly grown in the drier parts of sub Saharan Africa (SSA) it is widespread throughout tropical Africa (Brink and Belay, 2006). Historically, Bambara groundnut has been viewed as a subsistence crop and as the third most important legume crop in semi-arid Africa after groundnut and cowpea (Sellschop, 1962). Despite being the subject of very limited research and little support from agricultural or development professionals, the crop remains important in the region. Indeed, there is evidence that production has increased. In 2002, the FAO estimated worldwide Bambara groundnut production at 58,900 Mt (Azam-Ali et al., 2003) and over 100,000 Mt in 2008 (FAO, 2009). However, reflecting the general case with underutilised crops, the accuracy of estimates of Bambara groundnut production are difficult to establish due to its widespread use in subsistence farming systems for which reliable data are not collected. Other sources estimate its annual world production at about 330,000 Mts, of which 45 to 50% is produced in West Africa (PROTA, 2006; Alhassan and Egbe, 2013).

Reflecting a general trend in underutilised crop studies, limited data has not prevented significant claims being made for the crop. Within development circles and particularly in discussions of underutilised crops, the potential of Bambara groundnut is widely observed, as is the absence of large scale research concerning the crop. The State of The State of the World (SoW) (2011) made the following observation about Bambara groundnut:

"… this little bean, indigenous to tropical Africa, is highly overlooked by scientists, development agencies, and humanitarian programs, even though it packs a lot of nutrition. One reason the bean is growing in popularity is

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because it is a hardy plant, able to withstand high temperatures and dry conditions. …The Bambara bean is high in protein, particularly methionine, which makes the protein more complete than that in other beans".

Researchers have highlighted its ability to give acceptable yields on marginal soils (Hillocks et al., 2012) and under harsh environmental conditions (Azam-Ali et al., 2001). The crop's nutritional superiority has also been widely reported (Brough and Azam-Ali, 1992). Against the backdrop that Bambara groundnut does well under relatively harsh environmental and soil conditions it has been argued that cultivating the crop could make a significant contribution to alleviating the plight of small-scale farmers by provide a nutritious alternative to animal protein and providing a source of income (Hillocks et al., 2012)

In Northern Ghana, agriculture is the mainstay of the economy; however the unimodal rainfall pattern has meant that after the farming season is over, much of the region is affected by drought and people become unemployed or are compelled to migrate to the south. The high tolerance of Bambara groundnut to drought and poor soils, its benefits as a legume in a grain-dominated farming system, its market potential, as well as its nutritional advantages suggest that research and development interventions to promote its cultivation may offer possible pathways for improving the welfare of smallholder farmers in these areas. In order to establish the extent to which this is the case, this research investigated current Bambara groundnut production in Ghana with the specific objectives of (1) investigating the factors influencing the adoption of Bambara groundnut production in Northern Ghana and (2) determining the effects of adoption on farmers' welfare. This is undertaken with a view to informing the understandings of a wide range of potential stakeholders in the research and policy communities concerning how the potential of underutilised crops in development measures should be framed.

MATERIALS AND METHODS

Agronomic characteristics of Bambara groundnut

As already noted, Bambara groundnut is widely known as a hardy plant with several advantages including: high tolerance to drought; ability to yield on lands that are not fertile enough for the cultivation of many other crops; and good nutritional characteristics (Azam-Ali et al., 2001; Bamshaiye et al., 2011). As a leguminous crop, Bambara groundnut's fertilizer requirements are also low as compared to many other crops (Linnemann, 1990). The crop can grow well under an average temperature of 20 to 28°C, an annual mean rainfall of 500 to 600 mm and a soil pH of 5.0 to 6.5. Furthermore, Bambara groundnut is seen as being valuable in intercropping and crop rotation systems due to its nitrogen fixing ability. However, as an underutilised crop which has not been the subject of widespread formal breeding endeavour, it exists as a large number of landraces rather than varieties (Redjeki et al., 2011). The germplasm of the crop is characterised by significant genetic variability, reflected in considerable morphological and agronomic differences. This is evident in the wide range of colouration in the seed produced by different landraces varying from black, red, and brown, to cream/black eye, cream/brown eye, cream/no eye, and speckled/flecked/spotted patterning, as well as an average seed weight ranging between 280 and 320 g (Ojimelukwe and Ayernor, 1992). Lacroix et al. (2003) noted that the lack of genetic improvement alongside other issues arising from the lack of attention the plant has received, such as, inadequate knowledge on the taxonomy; reproductive biology, agronomic, and quality traits have obstructed the Bambara groundnut's wider adoption. Also, in the case of its utilisation, the lack of adequate processing techniques to address problems related to long cooking time hinders the crops wider use.

Study area

The study was carried out in the three northern regions of Ghana, namely; the Northern, Upper East and Upper West regions. Agriculture is the mainstay of the people in Northern Ghana. Major staple crops cultivated include maize, millet, yam, sorghum, rice, groundnut and cowpea as well as Bambara groundnut (Quaye, 2008). Farm activities in the region are challenged by erratic rainfall (drought), flood and in some instances, bushfires and declining soil fertility. Poverty in the north of Ghana is also more pronounced than in the south, with the former also having less infrastructural facilities (GSS, 2014). The cultivation of Bambara groundnut is more common in these regions than in the southern regions of Ghana perhaps reflecting its ability to thrive in marginal and drought affected areas.

Sampling, data collection and procedure

The study involved 240 respondents, 120 Bambara groundnut farmers and 120 non Bambara groundnut producers. The sample was selected through a multi-stage procedure. In the first stage, two districts from each of the three northern regions were randomly selected. Also by a simple random approach, two communities were then selected from each district making a total of four communities in each region. In the second stage, the farmers in each community were put into two strata: (1) Bambara groundnut farmers and (2) non-Bambara groundnut farmers. And then, 10 respondents from each of the stratum were selected from each community by simple random sampling. This allowed for 40 Bambara groundnut farmers and 40 non Bambara groundnut farmers to be selected in each region.

A semi-structured questionnaire was used in gathering the relevant data for the study. Data was collected on the socioeconomic characteristics of the farmers as well as the welfare status of his/her household. Thirteen key components were considered as indicators of household welfare. These included the annual household total expenditure on food, accommodation, clothing, education, health, utility, transportation, ceremonies, entertainment, communication, fuel, savings, maintenance of assets and others. These were aggregated and divided by the household size in line with the methods used by the Ghana Statistical Service (GSS, 2008) to give household per capita expenditure. Thus in this research, welfare is equivalent to household per capita expenditure or household per capita consumption. It is acknowledged that this is a limited definition of welfare since it does not take into account other elements of welfare such as quality of food, the environment, health status or happiness. However, taking into account the resource constraints under which the survey was conducted, the use of this approach serves as a preliminarily measure which is related to these other indicators of welfare.

Data analysis

In order to address the questions of adoption and contribution to welfare, two equations were estimated: one for the determinants of farmers' adoption of Bambara groundnut production and the other on the effects of Bambara groundnut production on welfare. In the case of the first equation, a limited dependent model such as the probit model is appropriate since the dependent variable in this case is binary: 1 if a household has adopted the cultivation of Bambara groundnut and 0, otherwise. On the other hand, the welfare equation can be estimated using a linear estimator, such as the ordinary least squares (OLS). However, to correct for a possible sample selection bias, we estimated a treatment effect model which adapts Heckman's two stage estimation for the correction of sample selection bias. In the sections that follow, an explanation of the probit model was offered as well as the steps involved in overcoming the problem of selectivity bias.

Probit model

The probit model is one of the specialized regression models of binomial response variables. For instance, the question asked in this study was, what is the relationship between households' adoption or non-adoption of Bambara groundnut production and their socio-economic characteristics? The implication is that during the farming season in question, some households cultivated Bambara groundnut while others did not. This meant that there were only two sets of respondents, Bambara groundnut producers and non-producers, leading to a dichotomous treatment variable. The probit model (or its logit equivalence) allows for estimating these 'choice' situations. The purpose of the model is to estimate the probability that an observation with a particular characteristic would fall into one specific category.
Mathematically,

$$y_i = \beta' x_i + u_i \qquad (1)$$

where y_i is a binary response variable. Stating the underlying response variable y^*

$$y_i^* = \beta' x_i + u_i \qquad (2)$$

where x_i is a vector of random variables that influences y_i and β_i is a vector of parameters to be estimated. In practice, y^* is not observed and instead a dummy variable was observed and defined as:

$y = 1 \; if \; y_i^* > 0$ or $y = 0$ if otherwise (3)

The respective probabilities are $-\beta' x_i$ and $1 - \beta' x_i$. In this case, $\beta' x_i$ is no longer $E(y_i/x_i)$ as in OLS but $E(y_i^*/x_i)$. From Equations 2 and 3,

$$Prob(y=1) = Prob(u_i > -\beta' x_i) \quad = 1 - F(-\beta' x_i) \qquad (4)$$

where F is the cumulative distribution function of u_i. Depending on x_i, the probabilities given in Equation 4 may vary, hence the likelihood function is:

$$L = \prod_{y_i=0} F(-\beta' x_i) \prod_{y_i=1} [1 - F(-\beta' x_i)] \qquad (5)$$

Since the probit model assumes that u_i is normally distributed $[N(0, \sigma^2)]$,

$$F(-\beta' x_i) = \int_{-\infty}^{-\beta' x_i/\sigma} \frac{1}{(2\pi)^{1/2}} exp\left(\frac{-t^2}{2}\right) dt \qquad (6)$$

From Equations 5 and 6, the expression $\beta' x_i/\sigma$ can be estimated as opposed to either β_s or σ. In predicting the effects of changes in the jth element of the x_i belonging to a group (that is, marginal effects), the following formulation can be used:

$$\frac{\partial}{\partial x_{ij}} \Phi(x'\beta) = \emptyset(x'\beta)\beta_j \qquad (7)$$

Selectivity bias and the treatment effect model

In practice, sample selection bias may arise for two reasons. First, one can observe welfare values for Bambara groundnut producers and not for non-Bambara groundnut producers. Similarly, there can be observable welfare values for both Bambara groundnut producers and non-producers, but the selection of the respondents by the researcher in both categories may follow a discretionary pattern and not by random; as is the case in this research. This means that Bambara groundnut producers may have unmeasured characteristics that are related to their welfare. If Bambara groundnut adoption is put into the substantive equation (welfare function) as an explanatory variable, the parameter estimates would be biased, and this would mean that the true effect of adoption on welfare would not be known (Heckman, 1976). In other words, Bambara groundnut producers may be different from their non-producing counterparts in many ways and if these characteristics of the producers are related with their welfare level, then the effect of Bambara groundnut production on welfare would be overestimated. To explain further, assuming after estimation of the welfare equation, it was found out that the welfare levels of Bambara groundnut producers, on a whole are higher than non-Bambara groundnut producers, what shows that it is Bambara groundnut production that has made the former richer and not the fact that they are intrinsically more hardworking than the latter? Heckman (1979) suggested several but similar ways in which the problem could be corrected depending on the relationship being examined. One of such model is the treatment effect model.

The treatment effect model is a special case of Heckman's two stage estimation procedure where the dependent variable of the selection equation is an additional explanatory variable in the substantive equation. Maddala (1983) and Greene (2003) have given a comprehensive theoretical explanation of the causes and treatment of the selectivity bias problem.
Following Greene (2003), Equation 1 may be re-written as:

$A_i^* = z_i' \gamma + e_{1i}$ (Selection equation) (8) where $A_i = 1$ if $A_i^* > 0$ the ith farmer has adopted Bambara groundnut production and zero if otherwise. Z is a vector of farm and household characteristics; and A_i is the observed value of the latent variable, adoption. e_{1i} is a two-sided error term with $N(0, \sigma_v^2)$.

Also let,

$$W_i = z_i\beta + A_i\delta + e_{2i} \quad \text{(Substantive equation)} \tag{9}$$

where W_i is welfare; e_{2i} is also a two-sided error term with $N(0, \sigma_v^2)$. β and δ are parameters to be estimated.

According to Heckman (1979), estimating Equation 9 with the observed values of adoption, A will result in biased estimates, and instead, he suggested that the selection Equation 8 should first be estimated so that the predicted values of A are used. Also, an Inverse Mills Ratio (IMR) should be formed using the predicted values of A as an additional regressor in the substantive equation. This is because the decision to adopt may be influenced by unobservable variables like management ability that may also influence welfare. This implies that the two error terms e_{1i} and e_{2i} in the selection and substantive equations respectively are correlated, leading to biased estimates of β and δ.

If we assume that e_{1i} and e_{2i} have a joint normal distribution with the form:

$$\begin{bmatrix} e_{1i} \\ e_{2i} \end{bmatrix} \sim N\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 & \rho \\ \rho & \sigma^2 \end{bmatrix}\right), \tag{10}$$

Then it follows that the expected welfare of those who adopt Bambara groundnut production is given as:

$$\begin{aligned} E[W_i \mid A_i = 1] &= z_i\beta + \delta + E[e_{2i} \mid A_i = 1] \\ &= z_i\beta + \delta + \rho\sigma\lambda_i \end{aligned} \tag{11}$$

where $\lambda_i = \dfrac{\phi(-z_i'\gamma)}{1 - \Phi(-z_i'\gamma)}$ is the IMR. (12)

ϕ and Φ are the standard normal and the cumulative density functions respectively. Equation 12 implies that if we estimate Equation 9 without the IMR, the coefficients β and δ will be biased, which justifies the use of Heckman's two-stage procedure.

According to Maddala (1983), if we use all observations on welfare for both categories of farmers, Equation 9 takes the form:

$$W_i = \beta'(\Phi_i z_i) + \delta'(\Phi_i A_i) + \sigma\phi_i + e_{2i} \tag{13}$$

where $\Phi_i \equiv \Phi(z_i'\gamma)$

Empirical models

Following the aforementioned theoretical model, the empirical model to investigate the factors that influence the adoption of Bambara groundnut production and its effects on households' welfare is as follows:

$$\begin{aligned} &Adoption = \\ &\beta_0 + \beta_1 Marital\ status + \beta_2 Household\ size + \beta_3 Education + \beta_4 Land\ ownership + \\ &\beta_5 Group\ membership + \beta_6 Extension\ visit + \beta_7 Credit\ access + \\ &\beta_8 Rainfall\ requirement + \beta_9 Maturity + u_i \end{aligned} \tag{14}$$

$$\begin{aligned} &Welfare = \omega_0 + \omega_1 Household\ size + \omega_2 Education + \omega_3 Land\ ownership + \omega_4 Off- \\ &farm\ activity + \omega_5 Credit\ acces + \omega_6 Adoption + \varepsilon_i \end{aligned} \tag{15}$$

Description of variables

Table 1 shows the variables included in the models, their units of measurements and expected effects on Bambara groundnut adoption and farmers' welfare.

RESULTS AND DISCUSSION

This section presents the results and discussion of the maximum likelihood estimation of the treatment effect model. The specific equations estimated are the adoption and welfare equations (Equations 14 and 15). It begins with descriptive statistics of the variables used in the estimation as well as the reasons for cultivating or not cultivating Bambara groundnut.

Descriptive statistics of variables

Table 2 shows the descriptive statistics of the variables used in the study. Thus the average Bambara groundnut producer is 40.3 years old and the non-producer is 38.8 years old. Education is generally low among the entire set of sampled farmers. The average farmer attended school up to lower primary level (not more than 3 years of formal education). Non-producers had one year of education more than the producers ((3.4) compared to 2.4 years). The average household size was 10. There were about two more people in the producers' households (10.9) than in the non-producers' households (9.4). The average number of years a farmer had been a member of a farmer group was low considering a mean of 1.4 years. This may be of significance since membership of a farmer group is sometimes a prerequisite for accessing credit. The respective figures for Bambara groundnut producers and non-producers were 1.3 and 1.5 years. On the average, Bambara groundnut producers had a higher number of extension contacts (2.3) than the non-producers (1.9).

Reasons for Bambara groundnut cultivation

Despite the characterization of underutilized crops as subsistence crops, Figure 1 shows that more than half of

Table 1. Definition of variables.

Variable	Measurement	A priori expectation	
		Adoption	Welfare
Adoption	Dummy; 1 if a farmer is a Bambara groundnut farmer and 0 if a non- Bambara groundnut farmer	NA	NA
Welfare	Household per capita expenditure per year.	NA	NA
Marital status	Dummy; 1 if a farmer is married and 0 if single.	+	NA
Education	Total number of years of a farmer's formal education.	-/+	+
Household size	Number of people in a farmer's household cooking from the same pot.	+	-
Land ownership	Dummy; 1 if farmer owns land and 0 if Rented/family/community land	+	+
Off-farm	Dummy; 1 if a farmer does not engage in off-farm activity and 0 if otherwise.	NA	-
Farmer group membership	Total number of years of group membership.	+	NA
Extension	Number of times a farmer had contact with an extension officer.	+	NA
Credit	Dummy; 1 if a farmer accessed credit and 0 otherwise	+	+
Perception of rainfall requirement	Dummy; 1 if the farmer perceives that Bambara groundnut cultivation requires little rainfall, 0 if Bambara groundnut cultivation is perceived to require much rainfall	+	NA
Perception about time of maturity	Dummy;1 if Bambara groundnut is perceived to mature earlier than other legumes and 0 if otherwise	+	NA

Table 2. Descriptive statistics of variables.

Variable	Bambara groundnut- Producers			Non-Bambara groundnut Producers			Pooled		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Age	19	75	40.3	19	70	38.8	2	75	39.5
Education	0	16	2.4	0	12	3.4	0	16	2.9
Household size	3	27	10.9	2	29	9.4	2	29	10.1
Farmer group membership	0	10	1.3	0	12	1.5	0	12	1.4
Extension	0	12	2.3	0	12	1.9	0	12	2.1

the farmers (53.3%) cultivated Bambara groundnut for both subsistence and for cash while 38.4% cultivated it solely for home consumption. A small number (7.5%) cultivated it solely for cash and 0.8% stated that they did so for social reasons such as funerals or having inherited the culture of cultivation from their families.

Reasons for non-cultivation of Bambara groundnut

The reasons cited for choosing not to cultivate Bambara

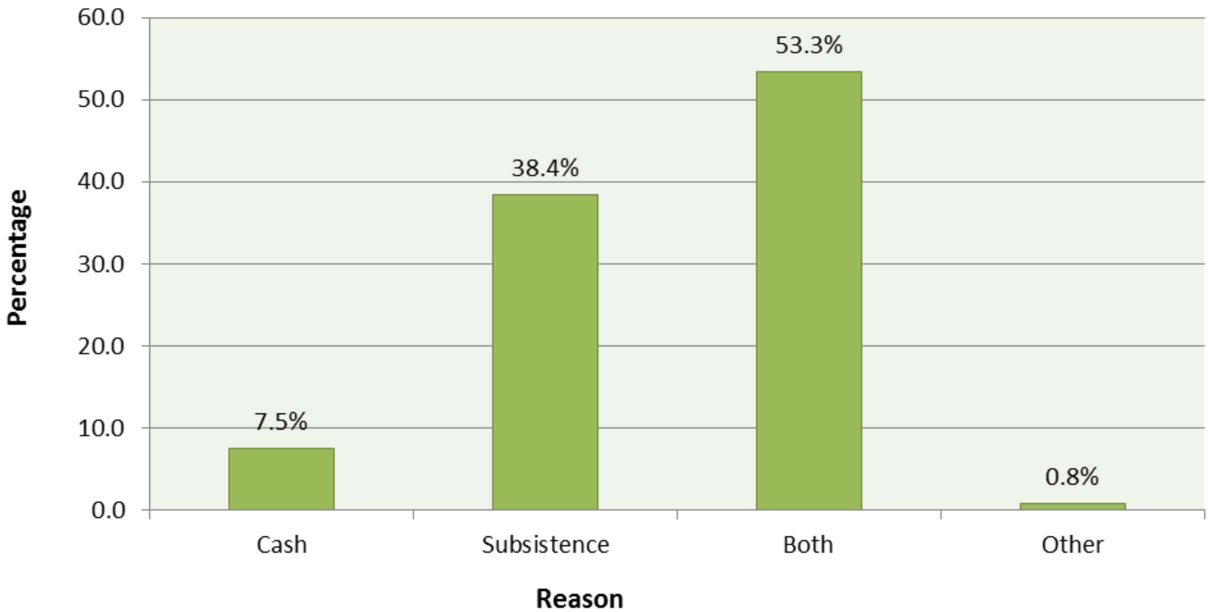

Figure 1. Reasons for cultivating Bambara groundnut.

groundnut in place of other competing crops are outlined as follows. These reasons provided justification for a continual marginalisation of the crop.

Difficult to cultivate (53.6%): Respondents indicated they considered the crop difficult to cultivate and harvesting is also very tedious, as compared to the other legumes.

Unavailability of enough land to cultivate the crop (33.2%): Some farmers indicated that they had used up all their nearby lands for the cultivation of other crops, and they were not prepared to travel far distances to cultivate Bambara groundnut.

Some farmers (36.1%) stated that they simply did not have the time to add Bambara groundnut to their existing cultivation. The farmers intimated that they are much into the cultivation of staple crops such as maize and cowpea, hence could not add Bambara groundnut to their production list.

No extra capital (42.4%): Some farmers also intimated that lack of extra capital was the reason they did not go into the production of Bambara groundnut.

Comparing Bambara groundnut to other legumes, some respondents (25.9%) stated that the other legumes like groundnut and cowpea produced higher yields than Bambara groundnut, hence they preferred cultivating those other legumes to Bambara groundnut.

Low demand by household members (27.2%). The demand for the crop in some households was so low that they did not see a need to cultivate it.

Nevertheless, 77.5% of the non-producers indicated that they would be willing to go into the production of the crop. This suggests that if supported, there is a potential to increase the current level of production of the crop.

Factors influencing the adoption of Bambara groundnut production

As indicated earlier, the first objective of this current study was to investigate the factors that influence farmers' adoption of Bambara groundnut production. From the results presented in Table 3, the factors that had a significant positive effect on the adoption of Bambara groundnut production were household size and extension services. Marital status, education and credit on the other hand had a negative influence on the adoption of Bambara groundnut production. The rest of the variables were not significant.

The implication of the positive marginal effect of household size is that farmers with larger households tended to cultivate Bambara groundnut more than those with fewer household members. This may indicate that in farming communities where household members are an important source of farm labour, Bambara groundnut cultivation could be linked to labour availability. This finding is consistent with that of Deressa et al. (2008).

Another equally important issue that is of relevance is the impact of extension visits. The positive significant marginal effect of this variable in the analysis suggests that extension staff have a positive impact on the cultivation of Bambara groundnut. As indicated earlier, farmers in the study area are more inclined to cultivate staple crops, such as maize, rice and millet. Somewhat counter to our *a priori* expectation, Bambara groundnut producers received extension visits 2.3 times during the farming season under review, as opposed to 1.9 times by non-producers. Deressa et al. (2008) also found similar effect of extension contact on the adoption of new crop

Table 3. Maximum likelihood estimates of the determinants of adoption of Bambara groundnut production.

Variable	Marginal effect	Standard error	Z-Value	P>Z
Constant	0.145	0.338	0.43	0.668
Marital status	-0.520 **	0.244	-2.13	0.033
Household size	0.034 *	0.019	1.81	0.071
Education	-0.0366 *	0.022	-1.67	0.095
Land ownership	-0.053	0.182	-0.29	0.769
Group membership	0.219	0.158	1.39	0.166
Extension visit	0.304 *	0.156	1.95	0.051
Credit	-0.536 **	0.242	-2.21	0.027
Rainfall requirement	0.030	0.155	0.20	0.845
Maturity	-0.152	0.139	-1.10	0.272
Chi sq.	11.96 ***	-	-	0.000

***, **, and * are significant levels at 1, 5 and 10%, respectively.

varieties.

In most farming communities, increased formal education is generally associated with people abandoning agriculture in favour of better paid off-farm employment. Ibekwe et al. (2010) indicated that as farm households' education increases, they tend to pursue non-agriculture occupations. This is because education improves their human capital and therefore becomes more skillful, risk prone and able to meet current demand for economic growth. However, in their case, Uematsu and Mishra (2010) argued that although higher formal education is associated with off-farm employment opportunities, farmers with higher education may also realize higher productivity in on-farm ventures. In addition, amongst those whose main occupation is agriculture, the better educated tend to favour established commercial crops over underutilised or “indigenous” crops such as Bambara groundnut. Schultz (1975) therefore noted that formal education has a much stronger effect in modernised agriculture than in traditional agriculture. It is not surprising therefore that in this current study, the probability of adopting Bambara groundnut production was inversely linked to the extent of farmers’ formal education. While farmers who cultivate the crop demonstrated an awareness of its benefits, there is no evidence that growers have an awareness of the benefits linked with the crop in scientific or policy literature. From an *a priori* perspective it might be assumed that better educated farmers are those more likely to respond positively to new information concerning the environmental adaptive capacity of alternative crops such as Bambara groundnut and thus more likely to adopt it should a convincing case be made for it. The fact that there is no such link in relation to Bambara cultivation in this study suggests that there has been little attempt to present the benefits of the crop to farmers.

From the literature, Bambara groundnut is believed to be a crop which requires only limited external inputs. This means that less money and resources are required to cultivate the crop when compared with other crops. Bambara groundnut production is also regarded as subsistence rather than a cash crop. This suggests that farmers are less likely to borrow to finance its production. The research appears to reflect this with an estimated negative marginal effect of credit being observed. It may be the case that those farmers who do have access to credit tend to use it to cultivate major commercial crops or staples which require higher levels of inputs. In the event that Bambara groundnut cultivation is up scaled to a commercial level, it is likely that credit will definitely play a more important role. However, as things stand, Bambara groundnut appears to be the choice of those with poor access to credit.

Determinants of Welfare

The second and key objective of the study was to estimate the welfare implications of the adoption of Bambara groundnut production. The study found that the cultivation of Bambara groundnut had a significant positive effect on the welfare of the farmers (Table 4). Other factors that were significant in determining welfare were household size, off-farm job participation and credit. However, while the coefficient of household size was negative, those of off-farm employment and credit were positive. Also, the significance of lambda in the model suggests that selectivity bias was present and therefore the estimation of a treatment effect model within the context of Heckman’s (1979) two stage procedure for correcting selectivity bias was appropriate. The estimated coefficients were, thus, freed from biasedness and therefore measured the true effect of adoption on welfare. The positive adoption coefficient meant that in general, Bambara groundnut farmers had greater welfare (that is, per capita consumption) than non-Bambara groundnut farmers. This is a very important finding which justifies, at the very least, support for increased research concerning

Table 4. Maximum likelihood estimates of the determinants of welfare.

Variable	Coefficient	Standard error	Z-Value	P>Z
Constant	819.782	132.458	6.19	0.000
Household size	-57.046 ***	9.788	-5.83	0.000
Education	12.562	11.164	1.13	0.261
Land ownership	-89.571	95.253	-0.94	0.347
Off-farm	120.038 *	71.820	1.67	0.095
Credit	253.438 **	122.154	2.07	0.038
Adoption	875.782 ***	131.339	6.67	0.000
Lambda	-500.187 ***	76.670	-	0.000

***, **, and * are significant levels at 1, 5 and 10%, respectively.

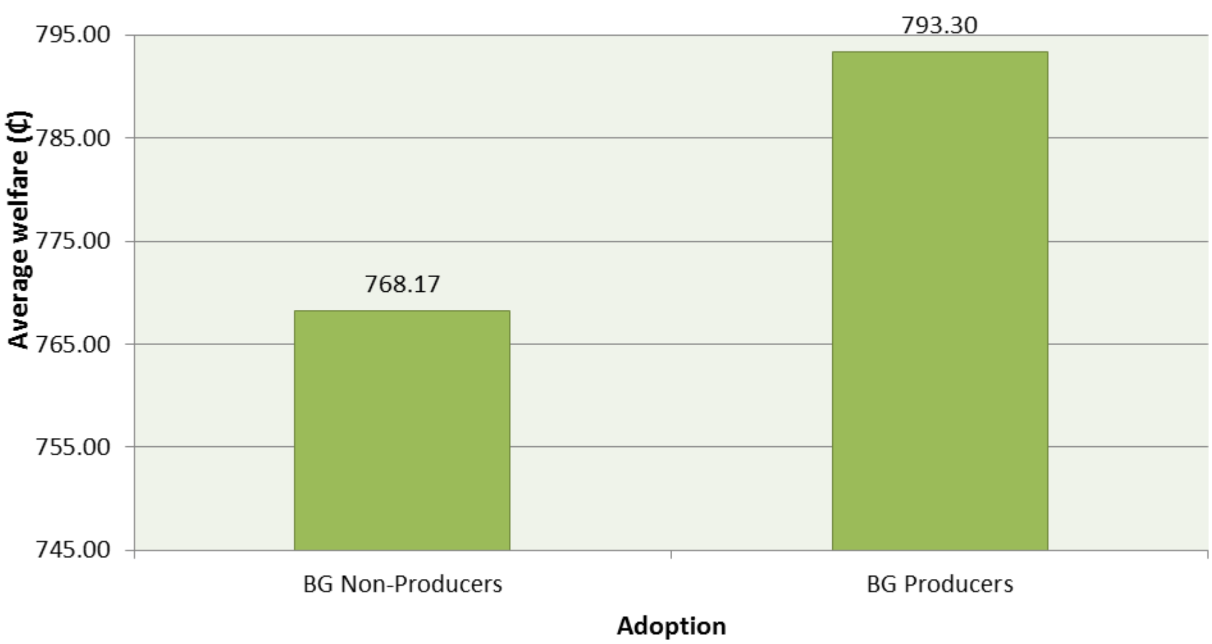

Figure 2. Adoption and average welfare.

the production of Bambara groundnut in the study area as well as into its welfare impacts. Figure 2 below confirms the estimated positive effect of adoption on welfare. On the average, Bambara groundnut producers had higher welfare (GH₵793.30 equivalent to $230.00) than the non-Bambara groundnut producers (GH₵768.17 equivalent to $220.00) it should however be noted that the overall level of this improvement was small and was not consistent across all three regions.

From Figure 3, it can be observed that among the producers, the highest level of welfare was recorded in the Northern region (GH₵879.24), followed by the Upper East (GH₵800.63) and Upper West (GH₵709.83). However, among the non-producers, while the highest level of welfare is still recorded in the Northern region (GH₵822.05), the Upper West region comes second (GH₵769.89) followed by the Upper East region (GH₵712.58). In Ghana, Upper West region is the poorest followed by Northern region and Upper East region (GSS, 2014)

Credit is an important aspect of household asset-building, and serves as an important production resource. The result indicated that those farmers who had access to credit in the 2013 production season had improved welfare as opposed to those who had no credit. With credit, farmers are able to acquire inputs which help to raise their productivity. However, it must be recalled that credit had a negative effect on the adoption of Bambara groundnut production. Thus, although farmers who had access to production credit were not likely to go into Bambara groundnut production, those who accessed it had higher welfare. An interesting question therefore is

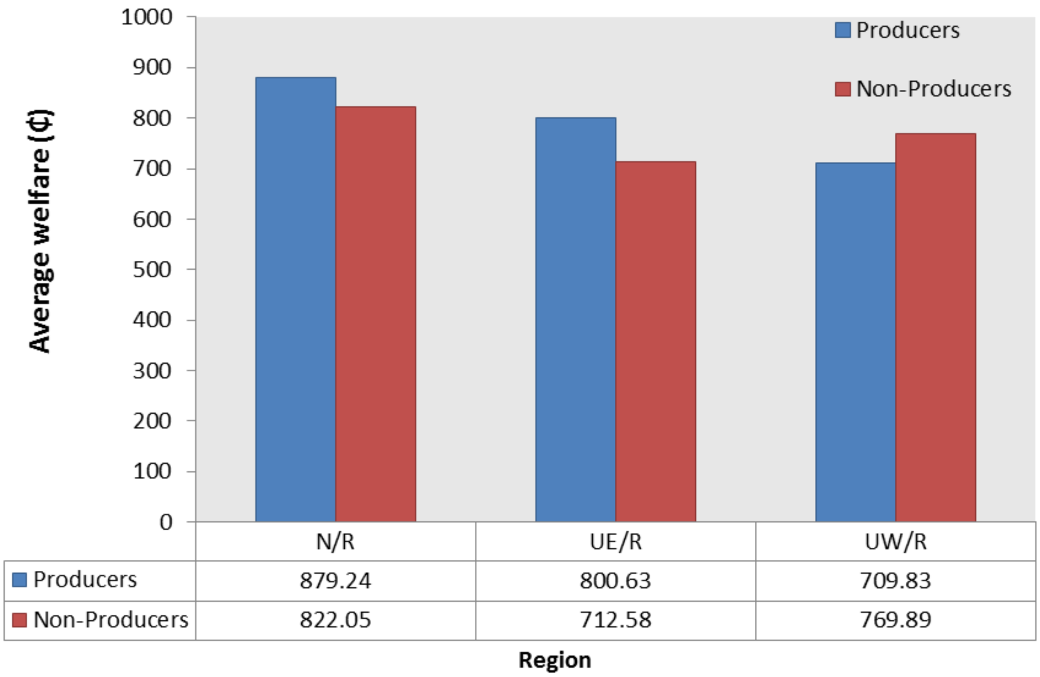

Figure 3. Welfare by region.

the extent to which the cultivation of Bambara groundnut can deliver increases in welfare when compared to welfare gains achieved through improving access to credit.

The negative coefficient of household size means that the larger a farmer's household, the smaller their welfare. This may be attributed to the fact that more household members put more pressure on household resources and the distribution of these resources among the individual members. This meets the *a priori* expectation and also confirms the findings by Donkoh *et al.* (2014). It is important to recall that household size had a positive impact on adoption. This means that although larger household augers well for Bambara groundnut production, it reduces farmers' welfare. In this context, it may be worth further examining the capacity of Bambara groundnut cultivation to play a role in mitigating the adverse impact of household size on the welfare of farming households.

The effect of off-farm participation also contradicted our *a priori* expectations. Considering the unimodal rainfall pattern of the area, one would expect that those with off-farm engagements would have higher welfare than those without. The opposite was found to be the case in this study; farmers who did not participate in off-farm activities had higher welfare. Possible explanations included the possibility that off-farm engagements fail to match the benefits that can be derived from full time farming; or that off farm employment is used as a coping strategy by those who do not have the capacity to generate an adequate livelihood from farming.

CONCLUSIONS AND RECOMMENDATIONS

Its regular description as an underutilised crop has resulted in the Bambara groundnut's depiction as a subsistence crop, often associated with women and used in intercropping systems. While such views are consistent with ideas about underutilised crops which are generally in circulation, the extent to which these ideas have been born out in empirical research is limited. By their very nature these crops have received very little research attention, furthermore, their status means that they often fail to feature in national statistics. However lack of visibility in national data sets needs not necessarily equate to lack of importance or lack of potential. It does however point to the need for a greater research effort concerning the role of such crops in current agricultural settings and a more informed discussion of their impact on welfare. The study sought to initiate such efforts by investigating the factors that influence the adoption of Bambara groundnut production and its effects on farmers' welfare in Northern Ghana. The method of analysis involved an estimation of a treatment effect model to correct for a possible sample selection bias. While some of the findings support the ideas often associated with underutilised crops in general and Bambara groundnut production in particular, such as the negative impact of levels of education and access to credit on Bambara cultivation, others contradicted them. At the very least, the study suggests that the picture of the crop's use and value in relation to smallholding in northern Ghana is more complex than the characterization of underutilised crops suggests. This raises questions concerning whether and in what circumstances the promotion of underutilised crops can be an effective means of improving the welfare of smallholder farmers.

The study revealed that Bambara groundnut is indeed a marginalised crop in the sense that farmers were more inclined to produce staple crops (e.g. maize, rice and millet) and what they perceived to be more important cash crops (e.g. groundnuts and cowpea) (see reasons for non-cultivation of Bambara groundnut). On the whole, however, Bambara groundnut producers had greater welfare (measured as per capita consumption) than non-producers. The study also demonstrated that Bambara groundnut is employed by small farmers living in marginal agricultural areas in ways which are consistent with the use of other crops. Distinctions between the production of crops for cash and subsistence are not clear and surpluses are made available for sale after household needs are met. Findings in relation to the positive link between extension visits and Bambara groundnut production and between single farmers and Bambara groundnut production also highlight the need for further research into the mechanisms and motivations which prompt farmers to grow a supposedly marginalised crop.

However, perhaps the key finding of the study is that Bambara groundnut farmers had increased welfare compared to that of non-producers. What makes this finding particularly compelling is that this was the case for farm households who otherwise lacked the characteristics associated with higher levels of welfare such as access to credit and smaller family size. Thus, the study raises the possibility that the development of programmes for underutilised crops may provide a useful alternative pathway through which to improve the welfare of smallholder households. Simultaneously however, it suggests that there are other circumstances under which it is unlikely that farm household welfare will be improved through the adoption of such crops. In this context it is perhaps notable that the question of assessing the overall impact of underutilised crop production on producing households welfare and indeed of identifying the circumstances under which this can yield better outcomes than alternative development strategies has not received sufficient attention in the literature concerning underutilised crops. This has generally promoted their use in marginal contexts without exploring the dynamics of their current use or exploring how and in what circumstances their positive impact on welfare may be of greater impact than alternative development strategies. At the very least, this study thus illustrates the need for further research concerning the circumstances under which farmers can benefit from the wider cultivation of underutilised crops. Or the means through which this can be transmitted to wider farmer networks is by extension workers.

More generally however, the study raises an important issue concerning the need to incorporate research which examines how programmes to promote underutilised crops can benefit smallholder welfare at an early stage in the design and implementation projects related to these crops. Policy makers and researchers also need to further examine questions concerning the merits of supporting the cultivation of Bambara groundnut. The perception that the crop involves extra labour raises critical questions as to the circumstances under which the crop's contribution to household welfare justifies its cultivation and as to whether research and development concerning the crop should aim to reduce labour requirements or deliver a sufficient premium to growers to cultivate it and indeed to identifying the circumstances under which this represents a viable development pathway. Similarly, given the status as an underutilised crop, the extent and mechanism through which extension impacts on the adoption of Bambara groundnut requires further exploration.

Conflict of interests

The authors have not declared any conflict of interests.

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