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Ridge formation with strip tillage alleviates excess moisture stress for drought-tolerant crops

Yoshihiro Hirooka[a,1], Koichi Shoji[b,1], Yoshinori Watanabe[c], Yasuhiro Izumi[d], Simon K. Awala[e], Morio Iijima[a,f,*]

[a] Graduate School of Agricultural Sciences, Kindai University, Nara, 631-8505, Japan
[b] Graduate School of Agricultural Science, Kobe University, Kobe, 657-8501, Japan
[c] Faculty of Agriculture, Fukushima University, Fukushima, 960-1296, Japan
[d] School of Environmental Science, The University of Shiga Prefecture, Hikone, 522-8533, Japan
[e] Faculty of Agriculture and Natural Resources, University of Namibia, Windhoek, 13301, Namibia
[f] JST/JICA, SATREPS, Japan

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ABSTRACT

The impact of climate change is expected to be more severe in semi-arid and arid ecosystems. Seasonal and high-rainfall floods have recently become a common occurrence in semi-arid sub-Saharan countries in southwestern Africa, where ridging is becoming an important method to alleviate flooding stress in drought-tolerant crops. The objective of this study was to propose a feasible tillage method and compare its agronomical effects to those of conventional tillage practices in northern Namibia in sub-Saharan Africa. Pearl millet and cowpea were grown in the field using different tillage methods in seasonal wetlands in this area. We investigated crop yield, growth parameters, soil moisture content, and the shape of the ridge. Soil tillage using a newly proposed disc ridger for two-wheel tractors resulted in higher yield and growth rate in both crops than using the other tillage methods *i.e.* single mouldboard ploughing with animals and/or disc harrowing with four-wheel tractor. Ridge formation with strip tillage (partial pulverization) using the disc ridger resulted in significantly lower soil moisture content after irrigation because of the higher aspect ratio of the ridge. It is likely that large undisturbed portion remained therewith prevented the ridge from collapsing because of the irrigation water that imitated natural rainfall in this region. Therefore, ridge formation with strip tillage leads to good drainage, and as a result, proper drying of soil prevents flooding stresses thus enhancing early growth and yield of pearl millet and cowpea.

1. Introduction

The impact of climate change is expected to be more severe in semi-arid and arid ecosystems owing to their marginal environment, degraded land, diminished biodiversity, and increased water scarcity (Zika and Erb, 2009; El-Beltagy and Madkour, 2012). Irregular floods (hereinafter specifically soil flooding or water logging *i.e.* excess soil moisture in the rooting zone) often cause crop failures and hence food insecurity in semi-arid regions worldwide (Awala et al., 2016). In fact, in recent years there has been a surge of flooding events in semi-arid sub-Saharan Africa as a result of high summer rainfall (Tsheko, 2003; Tschakert et al., 2010). In a series of basic research trials, crop growth and production, under the simultaneous occurrence of flooding and drought events, were reported to have been improved by the newly developed concepts of mixed-seedling (Iijima et al., 2016) and close mixed-planting techniques (Awala et al., 2016; Izumi et al., 2018; Yamane et al., 2018). Field research designed to overcome both flooding and drought events in the semi-arid region is necessary for further development of practical farm techniques.

Sub-Saharan Africa has the highest proportion of food insecurity amongst people of the world (Field, 2014). The production of drought-tolerant crops such as pearl millet (*Pennisetum glaucum*) and cowpea (*Vigna unguiculata*) plays an extremely important role in these regions (Rai et al., 1999; Belton and Taylor, 2004). The global production area in 2016 is estimated at 31.7 million ha for millet and 11.3 million ha for cowpea, with Africa constituting 63% and 93% of the crop areas, respectively (FAO, 2017). In semi-arid sub-Saharan Africa, researches on pearl millet and cowpea have been conducted mainly focusing on

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* Corresponding author at: Graduate School of Agricultural Sciences, Kindai University, Nara, 631-8505, Japan.
E-mail address: iijimamorio@nara.kindai.ac.jp (M. Iijima).

[1] These authors equally contributed to the research.

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improving the genetic and physiological traits associated with drought tolerance, and the resultant genotypes have been distributed to various countries in the region (Ahmed et al., 2000; Mgonja et al., 2005). As a result, grain production in this region often fails when high-rainfall floods occur, owing to the susceptibility of the drought-tolerant crops to flooding stresses (Promkhambut et al., 2010, 2011).

The majority of the population in sub-Saharan Africa make a living from rainfed agriculture, and depend to a large extent on small-holder and subsistence agriculture for their livelihood and food security (Rockstrom, 2000). Namibia is a semi-arid sub-Saharan country in south-western Africa, where seasonal and high-rainfall floods have recently become a common occurrence, particularly in the country's main cropping areas of the populous northern region (Mendelsohn et al., 2013). In northern Namibia, more than 90% of the smallholder farmers cultivate pearl millet as a staple food crop (McDonagh and Hillyer, 2003). In addition, 45% of the cultivated area is intercropped with cowpea (Matanyaire, 1998). Soil flooding or waterlogging has been caused by high-rainfall floods originating from the Angolan highlands, which triggers a chain of reactions in the soil solution (Suzuki et al., 2013; Mizuochi et al., 2014; Anthonj et al., 2015). Therefore, ridging is considered to be important to alleviate flooding stresses for drought-tolerant crops in this region.

Using a four-wheel tractor is believed to be a simple solution for preparing the ridges before sowing, yet it is too expensive for small-holder farmers. Typical tillage method for such soil preparation in this area has been mouldboard ploughing with donkeys or oxen, and ridging with a couple of return trips therewith is gaining popularity in flood-prone areas associated with recent periodical events of flood. These floods, often alternately occurring with droughts, concurrently lead to the decrease in the availability of animal power (Seo and Mendelsohn, 2007), and as an alternative, four-wheel tractors mounted with various types of harrow are becoming common, which are often operated by local contractors. However, the quality of the operation (timeliness, flat bed or ridging, or degree of soil pulverization) is not necessarily considered under current limited availability of the services. It is therefore natural that smaller machines such as two-wheel tractors are considered to be timeliness and flexibility, with increased number of the service providers and preferably with more suitable implements adapted to the environment.

In semi-arid regions, inter-tillage (agitation of surface soil during growth period) is commonly practiced as a part of weed control and is known to be useful to reduce water evaporation from the soil surface. It also enhances the efficient use of irrigation water that facilitates the development of an extensive root system (Ahmad et al., 2000). Nonetheless, the combined effect of the drought mitigation (inter-tillage) practice with the flood-mitigation (ridging) practice is unknown, as these practices have been aimed at the opposite purposes. The combined effect of the soil tillage practices (seedbed tillage and inter-tillage) should be tested in fields under semi-arid climate conditions. Our hypotheses are that flooding stress is mitigated by seedbed ridging tillage, and that drought stress is mitigated by inter-tillage.

The objective of this study is to propose a feasible tillage (flood-mitigating) method for seedbed preparation, to compare its agronomic effects to those of conventional tillage practices of northern Namibia, and to confirm their compatibility with the inter-tillage (drought-mitigating) practice.

2. Materials and methods

2.1. Study site and experimental design

The field experiments were conducted during the dry seasons of 2016/2017 in the experimental fields of the University of Namibia, Ogongo Campus (17°41′S, 15°18′E, 1109 m ASL), located in northern Namibia. Northern Namibia has a semi-arid climate, with an annual mean temperature of approximately 22 °C and annual average rainfall of 400–450 mm. The experiments were conducted in dry period under controlled water environment, and therefore we considered that one season of the trials was adequate. During the study period, weather data were collected using the Bowen ratio measuring system (C-AWS-BW3, Climatec, Japan) close to the experimental fields. Fig. 1 shows the seasonal change in average daily temperature and daily precipitation during the experiment. The top soil (0–20 cm) at the experimental site was classified as sandy, with a texture of 93.5% sand, 2.0% clay, and 4.5% silt, with 2.8 g total C kg^{-1}, 0.28 g total N kg^{-1}, 6.3 mg available P kg^{-1}, 38.1 mg K kg^{-1}, and a pH (H_2O) of 7.0 (Awala et al., 2016). This type of sandy soil is common in the study area; it shows lower infiltration and percolation rates, and at the surface it tends to hold excess moisture (Crescimanno et al., 1995).

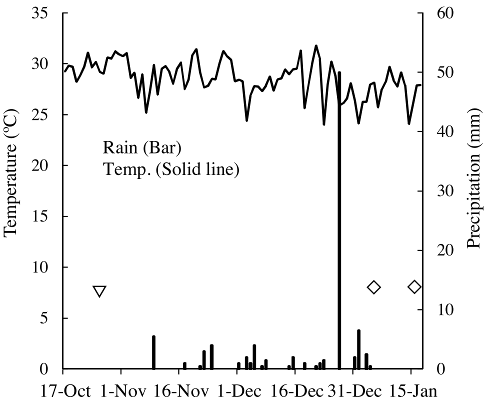

Fig. 1. Daily average temperature (solid line) and daily precipitation (bar) during growth periods. ▽ represents the sowing date 16 Oct 2016, and ◇ represents the harvesting date (8 Jan for pearl millet; 16 Jan for cowpea.).

In the study, we used pearl millet (*P. glaucum* L. 'Okashana 2′) and cowpea (*V. unguiculata* L. 'Nakare') as the experimental crops, as they are adapted to the semi-arid conditions of the region. The seeds of Okashana 2 and Nakare varieties were obtained from Namibian Seed Company. Both crops were sown on 17 Oct 2016. The field was tilled for seedbed preparation using three different methods [MP (mouldboard plough), DH (disc harrow) and DR (disc ridger), details in the next section], with the inter-row spacing set at 1.2 m apart on 7 Oct for the pearl millet and on 12 Oct for the cowpea. Following local recommendations, a basal fertilizer was incorporated into the 15-cm surface soil layer with a rotavator at a rate of 30 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1} one day before the seedbed tillage.

The pearl millet experiment was carried out on 14.4 m^2 (6 m × 2.4 m) plots with six replications, whereas the cowpea experiment on 12 m^2 (5 m × 2.4 m) plots with three replications. Planting densities were 1.4 plants per m^2 (1.2 m × 0.6 m) for pearl millet and 3.3 plants per m^2 (1.2 m × 0.25 m) for cowpea. Soil flooding was achieved by applying approximately 11 mm of irrigation water with sprinklers every two to three days during the growing period (a total of 330 mm, which is equivalent to the annual rainy season in the study area), except for after one heavy day of rain, on the 27 Dec. No pesticides were used for insect or disease control, as their incidence and the damage caused were negligible.

We set inter-tillage (It+) and non-intertillage (It-) treatments on 7 Nov and 23 Nov for both experiments. The It + was done by hand hoeing, which also involved weeding action, whereas for the It-, weeds were simply cut at the soil surface level using scissors to avoid disturbance to the soil in order not to add the effect of surface tillage when weeding.

2.2. The seedbed tillage implements

Three tillage implements used were mouldboard plough (MP), disc harrow (DH), and disc ridger (DR) as shown in Fig. 2 and Table 1.

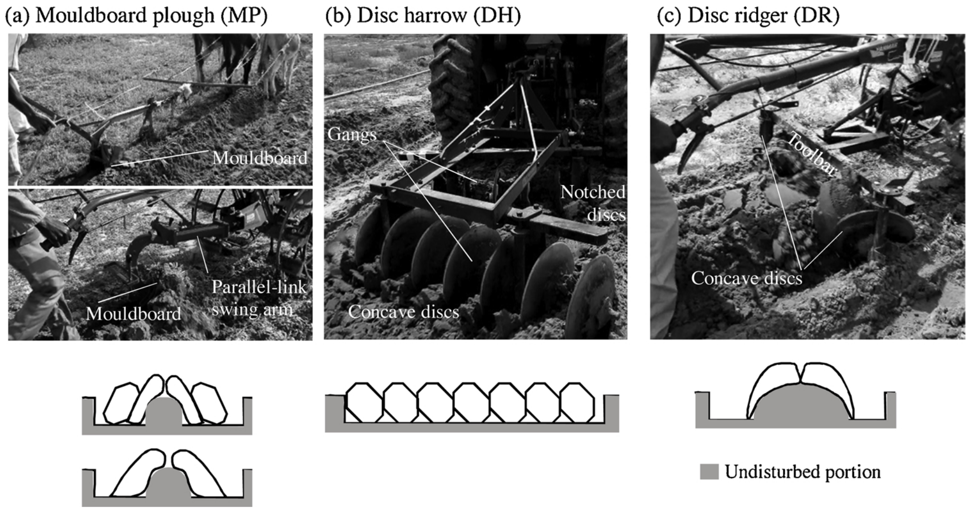

Fig. 2. Overview of the tillage implements and the schematic views of the placement of the soil slices for MP, DH, and DR treatments.

The mouldboard plough (MP) used in the pearl millet experiment was pulled by three donkeys. Donkeys are often used for tillage purposes in the study area (Newsham and Thomas, 2011). The plough (model number and manufacturer unknown) was made of steel, and the front coulter was disabled. The operator started ploughing with *ca.* 20 cm- wide undisturbed portion at the center and made two return trips to form a ridge. For the cowpea experiment, because of unavailability of the donkeys and the operator, a reversible mouldboard plough (MR-83 N, Niplo-MATSUYAMA Co., Japan) was directly fixed on a two-wheel tractor. The lateral position of the plough was adjusted through the parallel-link swing arm, to maximize the lateral displacement of the soil, so that a similar ridge to the one with the mouldboard plough in the pearl millet experiment could be formed at one return trip. The operating depths of MP were *ca.* 15 cm on the average.

The disc harrow (DH) was directly hitched and pulled by a four-wheel tractor, and is currently the most popular method used by local contractors. The implement used in the experiment (model number unknown, BP Implemente, South Africa) was an offset harrow, on which the front and the rear discs formed nearly flat with minimal displacement of the soil. This flat tillage with a locally available implement (DH) was in contrast to the ridging with MP.

The disc ridger (DR) consisted of two discs (Bajak Pirangan Granda, Yanmar Diesel, Indonesia) symmetrically fixed on the toolbar connected to the two-wheel tractor. They were fabricated upon modification at the machine shop of University of Namibia, Ogongo Campus. With this tillage implement at the operating depth of ca. 15 cm or slightly more, a high ridge was readily formed at one path with nearly complete soil cover except near the center. Large portion of the soil remained untilled, especially near the bottom of the ridge, yet the soil near the original surface was scratched and displaced (described as rounded edges of the undisturbed portion in the figure) and the soil shifted toward the center. This configuration is not in line with the regular use of disc ridgers (*e.g.* Nkakini, 2014), where the soil is usually supposed to be tilled before the ridging.

2.3. Measurements

Yield survey was conducted after the plants had reached maturity. Four plants of pearl millet were harvested from each plot at 84 days after sowing, and four plants of cowpea between 92 and 99 days after sowing. The sample plants of pearl millet were chosen to represent the plant canopy based on the number of tillers and plant height, and those of cowpea were chosen to represent the plant canopy based on plant height. Panicles of the pearl millet and pods of the cowpea were air-dried and threshed, and the clean grains and seeds were weighed. The grain and seed moisture content was measured using a Grain Moisture Tester (PM-830-2, Kett, Japan). The grain and seed weights were adjusted to 14% moisture content to obtain the grain and seed yields (YIELD). The above-ground biomass, except for the grains or the seeds, was weighed after three days drying in an oven at 80 °C to obtain the total dry weight at maturing (TDW).

At the heading stage of pearl millet and flowering stage of cowpea, three plants were harvested from each plot, and plant height (PH) and panicle number (PN) of pearl millet were measured. The harvested plants were placed in an oven and dried at 80 °C for three days, and the above-ground biomass was measured (DW). Leaf chlorophyll content

Table 1
Specification of the seedbed tillage methods.

MP (Mouldboard plough)	DH (Disc Harrow)	DR (Disc Ridger)
Single 20 cm- bottom mouldboard plough	Seven-row offset disc harrow	Double symmetrical discs
Three-donkey drawn Ridging at 2 return trips	Four-wheel tractor drawn	Two-wheel tractor drawn
	Flat tillage at one-way trip	Ridging at one-way trip
Single 25-30 cm- bottom mouldboard plough	Disc diameter: 50 cm	Disc diameter: 40 cm
	Disc depth: 5 cm	Disc depth: 5 cm
	Disc pitch: 23 cm	Tilt angle$^{2)}$: 15º
Two-wheel tractor drawn	Gang angles$^{1)}$: 14º, 18º	Disc angle$^{3)}$: 32º
		Rear clearance: 52 cm
Ridging at 1 return trip		

1) Angle between the gang shaft and the lateral direction.
2) Angle of the disc shaft against the horizontal plane.
3) Angle between the lateral direction and the disc shaft projected in the horizontal plane.

Fig. 3. The plate containing 2 cm- grid lines for measuring the profile of the ridge in MP treatment in pearl millet experiment.

(SPAD), photosynthetic rate (Pn), and transpiration rate (Tn) of the uppermost fully expanded leaves of the crops were measured using the SPAD meter (SPAD-502; Minolta Camera Co. Ltd, Japan) and a portable photosynthesis analyzer (LCpro SD, ADC BioScientific, UK), respectively. For the measurement of Pn and Tn, the photosynthetic photon flux density and the concentration of CO_2 in a chamber were set to 1300 μmol photon $m^{-2} s^{-1}$ and 380 μmol $mol^{-1} s^{-1}$, respectively. Leaf area index (LAI) was measured with a plant canopy analyzer, (LAI-2200, LI−COR Inc., Lincoln, NE, USA) using the single sensor mode in a sequence of the two above and four below the canopy in each plot.

Soil moisture content (SMC) (0–20 cm) was measured using a hand-held sensor (ML2x Theta Probe, Delta-T Devices Ltd, England) in each plot, by setting the tip of the 10-cm long probes at depths of 10 cm and 20 cm from the soil surface at an intra-row spacing. SMC was measured at one day after irrigation on 14 Dec, when the shape of the ridges was expected to be determined toward the end of the crop season. To correlate the shape of the ridges to SMC, one side of a rectangular plate with grids (Fig. 3) was aligned with the center of the ridge and the plate was inserted down to reach the bottom of the furrow. This procedure was repeated 3 times for each plot on 20 Dec. From the photos, the height was defined as the vertical distance to the highest elevation, whereas half the width was as the horizontal distance from the center to the lowest elevation. The aspect ratio of the ridge therewith was defined as its height divided by its width.

2.4. Data analyses

The harvest index (HI) was calculated as the ratio of YIELD to TDW (YIELD/TDW). The crop growth rates (CGR; g m^{-2} day^{-1}) before and after the heading or flowering period were calculated from the dry weight (DW) and the number of growing days.

Two-way analysis of variance (ANOVA) was used to test for the main effects of the different seedbed tillage and inter-tillage treatments and their interactions on all the parameters.

For all multiple comparisons, Fishers' LSD test was performed at the 0.05 probability level. All statistical analyses were carried out using BellCurve for Excel (Social Survey Research Information Co., Ltd. Tokyo, Japan) for statistical evaluation.

3. Results

3.1. Pearl millet experiment

The seedbed tillage methods had significant effects on grain yield (YIELD) ($p < 0.05$), total dry weight (TDW) ($p < 0.01$) at maturing stage and crop growth rate before heading (CGR_1) (Table 2). The YIELD ranged from 1.82 t ha^{-1} (DH and It-) to 2.99 t ha^{-1} (DR and It-), and was influenced by TDW ranged from 3.48 t ha^{-1} (DH and It-) to 6.13 t ha^{-1} (DR and It+). The YIELD was significantly higher in the DR plots than in the DH plots; while TDW was significantly higher in the DR plots than in both the MP and DH plots. The seedbed tillage methods had no significant effects on harvest index (HI), but the HI values ranged from 0.46 (DR and It-) to 0.57 (DH and It+). While there was no significant difference in crop growth rate after heading (CGR_2) among the three tillage methods, crop growth rate before heading (CGR_1) was significantly higher in the DR plots than in the DH plots (Table 2). There were no significant effects of the inter-tillage and its interaction on YIELD, TDW, HI, and CGR (Table 2).

Table 2
Grain yield (YIELD), total dry weight at maturing stage (TDW), Harvest index (HI), crop growth rate before heading (CGR_1) and after heading (CGR_2) of pearl millet. MP, mouldboard plough; DH, disc hurrow plough; DR, Disc ridger plough.

	YIELD (t ha^{-1})	TDW (t ha^{-1})	HI	CGR_1 (g m^{-2} d^{-1})	CGR_2 (g m^{-2} d^{-1})
Seedbed tillage (St)					
MP	2.46ab	5.42b	0.45	2.89b	8.61
DH	2.01b	4.31b	0.47	2.17b	7.00
DR	2.82a	6.78a	0.42	4.06a	10.07
Inter-tillage (It)					
It-	2.46	5.58	0.45	3.04	8.80
It+	2.40	5.43	0.44	3.04	8.33
ANOVA					
St	*	**	ns	**	ns
It	ns	ns	ns	ns	ns
St*It	ns	ns	ns	ns	ns

Grain yield with a 14% moisture content. *, ** represents the significance at 0.05, 0.01 probability levels, respectively.
ns means non-significant at P = 0.05 level. Different letters indicate significant difference by Fisher's test at $P < 0.05$ level.

The seedbed tillage methods had significant effects on growth characteristics such as dry weight (DW), plant height (PH), stem number (SN), and leaf area index (LAI) at heading stage ($p < 0.01$; Table 3). In contrast, they had no significant effects on physiological characteristics such as SPAD, photosynthetic rate (Pn) and transpiration rate (Tn). DW ranged from 85.9 g m^{-2} (DH and It-) to 159 g m^{-2} (DR and It-), and SN ranged from 12.3 m^{-2} (DH and It-) to 18.2 m^{-2} (DR and It-). DW and SN were significantly higher in the DR plots than in both the DH and MP. PH plots ranged from 126 cm (DH and It-) to 151 cm (DR and It-). LAI ranged from 1.23 $m^2 m^{-2}$ (DH and It-) to 2.01 $m^2 m^{-2}$ (DR and It+). The PH and the LAI were significantly greater in the DR plots than in the MP and DH plots. Neither the inter-tillage nor interaction effect show any significant effect on all the measurements of pearl millet around heading stage (Table 3).

Soil moisture content was related with crop growth rate before heading and the shape of the ridge. A significant negative correlation was found between SMC and CGR (Fig. 4; $r = -0.701$; $p < 0.01$), and between ridge aspect ratio and SMC (Fig. 5; $r = -0.522$; $p < 0.01$).

3.2. Cowpea experiment

The seedbed tillage methods had significant effects on seed yield (YIELD), TDW and HI at maturing stage (Table 4). The YIELD ranged from 0.53 t ha^{-1} (DH and It-) to 1.99 t ha^{-1} (DR and It-), and was influenced by TDW that ranged from 1.41 t ha^{-1} (DH and It-) to 2.77 t ha^{-1} (DR and It+) and the HI ranged from 0.35 (DH and It+) to 0.67 (DR and It+). The YIELD and the TDW were significantly higher in the DR plots than in the DH plots. Similarly, they had significant effect on HI ($p < 0.01$); it was significantly higher in the DR and MP plots than in the DH plots. Although there was no significant difference in CGR_2 among the three seedbed tillage methods after flowering, tillage

Table 3
Dry weight (DW), stem number (SN), plant height (PH), leaf area index (LAI), leaf chlorophyll content (SPAD), photosynthetic rate (Pn) and transpiration rate (Tn) of pearl millet at heading stage.

	DW ($g\,m^{-2}$)	SN (m^{-2})	PH (cm)	LAI ($m^2\,m^{-2}$)	SPAD	Pn ($\mu mol\ CO_2\,m^{-2}\,s^{-1}$)	Tn ($mmol\ H_2O\ m^{-2}\,s^{-1}$)
Seedbed tillage (St)							
MP	130.0b	13.9b	144ab	1.33ab	44.5	25.4	4.05
DH	97.8b	13.1b	132b	1.24b	42.5	23.5	3.92
DR	182.5a	17.5a	150a	1.90a	45.2	24.5	3.91
Intertillage (It)							
IT-	136.7	14.9	139	1.35	44.9	24.2	3.91
IT+	136.8	14.8	145	1.29	43.2	24.7	4.00
ANOVA							
St	**	**	**	**	ns	ns	ns
It	ns	ns	ns	ns	ns	ns	ns
St*It	ns	ns	ns	ns	ns	ns	ns

** represents the significance at 0.01 probability level.
ns means non-significant at P = 0.05 level. Different letters indicate significant difference by Fisher's test at $P < 0.05$ level.

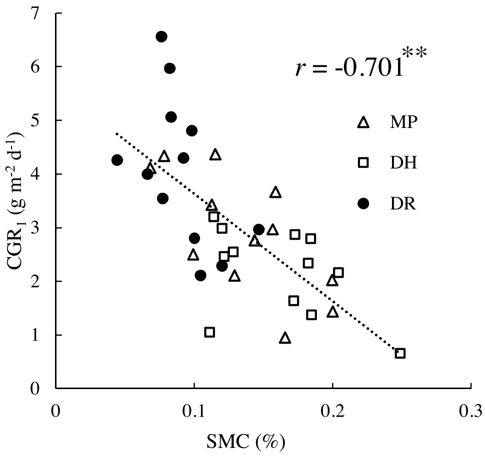

Fig. 4. The relationships between the crop growth rate from sowing to heading (CGR_1) and soil moisture content (SMC) at 1 day after irrigation of pearl millet.

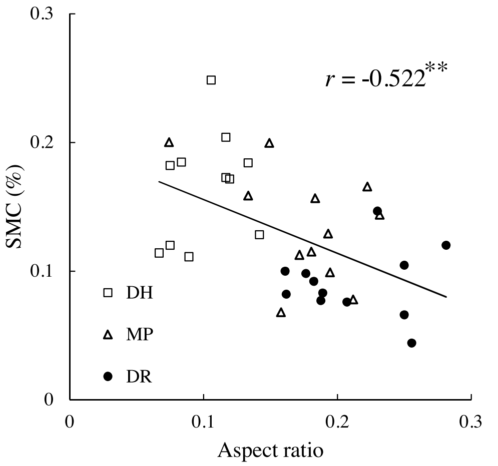

Fig. 5. The relationship between the soil moisture content at 1 day after irrigation (SMC) and aspect ratio (Height/Width) of ridge for pearl millet.

methods significantly influenced CGR_1 before flowering ($p < 0.01$); it was significantly higher in the DR plots than in the MP and DH plots (Table 4).

The seedbed tillage methods had significant effects on growth characteristics such as DW and LAI ($p < 0.01$) (Table 5). In contrast, they had no significant effect on physiological characteristics such as SPAD, Pn, and Tn. DW ranged from 21.5 $g\,m^{-2}$ (for DH and It+) to 87.7 $g\,m^{-2}$ (DR and It+), and LAI ranged from 0.98 $m^2\,m^{-2}$ (DH and It+) to 1.84 $m^2\,m^{-2}$ (DR and It-). Both indicators were significantly higher in the DR plots than in the DH and MP plots. The effects of inter-tillage was not significant on any of the parameters measured around the flowering stage. Similarly, the interaction between the seedbed tillage and inter-tillage methods did not have significant effects on the parameters measured.

Soil moisture content was related with crop growth rate before flowering and the shape of the ridge. A significant negative correlation was found between SMC and CGR (Fig. 6; $r = -0.717$; $p < 0.01$) and between ridge aspect ratio and SMC (Fig. 7; $r = -0.573$; $p < 0.05$).

4. Discussion

Our findings indicated that seedbed tillage with the disc ridger improved the yield and the growth of pearl millet and cowpea than with common methods practiced in some countries in sub-Saharan Africa. The seedbed tillage with large four-wheel tractors is capital-intensive, while the tillage by donkeys is labor intensive and has a limitation on the coverage. In contrast, direct application of the disc ridger to untilled soil has been proven to be an effective method for avoiding flood-induced plant disorders at an affordable power requirement that can be fulfilled with a small two-wheel tractor, and is beneficial to cropping systems similar to those found in northern Namibia. For example, this tillage method can be applied to the ridge-and-furrow mixed cropping technique (Awala et al., 2018; Iijima et al., 2018) adapted to flood and drought conditions. This cropping system is known to be efficient in terms of its ability to utilize natural resources (*e.g.* water, light, and nutrients) (Hailu, 2015).

Soil flooding reduces plant height, dry matter, and root density in pearl millet and cowpea (Zegada-Lizarazu and Iijima, 2005; Dasila et al., 2017). Recently, floods have frequently occurred, alongside recurrent droughts, in sub-Saharan Africa, decreasing the productivity of drought-tolerant crops. In fact, local farmers mainly grow drought-tolerant crops such as pearl millet and cowpea (Awala et al., 2016), which are susceptible to flooding stress. Jackson and Colmer (2005) have found that flooding stress has a greater impact on the crop growth during the vegetative stage. In the pearl millet experiment, the grain yield in the DR plots was 1.4 times higher than in the DH plots, which was attributed to the higher CGR in the DR plots before heading. Higher soil moisture content negatively affected the growth during the vegetative stage. Seed yield of cowpea in the DR plots was also higher than in the DH plots, which is also confirmed by the higher CGR before flowering. Particularly, the HI of cowpea in the DR plots was significantly higher than in the DH

Table 4

Seed yield (YIELD), total dry weight at maturing stage (TDW) and harvest index (HI) of cowpea.

	Yield (t ha^{-1})	TDW (t ha^{-1})	HI	CGR$_1$ (g m^{-2} d^{-1})	CGR$_2$ (g m^{-2} d^{-1})
Seedbed tillage (St)					
MP	1.13ab	1.99ab	0.59a	0.79a	4.12
DH	0.65b	1.45b	0.41b	0.53a	3.05
DR	1.78a	2.56a	0.69a	1.59b	4.48
Intertillage (It)					
IT-	1.20	1.91	0.59	1.01	3.61
IT+	1.18	2.01	0.52	0.94	4.16
ANOVA					
St	*	*	**	**	ns
It	ns	ns	ns	ns	ns
St*It	ns	ns	ns	ns	ns

Seed yield with a 14% moisture content. ** and * represents the significance at 0.05 and 0.01 probability level, respectively.
ns means non-significant at $P = 0.05$ level. Different letters indicate significant difference by Fisher's test at $P < 0.05$ level.

Table 5

Dry weight (DW), leaf area index (LAI), leaf chlorophyll content (SPAD), photosynthetic rate (Pn) and transpiration rate (Tn) of cowpea around flowering stage.

	DW (g m^{-2})	LAI (m^2 m^{-2})	SPAD	Pn (μmol CO$_2$ m^{-2} s^{-1})	Tn (mmol H$_2$O m^{-2} s^{-1})
Seedbed tillage (St)					
MP	42.6a	1.16a	64.4	17.3	4.1
DH	28.7a	1.02a	66.0	18.3	4.3
DR	86.1b	1.77b	69.9	17.6	4.2
Intertillage (It)					
IT-	54.3	1.35	64.8	16.9	4.1
IT+	50.7	1.29	68.8	18.5	4.3
ANOVA					
St	**	**	ns	ns	ns
It	ns	ns	ns	ns	ns
St*It	ns	ns	ns	ns	ns

** represents the significance at 0.01 probability level.
ns means non-significant at $P = 0.05$ level. Different letters indicate significant difference by Fisher's test at $P < 0.05$ level.

plots, indicating that higher soil moisture content negatively affected the yield and growth, not only during the vegetative stage but also during the reproductive stage. Considering these positive effects of the DR method, *i.e.* direct disc ridging on partially tilled soil on pearl millet and cowpea, we recommend this tillage method to be applied to other drought-tolerant crops such as sorghum, in sub-Saharan Africa, to enhance yield and biomass production.

One of the aims of testing the different tillage methods for soil preparation in this study was to evaluate the feasibility of the disc ridger pulled by a small two-wheel tractor as compared to the conventional implements pulled by donkeys or by a large four-wheel tractor. The ridging on the undisturbed soil (DR) at one path, which was freshly prepared with a pair of symmetrical discs, was a drastic measure, where 52-cm width *i.e.* the rear clearance, was left untilled in reference to the actual working width of 95 cm. In fact, the tractor

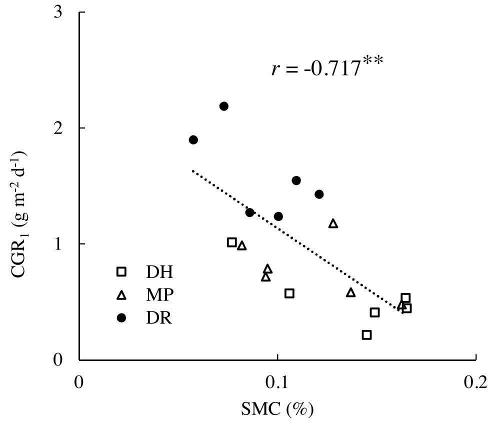

Fig. 6. The relationships between the crop growth rate from sowing to flowering (CGR$_1$) and soil moisture content at 1 day after irrigation (SMC) of cowpea.

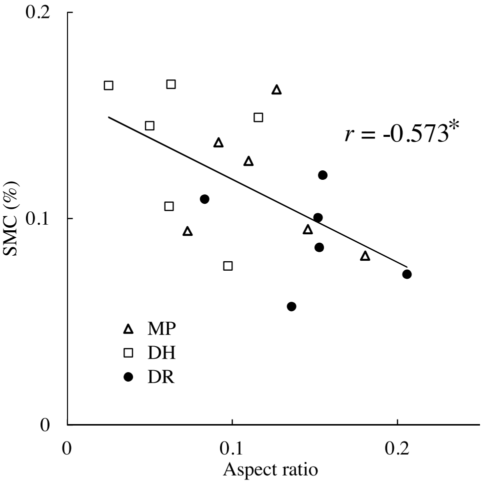

Fig. 7. The relationship between the soil moisture content at 1 day after irrigation (SMC) and aspect ratio (Height / Width) of ridge for cowpea.

was running at its full traction (around 1.5 kN, *i.e.* about half the weight of the tractor + the implement) at a pull test on the same soil condition, just as much as when it pulled the single bottom plough that required two paths, *i.e.* a return trip to form a ridge in the MP plots. This means that the DR potentially resulted in as much as half the time required and the fuel consumed as the MP, owing to the large portion of the untilled soil. Direct comparison of the draught required for the DR to that required for the DH may be difficult; however, we can assume that the (apparent) specific draught of DR may have been about a quarter to a half of that of the DH, considering that the DH inverted the soil twice and that the untilled width of the DR was more than a half of the actual operating width.

The aspect ratio (height/width) of the ridge represented the extent of drainage or drying of the soil: the narrower the width and the greater the height, the easier the drainage or drying of the water from the root zone of the crop on the ridge. The DR showed a high aspect ratio, and as a result, the soil moisture content just after irrigation remained lower than for other tillage treatments (Figs. 5 and 7). This is probably because the undisturbed portion was the largest in DR plots (Fig. 2), which prevented the ridge from collapsing by the irrigation water during the growth periods. Therefore, ridging with strip tillage with the DR is assumed to have formed more efficient ridges against flooding stresses than those formed by other common tillage methods.

Physiological characteristics, such as SPAD, Pn, and Tn, were measured only at the heading period for pearl millet and at flowering for cowpea, and significant difference was not noted between the seedbed tillage and inter-tillage treatments. This reflects no significant difference in crop growth rate after heading or flowering period (CGR_2) among the treatments. Photosynthesis is considered a good proxy for overall performance in crops (Kalaji et al., 2018). In particular, crop photosynthetic function, including chlorophyll fluorescence parameters, under abiotic stress conditions determines the degree of resistance (Iqbal et al., 2018; Dąbrowski et al., 2019). In this study, both crops especially in the DH treatment were damaged by flooding stress early during the growth period, as indicated by the difference in CGR_1 (Tables 3 and 5). Therefore, if consecutive monitoring of photosynthetic function had been implemented through the growth periods, better understanding could have been achieved of the eco-physiological mechanisms of crop tolerance against flooding.

Coping with extreme weather conditions such as frequent soil flooding and drought is required in seasonal wetlands and is commonly seen in the fields of smallholder farmers in some countries in sub Saharan Africa (Awala et al., 2016). In this study, improvement in crop productivity resulted from well-drained partially tilled ridges (DR). Thus, this tillage method for soil preparation is a useful technique to alleviate flooding stresses in drought-tolerant crops in sub-Saharan Africa. To prepare for unexpected events of drought, which brings about water shortage stress for crops on the well-drained ridges, several options are available. In general, lowering the ridges in the middle of cropping season to prepare for the drought is technically easier than raising or maintaining the ridges, therefore a high-ridge tillage practice such as the DR method is suggested under adequate soil moisture content. For soils containing more silt and clay than we tested, water is expected to come up through undisturbed portion from the subsoil layer (Yoshinaga et al., 2008). Future studies on the application of the strip tillage method under similar conditions are necessary.

The inter-tillage treatment conducted in this study did not show any effect on the growth or yield of both pearl millet and cowpea. The inter-tillage or surface tillage commonly seen in semi-arid regions is hypothesized to prevent the evaporation of water lifted up through capillary phenomenon from the subsoil (Ahmad et al., 2000). In this study, however, the soil mostly consisted of sand and the crop was not damaged by drought stress in this study, and therefore, the inter-tillage treatment did not significantly affect water evaporation from the soil surface. In contrast, the effect of ridging with strip tillage is remarkable. Further studies investigating the interaction effect of seedbed tillage and inter-tillage treatment on the crop and weed growth management under various soil and water conditions are needed.

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