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Field evaluation of mixed-seedlings with rice to alleviate flood stress for semi-arid cereals

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ABSTRACT

Flash floods, erratically striking semi-arid regions, often cause field flooding and soil anoxia, resulting in crop losses on food staples, typically pearl millet (*Pennisetum glaucum* L.) and sorghum (*Sorghum bicolor* (L.) Moench). Recent glasshouse studies have indicated that rice (*Oryza* spp.) can enhance flood stress tolerance of co-growing dryland cereals by modifying their rhizosphere microenvironments via the oxygen released from its roots into the aqueous rhizosphere. We tested whether this phenomenon would be expressed under field flood conditions. The effects of mix-planting of pearl millet and sorghum with rice on their survival, growth and grain yields were evaluated under controlled field flooding in semi-arid Namibia during 2014/2015–2015/2016. Single-stand and mixed plant treatments were subjected to 11–22 day flood stress at the vegetative growth stage. Mixed planting increased plant survival rates in both pearl millet and sorghum. Grain yields of pearl millet and sorghum were reduced by flooding, in both the single-stand and mixed plant treatments, relative to the non-flooded upland yields, but the reduction was lower in the mixed plant treatments. In contrast, flooding increased rice yields. Both pearl millet–rice and sorghum–rice mixtures demonstrated higher land equivalent ratios, indicating a mixed planting advantage under flood conditions. These results indicate that mix-planting pearl millet and sorghum with rice could alleviate flood stress on dryland cereals. The results also suggest that with this cropping technique, rice could compensate for the dryland cereal yield losses due to field flooding.

1. Introduction

Irregular floods increasingly strike semi-arid regions worldwide, often causing crop failures and hence food insecurity in the regions. In these regions, crop cultivation is dominated by drought-adapted cereals, such as pearl millet (*Pennisetum glaucum* L.) and sorghum (*Sorghum bicolor* L.) (Rai et al., 1999). Both crops are the staple food for most of the resource-poor smallholder farmers (Belton and Taylor, 2004). The global production area in 2014 was estimated at 31.1 million ha for pearl millet and 44.2 million ha for sorghum, with Africa constituting 63% and 65% of the crop areas, respectively (FAO, 2015), but Sub-Saharan Africa has the highest proportion of food-insecure people (Porter et al., 2014). In semi-arid Sub–Saharan Africa, research on pearl millet and sorghum has been conducted mainly focusing on improving the genetic and physiological traits associated with drought tolerance, and the resultant genotypes have been distributed in various countries in the region (Ahmed et al., 2000; Mgonja et al., 2005). However, grain production in this region usually fails when high rainfall floods occur, because of the susceptibility to the flood stress of pearl millet (Sharma and Swarup, 1989; Zegada-Lizarazu and Iijima, 2005) and sorghum (Orchard and Jessop, 1984; Promkhambut et al., 2010, 2011). In Namibia, a semi-arid Sub–Saharan country in southwestern Africa, seasonal, 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;

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Table 1
Growth conditions during field experiments in 2014–2016.

Experimental period				Temperature (°C)			Relative humidity (%)				
Year	Duration (from sowing to end of experiment)	Description	Flooding period (DAS)[a]	Mean	Max.	Min.	Mean	Max.	Min.	Solar radiation ($MJ\,m^{-2}\,d^{-1}$)	Rainfall (mm)
2014/2015 a	18 Sep.–19 Jan.	Survival and production	21–43	27.0	34.6	19.5	42.2	66.5	23.3	25.7	127.2
2014/2015 b	30 Oct.–17 Mar.	Survival and production	21–36	26.9	34.2	19.7	45.4	70.9	24.7	26.4	185.7
2014/2015 c	30 Oct.–18 Dec.	Survival	21–36	24.3	30.5	18.4	63.9	86.7	40.8	22.4	69.9
2014/2015 d	13 Nov.–29 Dec.	Survival	21–32	27.3	35.1	18.9	26.8	48.7	12.6	29.1	0.6
2015/2016	17 Sep.–18 Jan.	Production and LER	21–36	28.5	36.1	20.3	38.4	62.2	21.5	33.2	113.0

The seedlings were transplanted to the field at 21 and 28 days after sowing of pearl millet (and/or sorghum) and rice, respectively. Weather data were collected starting from the flooding treatment to the end of the experiments. LER, Land Equivalent Ratio.

[a] Days After Sowing of pearl millet and/or sorghum; Max., maximum; Min., minimum.

Iijima, 2011; Suzuki et al., 2013; Mizuochi et al., 2014), causing losses in the yield of pearl millet and sorghum (Anthonj et al., 2015).

Soil flooding or waterlogging triggers a chain of reactions in the soil solution. These include the induction of hypoxia (sub-optimal oxygen [O_2]) or anoxia (depletion of O_2); elevation of carbon dioxide, methane and ethylene concentrations; reduction of aerobic and proliferation of anaerobic microbe populations and the accumulation of organic acids and reduced phytotoxins such as Fe^{2+}, Mn^{2+} and H_2S in the soil solution (Colmer and Voesenek, 2009). Because O_2 is a fundamental requirement for plant growth, plants that do not possess mechanisms for flood tolerance, such as most dryland crops, experience poor growth and may even die because of flood stress (Setter and Belford, 1990). Rice (*Oryza* spp.) is a grain crop adapted to wetland environments, and the demand for rice in Sub–Saharan Africa has been increasing. Unlike most dryland crops, rice roots possess an efficient internal aeration system and release O_2 into the aqueous rhizosphere by radial O_2 loss, which are the mechanisms that allow rice roots to grow in flooded, anoxic soils (Joshi et al., 1973; Armstrong, 1979; Colmer, 2003; Kirk, 2003). In the rhizosphere, O_2 is used by soil microbes for respiration but also serves to re-oxidize reduced phytotoxins, mobilize nutrients and maintain aeration (Armstrong, 1979; Ando et al., 1983; Colmer, 2003; Kirk and Kronzucker, 2005), thus mitigating the unfavourable effects of soil flooding on plants (Armstrong and Armstrong, 2005).

Mixed cropping or intercropping generally induces competition for resources, but the co-growing plants can also improve the microclimate of their neighbours through rhizosphere interaction (Brooker, 2006; Brooker et al., 2015). Thus, under mixed cropping, both suppressive and supportive effects of plants on their neighbours occur simultaneously, and the net growth will be the outcome of these opposing effects (Maestre et al., 2003; Zhang and Li, 2003). One of the supportive or facilitative effects is the supply of nitrogen nutrition by legumes to non-leguminous crops such as cereals (Li et al., 1999; Xiao et al., 2004; Mucheru-Muna et al., 2010; Ramirez-Garcia et al., 2015).

Besides nutritional interactions, our previous study indicated that wetland-adapted plant species could alleviate the adverse effects of soil flooding on susceptible species (Iijima et al., 2016). Mix-planting pearl millet or sorghum with rice improved the photosynthetic rate, transpiration rate and biomass of co-growing pearl millet and sorghum seedlings grown under O_2-deficient solution culture conditions. The mixed-seedling cropping technique could serve as one of the agronomic countermeasures to ensure constant staple grain production under flood conditions. However, the solution culture experiments could only demonstrate the possible scenario; therefore, there was a need to certify whether the phenomenon observed in the solution culture would be expressed in the field, where O_2 diffusion would be slower and microbial O_2 demand would be higher. In the present study, we assessed the effect of rice on the survival rate and grain production of companion pearl millet and sorghum subjected to field flooding at the vegetative growth stage, and evaluated the productivity of the crop mixtures.

2. Materials and methods

2.1. Experimental sites

Mixed cropping experiments (Table 1) were conducted for 2 cropping seasons (2014/2015 and 2015/2016) at the University of Namibia Ogongo Campus (17°41′S, 15°18′E, 1109 m ASL), located in North-Central Namibia. North-Central Namibia has a semi-arid climate, annual mean temperature of >22 °C and annual average rainfall of 400–450 mm. This area is located in the Cuvelai drainage basin, originating in southern Angola where rainfall is higher. The basin is characterized by a huge network of seasonal wetlands (locally called *oshanas*), which irregularly overflow into local croplands owing to inflows from Angolan highlands or occasionally from localised high summer rainfall (Mendelsohn et al., 2013). During the study period, the weather data were collected using the Bowen ratio measuring system (C-AWS-BW3, Climatec, Japan) close to the experimental field. Growth periods and mean daily temperature, relative humidity, solar radiation and total rainfall for each experiment are demonstrated (Table 1). The topsoil (0–20 cm) at the experimental site in Namibia was classified as sand, 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.

2.2. Plant materials

In the present study, we used pearl millet (*Pennisetum glaucum* L. cv. Okashana 2) and sorghum (*Sorghum bicolor* (L.) Moench cv. Macia), adapted to semi-arid conditions, and rice (Interspecies of *Oryza. sativa* L. and *O. glaberrima* Steud. cv. NERICA4) as the flood-adapted crop. Okashana 2 and Macia, cultivated in several Southern African countries such as Namibia, were acquired from a Namibian seed company. NERICA4, an upland cultivar sourced from AfricaRice, Benin, West Africa, is promoted for cultivation among subsistence farmers in many Sub–Saharan African countries, such as Namibia.

2.3. The use of mixed-seedlings and seedling establishment

Seed pre-germination and sowing were performed as per the methods described previously (Iijima et al., 2016). The seedling mix of the wetland-adapted (rice) and dryland-adapted (pearl millet and sorghum) crop species (Fig. 1) was used in this experiment. This mixed-seedling system was intended to enhance the intertwining of the roots of the two species. It involved growing the mixed-seedlings in a small container, to allow the development of a dense root mat under the container. This was thought to contribute