MITIGATION OF FLOOD STRESS FOR SEMI-ARID CEREALS BY THE MIXED-SEEDLING WITH RICE (*Oryza sativa*)

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AWALA, SIMON KAMWELE

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CERTIFICATION PAGE

I certify that this research work, **MITIGATION OF FLOOD STRESS FOR SEMI-ARID CEREALS BY THE MIXED-SEEDLING WITH RICE (*Oryza sativa*),** was carried out by **AWALA, Simon Kamwele**

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DEDICATION

I dedicate this research work to my late father, **Petrus Shoombe SHIMBINGO-AWALA 'Ombwa ya Nandjala'**

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ABSTRACT

This study investigated the flood-mitigation effect of rice (*Oryza* spp.) on the performance of companion flood-sensitive, semi-arid, dryland cereals of pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*) subjected to field flooding. In semi-arid regions, crop production is generally constrained by drought; however, due to climate change, seasonal floods have also become frequent in these regions. Therefore, both droughts and floods cause crop damage and food deficit among residents, who are mostly resource-poor farmers that depend on sorghum and pearl millet for food and nutrition, owing to the crops' high adaptation to the prevailing semi-arid environment.

Globally, Sub-Saharan Africa has the highest proportion of food-insecure people. In semi-arid Sub-Saharan Africa, research on major dryland cereals has been conducted mainly focusing on improving the genetic and physiological traits associated with drought tolerance. However, grain production in this region usually fails when high rainfall floods occur, because pearl millet and sorghum are intolerant of flood stress. In Namibia, a semi-arid Sub-Saharan country in southwestern Africa, seasonal, high-rainfall floods have recently become a common occurrence, causing losses in the yield of pearl millet and sorghum. Field flooding causes soil oxygen (O_2) depletion (anoxia), which in turn causes poor growth and yields in plants not adapted to flood conditions, including

most dryland crops. Rice is a grain crop adapted to wetland environments; and its demand 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 (ROL), allowing its roots to grow in flooded, anoxic soils. In the rhizosphere, O_2 performs numerous functions, including aeration thus mitigating unfavourable effects of anoxia on plants.

In this study, we assessed the potential of rice to mitigate flood stress on the dryland cereals by planting the two species closely in the same hill, using a new mixed cropping technique called close mixed-planting. Our earlier glasshouse solution culture study indicated that rice could alleviate the adverse effects anoxia on susceptible, dryland crop species. However, so far field data concerning the new concept of close mixed-planting are lacking. Therefore, in this 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.

Mixed cropping experiments were conducted for 2 cropping seasons (2014/2015 and 2015/2016) at the University of Namibia Ogongo Campus, North-Central Namibia. In these experiments, the seedling mix of rice and the dryland cereals was used. It involved growing the mixed-seedlings in a small container such that their root systems are in direct contact with each other to enhance root entanglement between the two species, and expose the dryland-crop roots to the O_2 being lost radially from rice roots. The pre-germinated seeds were sown in soil media in cell trays, i.e., one seed (for a single-species crop) or two seeds (for mixed species crops) were sown per cell. For the mixed species, seeds of the dryland cereals were relay-planted into cell compartments, containing 1-week-old rice seedlings and plants were grown for 3 weeks in solution culture under greenhouse conditions before being transplanted to flooded field plots.

Five cropping systems namely, single-stand pearl millet, single-stand sorghum, single-stand rice, pearl millet mix-planted with rice and sorghum mix-planted with rice were tested in five different experiments to evaluate the mixed cropping concept. Four of the experiments were conducted to test the effects of close mixed-planting on the survival rate and grain production of pearl millet and sorghum. In the last experiment performed for productivity analysis using the land equivalent ratios, the cropping systems were tested under two flood treatments: non-flooded control and flood. Beginning from transplanting, plants were exposed to flood stress for 11–22 days at a mean water level of 5–9 cm above the soil surface. Dryland cereals' survival rates were assessed during the flood treatments; production and productivity assessments were done using grain yields obtained from plants that survived flood stress.

The results indicated that mixed planting increased survival rates in the dryland cereals. Grain yields in 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 significantly lower in the mixed plant treatments. In contrast, flooding increased rice yields, thereby complementing the low yields of the dryland cereals. A crop mixture of rice and either pearl millet or sorghum under flooding condition demonstrated higher biological efficiency (land equivalent ratios > 1.0), indicating a mixed planting advantage. These results indicate that mix-planting the dryland cereals with rice could alleviate flooding stress on the dryland cereals, and that rice could compensate for the dryland cereal yield losses under extended field flooding.

Conclusively, this study for the first time proved that mixed-seedlings of pearl millet and rice or sorghum and rice mitigated the effects of short-term flooding on pearl millet and sorghum. The results of our study have significant implications for smallholder farmers in flood-affected semi-arid regions. By using the new concept of close mixed-planting, the farmers could obtain grain yields from both rice and dryland cereals during flood years. However, continuous research and development work are warranted to provide agronomic countermeasures in order to ensure constant staple food production under flood conditions occurring in semi-arid regions because of climate changes. Flood stress mitigation by this new cropping technique may be enhanced through judicious agronomic practices, including nutrient management, and through the selection of compatible cultivars that would reduce competition and enhance their complementarity.

CHAPTER 1

GENERAL INTRODUCTION

1. Crop production in semi-arid regions

In semi-arid regions, crop production is generally constrained by drought, but the irregular occurrence of seasonal floods also causes crop damage and food insecurity to these regions (Tsheko, 2003; Tschakert et al., 2010). The semi-arid regions account for about 15% of the total earth's land surface, and are the habitats for about 15% of the human population (Fensholt et al., 2012; Huang et al., 2015). Sorghum (*Sorghum bicolor* L.) and pearl millet (*Pennisetum glaucum* L.) are the major cereals cultivated in these regions owing to their high adaptation to the prevailing drought and poor soil conditions (Rai et al., 1999). Both crops are the staple food and most of the farmers are resource-poor smallholders (Belton and Taylor, 2004).

Globally, in 2014 sorghum and millets ranked as the fifth and sixth major cereals, respectively, after wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), rice (*Oryza sativa* L.) and barley (*Hordeum vulgare* L.) in terms of production area (FAO, 2015). The global production area was estimated at 44 million ha for sorghum and at 31 million ha for millets, with the corresponding yields of 1.5 t ha^{-1} and 0.9 t ha^{-1}. Africa constituted 63%

of the millets' area and 65% of the sorghum area, followed by Asia with 33.8% and 18.7% of the crop area, respectively. In Africa the leading producers of pearl millet were Nigeria, Niger, and Mali, while for sorghum the major producers were Nigeria, Sudan and Ethiopia. These countries are also among the world's leading producers, and most of them are located in the Sahel Region of Sub-Saharan Africa in which many countries are affected by semi-arid climate.

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 released in various countries in the region (Ahmed et al., 2000; Mgonja et al., 2005). Despite these efforts, grain and overall food security in this region have not substantially improved, thus the region has been one of the global hot spots of poverty, hunger and malnutrition (Sanchez, 2002; Sanchez and Swaminathan, 2005; Lal, 2006; Rockström et al., 2007; Porter et al., 2014), a situation which may have been exacerbated by global climate change. Recent studies in semi-arid and arid regions worldwide have reported rising temperatures (Tabari et al., 2011a, 2011b; Thornton et al., 2011; Huang et al., 2012; Chabala et al., 2013), variable precipitations, and delayed onset and reduced length of the growing season (Gong et al., 2004; New et al., 2006; Sarr, 2012; Vicente-Serrano et al., 2015; Yamusa et al., 2015).

Crop growth, development, yield and quality are affected by climate variability (Porter, 2005; Porter and Semenov, 2005). Therefore, existing crop varieties may not be able to cope with new growing conditions created by climate change and climate variability, consequently decreasing agricultural production and hence causing food insecurity. The impact of climate change is nonetheless expected to be more severe in semi-arid and arid ecosystems owing to their marginal environments of degraded land, diminished biodiversity and increased water scarcity (Zika and Erb, 2009; El-Beltagy and Madkour, 2012). In fact, in recent years, there has been a surge of floods in semi-arid Sub-Saharan Africa as a result of high summer rainfalls (Tsheko, 2003; Tschakert et al., 2010; Mendelsohn et al., 2013; Anthonj et al., 2015). Under such conditions, cereal production in the region usually fails because of the susceptibility to 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), thus increasing food shortage in the region.

Namibia, situated in southwestern Africa, is a semi-arid Sub-Saharan country with two world-famous deserts, the Namib Desert in the west along the Atlantic coast and the Kalahari Desert in the east (Mendelsohn et al., 2002, 2009). Like other semi-arid regions, Namibia is associated with recurrent droughts, but the country is also attacked by seasonal floods. This situation makes local food production systems highly unstable as both drought and flood negatively impact agriculture. As a result, since its political independence in 1990, the country has been facing a daunting challenge of producing sufficient food for the growing population. At independence, Namibia's total population was only 1.4 million people; but in 2011, just 20 years after independence, the population had grown by 40% to 2.1 million; moreover, during the same period urban population had doubled (NSA, 2013). Meanwhile, total population has been projected to reach 3.0 million by 2031 (NSA, 2014). These demographic trends have major implications for the country's present and future food security. Sustainable crop production in semi-arid regions such as Namibia may need integrated cropping systems that can mitigate the adverse effects of both drought and flood (Iijima et al, 2016).

2. Cereal production and supply in Namibia

Pearl millet (locally called *mahangu*) is Namibia's staple crop, but the local farmers also grow sorghum, cowpea (*Vigna unguiculata* L.) and melons (*Citrullus* spp.) in disproportionately smaller plots or as mixed crops with pearl millet. Maize and wheat are the other important grains used in Namibia, although they are mainly imported from South Africa and other countries. Based on the country's production records for the period 2002–2011 (FAO, 2015), average pearl millet production area was 232,000 ha, accounting for 89% of the country's cereal area; whereas maize and wheat only occupied

10.5% and 0.5% of the cereal area, respectively.

Namibia's production records for the period 1992–2011 (FAO, 2015) indicated that average production of pearl millet, maize and wheat during the first decade (1992–2001) was 86,940 tons, but during the last decade (2002–2011) production increased by 36% to 118,000 tons. Moreover, average maize and wheat imports during the first decade was 186,940 tons, however their import volume during the last decade decreased by 31% to 132,500 tons.

The increase in domestic production between the two decades was however mainly due to increases in the production of maize and wheat, which respectively, constituted 25% and 8% of the overall increase; this in turn triggered 28% and 3% reduction in maize and wheat imports, respectively. Pearl millet, which is the staple crop, only accounted for 3% of the overall increase in domestic production. Besides maize and wheat importation, Namibia also imports rice as a milled product, with average annual import of 7,000 tons during the last decade (FOA, 2015).

Production data also revealed that domestic cereal production over the 20–year period rarely reached 50% of the national grain requirements, thus the shortfalls were covered by the imported grains and grain products. The stagnation of pearl millet production is quite worrisome as far as national food security is concerned. The low domestic cereal production and high import volume trends are likely to persist for some time in future, thereby threatening national food security.

In Namibia, maize and wheat are mainly produced commercially in few large private farms under both rain-fed and irrigated conditions, and also under full irrigation on government farms, the Green Scheme Projects, located in various parts of the country (NAB, 2015). Pearl millet on the other hand is solely a subsistence crop cultivated under rain-fed conditions by resource-poor smallholders, who are concentrated in the country's northern communal areas where annual rainfall is relatively higher compared with the rest of the country. Average annual rainfall in northern Namibia ranges from 650 mm in the east to about 300 mm in the extreme west, (Mendelsohn, 2006).

The pearl millet farms are low input-low output, based mainly on family labour (Mendelsohn, 2006). Also, the crop is generally cultivated under infertile sandy soils and erratic rainfall conditions of the local semi-arid environment, but most local farmers rarely apply improved technologies such as the use of improved seeds, fertilizers, conservation agriculture and improved crop management practices such as timely planting and pest control to increase farm production. The combined effects of these poor soils, inappropriate crop management practices, drought and flood are the major factors responsible for the low yields of pearl millet in Namibia.

Recently, there have been attempts by the Ministry of Agriculture, Water and Forestry to increase the small-scale farm production via its Dryland Crop Production

Program by providing, amongst others, subsidies for farm services and inputs including purchasing of improved seeds and fertilizers (MAWF, 2010). However, this approach has not solved the problem of crop failure by drought or flood, thus aggregate production output remains virtually unchanged. Floods strike northern Namibia via seasonal wetlands (called locally *oshanas*) and river floodplains (Mendelsohn et al., 2009).

Rice (*Oryza* spp.) is a grain crop cultivated in both wetland and upland agro-ecosystems, and demand for rice in Sub-Saharan Africa has been increasing. The advent of upland NERRICA (New Rice for Africa; the interspecies of *O. sativa* L. [Asian Rice] and *O. glaberrima* Steud. [African Rice]) (Jones et al., 1997) has created an opportunity to extend rice production into semi-arid, Sub-Saharan agro-ecosystems. The seasonal wetlands in northern Namibia can be utilized for rice production by the local subsistence farmers to complement the low yields of the traditional local crops. This could reduce poverty and cereal imports, and increase household and national food security. The *oshanas* (Fig.1-1) are a characteristic of the densely populated North-Central Namibia. Recently, there have been concerted efforts to introduce rice to northern Namibia (Iijima, 2011; Iijima et al., 2013; Suzuki et al., 2013, 2014; Mizuochi et al., 2014).

3. Introduction of subsistence rice cropping system in seasonal wetlands in northern Namibia

3.1. North-Central Namibia

The process of rice introduction to northern Namibia has previously been described (Iijiam et al., 2013). The highest human concentration in Namibia is found in its north-central region which comprises four administrative regions, Omusati, Oshana, Ohangwena and Oshikoto. More than 40% of Namibia's population lives in this region (NPC, 2012). The average annual rainfall in the north-central is about 400 mm (Mendelsohn et al., 2000, 2013); therefore, drought in this populous area is a common phenomenon. However, during the summer rainy season, the region often receives floodwaters from the Angolan plateau, and this creates a network of shallow, inland seasonal wetlands—the *oshanas* (Mendelsohn et al., 2000, 2013).

In recent years, the amount of floodwaters received in the *oshanas* and local rainfall intensities have been changing significantly, causing drought or flood to the area (Mendelsohn et al., 2013). This unpredictable situation has been associated with high crop failure, poor veld conditions and increased livestock losses, subjecting local farmers to constant food insecurity and poverty. In fact, floods have also become a common occurrence in this semi-arid area (Mendelsohn et al., 2009, 2013; Iijima, 2011; Suzuki et al., 2013, 2014; Hiyama et al., 2014; Mizuochi et al., 2014), causing losses in the yields of pearl millet and sorghum (Anthonj et al., 2015). Currently, the water resource of the seasonal wetlands is not utilized for cropping but mainly for small-scale livestock grazing and fishing (Mendelsohn et al., 2000, 2013). Although there is potential to utilize the wetlands' water resource to diversify crop production, utilization of water from the *oshanas* needs to be carried out cautiously without affecting the vulnerable ecological balance of the system. Therefore, development activities in the *oshanas*' system need to be harmonized with environmental conservation.

3.2. The formation of the seasonal wetlands

The dense population of North-Central Namibia is attributed to the easy access to shallow well water, which occurs because of the high groundwater level derived from the local flooding of the *oshanas*. The *oshanas* are a result of a complex endorheic system and shallow basin topography. They are a part of the Cuvelai Drainage System, originating in southern Angola (Mendelsohn et al., 2000). Their network system forms a massive inland delta in the north-central region; and downstream, the system converges to drain into the Etosha Pan in the Etosha National Park (Mendelsohn et al., 2000, 2009; Mendelsohn and Weber, 2011). During the rainy season, water from the upper catchments of the Cuvelai Drainage System in Angola, where rainfalls often exceed 700 mm, contributes to the local flow of the *oshanas* (Mendelsohn et al., 2002; Mendelsohn and

Weber, 2011). The duration and amount of water stored in the *oshanas* are unpredictable and depend largely on the amount of rainfall in the upper catchment areas of Angola covering approximately 37,000 km^2 (Lindeque and Archibald, 1991).

Beside the *oshanas*, North-Central Namibia also possesses another type of wetland ecosystem, which is locally called *ondombe* (plural, *oondombe*). The *oondombe* are individual water bodies that may not be connected to the larger Cuvelai Drainage System. Normally, an *ondombe* is smaller in extent but much deeper than an *oshana* and hence tend to store water for a much longer duration, but their inflows depend largely on local rainfall since they are not necessarily part of the Cuvelai Drainage System.

Normally, local rainfall in the north-central region is not likely to contribute to the duration or severity of flood because of the low annual precipitation, high evaporation rates, and high infiltration rates of the sandy soils which leads to minimal run-off (Lindeque and Archibald, 1991). However, since the amount of floodwaters received from Angola and the local rainfall intensities have been changing variably in recent years, during the 2007/2008, 2008/2009 and 2010/2011 rainy seasons, the area had received higher rainfalls than in earlier years, causing severe floods to the region. For example, the Omahenene Research Station, a local government research station, had recorded 780 mm, 820 mm and 900 mm of rainfall during the respective seasons; the average rainfall for the past 25 years (1990/1991–2014/2015) at the station was 470 mm. The higher rainfalls also coincided with heavy floods from Angola, causing extensive damage to the area (Anthonj et al., 2015). In contrast to the floods, during the rainy seasons 2012/2013–2015/2016, the region, like the whole country, was stricken by severe droughts. Local rainfall was mostly extremely low, being 150, 420, 295, 251 mm during the four consecutive seasons at Omahenene, and no floodwaters were received from Angola.

The formation of seasonal wetlands is a common phenomenon observed widely in the world, and the characteristics of the *oshanas* in North-Central Namibia are similar to those of other wetlands in other semi-arid parts of the world (Breen, 1991). The *oshanas* act as reservoirs, storing water during the rainy season and releasing it slowly at later stages. The *oshanas* are estimated to cover an area of approximately 7,000 to 11,550 Km^2, 85% of which is used communally (Schrader, 1991). Although the *oshanas* are generally used for grazing and fishing (Mendelsohn et al., 2000), the livestock farmers also grow pearl millet as their staple food crop. The higher lands within the wetland system are the pearl millet fields, although there is a risk of crop failure due to the irregular occurrence of seasonal floods (Mendelsohn et al., 2013; Anthonj et al., 2015). Better utilization of this water resource could help stabilize local crop production, thereby alleviating the plight of food deficit often experienced by the residents.

3.3. Dryland cropping in the wetland region

In North-Central Namibia, more than 90% of the farmers cultivate pearl millet as a staple food (McDonagh and Hillyer, 2003; Mendelsohn and Weber, 2011), because this is the only cereal crop that can ensure grain production under rain-fed conditions of the local semi-arid environment. Although data on pearl millet yield in this region is lacking, the average yield was as low as 225 kg ha^{-1} from 1990 to 1993 (Matanyaire, 1998a), but the yield had increased slightly during the period 2002–2011 to 250 kg ha^{-1}, which was still lower (three times lower) than the 2014 world average of 900 kg ha^{-1} (FAO, 2015). For many years, the local small-scale farmers have survived on the low yields obtained from pearl millet; they are amongst the few populations in Africa that have successfully developed an integrated food storage system and hence can store their grain in storage baskets for up to five years (NAB, 2015). The farmers store surplus grains produced in good years as a contingency for production failure by drought or flood.

As a measure to stabilize crop productivity and to reduce the high risk of crop failure, most local farmers practice mixed cropping systems in which cowpea is usually intercropped with pearl millet (McDonagh and Hillyer, 2003). However, the effects of intercropped cowpea on pearl millet are complicated and vary greatly with the soil moisture and plant density. A series of experiments were therefore conducted under different growing environments, including field experiments at the University of Namibia

(UNAM) Ogongo Campus in the north-central region, between 2005 and 2007 to elucidate the water use characteristics of mix-cropped pearl millet and cowpea (Zegada-Lizarazu et al., 2005; 2006; 2007). Plant water sources were determined using hydrogen stable isotope technique. The results indicated higher ability of cowpea to acquire existing soil water, forcing pearl millet to develop deep roots and shift to the recently applied surface irrigation water. Furthermore, the sources of water used by pearl millet seem to be closely related to the plant size, with the plants becoming more reliant on the recently supplied water as the above ground biomass is decreased by competition. Increasing crop production among the subsistence farming communities of northern Namibia has been the focal point for research recently.

3.4. Rice introduction to northern Namibia

Although the potential of rice production in Namibia was only confirmed recently (Iijima et al., 2013), efforts to introduce rice cultivation to northern Namibia started more than four decades ago. The former colonial South African government seemed to have conducted rice trials in an *oshana* at the Omahenene Research Station between 1972 and 1974; however, no subsequent efforts were made to popularize production (no written evidence was found, but only personal communication). In the late 1980’s the same administration had recruited Filipino experts to carry out commercial rice production in the Zambezi River floodplains at the Kalimbeza Rice Project in the Zambezi Region, northeastern Namibia, but this work was terminated. Records of the Ministry of Agriculture, Water and Forestry, Namibia, also showed that the current government had hired a consultant by the name of Mark Spoelstra to conduct rice trials in the *oshanas* between 1996 and 1998, but this study failed thus yielded no scientific data. This study was associated with a rural development project in which extension officers distributed rice seeds from Zimbabwe to local farmers during the same period. However, no technical support was given to the farmers, thus this attempt at rice cultivation also failed.

It was evident that initial rice introduction efforts by the Namibian government were inconclusive; therefore, there had not been proof that rice could be cultivated successfully under northern Namibian environment until recently when this was confirmed by a joint project between UNAM and Nagoya University, Japan. Japanese expert, Prof. Morio Iijima (previously at Nagoya University) had worked as an expert for the JICA (Japan International Cooperation Agency) capacity building program for UNAM staff from 2002 to 2004. During this time, Prof. Osmund Mwandemele of UNAM had encouraged his colleague the late Prof. Luke Kanyomeka, and Iijima to introduce rice to the seasonal wetland region. In December 2002, the three started the discussion about how they should re-initiate rice research work in northern Namibia. First, they had requested JICA to initiate a follow-up program on the former capacity development program. The follow-up program entitled "Rice Introduction Theory", which was a training program for Namibian researchers to study at Japanese Universities and also to conduct rice field days in Namibia, started from 2004 and ended in 2010. Also, the late Kanyomeka had started small rice trials in an *ondombe* inside the Ogongo Campus and in a floodplain at the Kalimbeza Rice Project in 2003/2004 season.

In addition to the JICA follow-up program, a four year basic scientific research project entitled "Introduction of rice by the use of floodwaters in the pearl millet growing region", which was funded by Japanese Society for Promotion of Science (JSPS), was initiated from April 2004. This project had constructed rice cultivar selection fields at both Ogongo Campus and Kalimbeza Rice Project, and started basic research work from 2005/2006 rainy season (1st season). The author, who by then was a long-term JICA trainee at Nagoya University (from September 2005 to March 2008), had conducted rice cultivar selection studies in both locations and the results were summarized by his Master's thesis submitted in March 2008. In the initial production study, 130 rice genotypes from the three cultivated species: *O. glaberrima*, *O. sativa* and their interspecies (NERICAs) were assessed for growth and grain yields in an *oshana* at the Ogongo Campus, and Zambezi River floodplain at the Kalimbeza Rice Project during the 2005/2006, 2006/2007, and 2007/2008 rainy seasons; the results were partly presented by Awala et al. (2009). This germplasm collection consisted of rice genotypes imported from

Nagoya, Japan and West Africa. The overall results showed higher rice yields under the *oshana* than under the floodplain conditions.

Furthermore, demonstrations and extension activities were performed in the wetland region by planting rice in farmers' fields starting 2005/2006 season. This exercise had ever since continued and was still underway until the time when this study was completed (2015/2016 season). Also, rice production under a saline-affected *oshana* was investigated at the Ogongo Campus during 2006/2007 rainy season (Kanyomeka et al., 2008). Salinity reduced overall paddy yield; and when the same experiment was repeated during the dry season, most genotypes were killed by salinity within a few days after transplanting, indicating that the *oshana's* salinity level increased during the dry season.

3.5. Interdisciplinary research trials

After the initial rice introduction trials, an interdisciplinary basic research program entitled "Introduction of subsistence rice cropping harmonized with the water environment and human activities in the seasonal wetland" was conducted from 2008 to 2012, using funding from JSPS (Japan Society for the Promotion of Science). Several studies were conducted through this project, including crop physiological study on water use efficiency of different rice species in Namibia (Suzuki et al., 2013) and hydrological study on evapotranspiration by rice field in a seasonal wetland in the Ogongo Campus

(Suzuki et al., 2014). In the first cropping season of the hydrological study, rice plants were submerged by the strong flood that prevailed in the area during February and March of 2009. However, the final results of this study indicated that the water environment of the *oshanas* would not be modified by extensive rice cultivation with low yield levels. Additionally, 24 rice genotypes selected from the initial rice trials were evaluated further over three cropping seasons from 2008/2009 to 2010/2011 in a non-saline *oshana* at the Omahenene Research Station, which is 70 km west of the Ogongo Campus. Overall results from the field trials had indicated that rice production in the seasonal wetlands (*oshanas*) and floodplains in northern Namibia is feasible, with the *oshanas* being more suitable than the Zambezi floodplains. However, rice cultivation in the saline-affected *oshanas* may not be viable due to the effects of salinity.

The project had also been conducting on-farm demonstration trials with selected farmers, assessing production potential under farm conditions, including testing pearl millet-rice and sorghum-rice mixed cropping systems. These trials also served to create an understanding about local farmers' perceptions towards rice cropping, a component that was being dealt with by the Development Study Team of the current project, described in the next section. Interdisciplinary trials are long-term, therefore, field evaluation and data collection activities would continue. The results so far indicated that farm activities would not significantly compete with each other due to the rice introduction to the pearl millet growing subsistence farming communities, except for land preparation using donkeys and oxen.

In addition to research, the rice team had also been involved in extension activities, creating awareness on rice cultivation among the farming communities in northern Namibia. Two rice farmers' associations were formed in 2006, one in Omusati Region where Ogongo Campus is located, and the other in the Zambezi Region. As a result of this, some farmers in the north-central region started cultivating rice in small plots, and in response the project opened a 4 ha field for seed multiplication and demonstration activities at the Ogongo Campus in 2010.

Furthermore, the team had initiated commercial rice production at the Kalimbeza Rice Project through collaboration with staff members of the Ministry of Agriculture, Water and Forestry, using funding from the Ministry. In 2009, His Excellency President Pohamba declared the Kalimbeza Rice Project a national project. This project has a total area of 229 ha and 12 permanent employees of the Ministry. Due to the annual summer overflow of the Zambezi River, the rice fields are usually flooded, with floodwater levels rising as high as above 1 m, causing damage to short plant-type rice genotypes. Since both floods and droughts occur in northern Namibia, cropping systems that could accommodate both weather events are necessary to stabilize cereal production.

4. The flood- and drought-adaptive cropping system

The flood- and drought-adaptive cropping system has previously been described (Iijima et al. 2013). Food security in North-Central Namibia could be improved through crop diversification and the efficient utilization of local natural resources. The *oshanas*' floodwaters could be utilized more effectively for cropping to ensure food security. Moreover, water resource conservation is also important because of the irregular severe droughts that often strike the area. For example, as was stated earlier, the case of recent dry rainy seasons that had caused food deficit in the area**.** Long-term rainfall information by Mendelsohn et al. (2009) shows that in every decade, drought strikes the area. The 2012/2013 cropping season's severe drought was compared with the one experienced in 1981, 30 years before. The frequency and duration of drought or flood events are important for food production and food security (Porter, 2005). In years of severe flood or severe drought, the subsistence farming communities generally suffer food deficits as they have no other options to secure crops. They, therefore, rely on government for food handouts.

As a result of such situation, the Namibian government had requested the Japanese government for a scientific and technical cooperation project to develop a flood- and drought-adaptive cropping system which can preserve water resources and cope with the yearly fluctuation of flood and drought. For this purpose, a five-year joint research project entitled “Flood- and Drought-Adaptive Cropping Systems to Conserve Water Environment in Semi-arid Regions” was launched in February 2012 at the Ogongo Campus. This project was funded by JST (Japan Science and Technology) and JICA, which also implemented it jointly with UNAM. Targeting the north-central region, the project had proposed a rice-based mixed cropping system model which recognizes the common landscape of crop fields in the area. Most local crop fields in this area are characterized by three distinct regions in terms of slope and water conditions, the upper (upland) region, lower (lowland) region, and the transitional region, which lies between the other two regions (Iijima et al. 2013; Awala et al. 2013).

The transitional region is characterized by fluctuating water or soil moisture levels during the rainy season. The upland region lies above the seasonal wetland system, thus it is usually not flooded under normal circumstances and therefore the one used for growing upland, dryland crops of pearl millet, maize, and sorghum. By contrast, both the lowland and transitional regions are parts of the wetland system and therefore prone to flooding, making them unsuitable for upland crop cultivation. However, from the waterlogged center of a wetland towards the dry uplands, there is a moisture gradient with more favorable moisture conditions for crop production. In the semi-arid Sahelian environment, which is almost identical to that of North-Central Namibia, the yield of pearl millet increased when the crop was planted towards the lower, wetter slopes (Rockström and de

Rouw, 1997). In Namibia, the water accumulated in the lower parts of the slope also contributed to the yield gradients of mix–planted pearl millet and cowpea (Zegada-Lizarazu et al., 2007).

In the new model, rice was cultivated in the lowland region, the local dryland cereals on the upland region and a mixed crops or intercrops of rice and the dryland cereals at the transitional region of the field. The new cropping system was developed through scientific trials in the field of Crop Science, Development Studies, Hydro-meteorology and Integrated Study of Agricultural and Social Sciences. Field experiments were carried out at a model sloped field constructed at the Ogongo Campus. In this cropping model, pearl millet, sorghum and various rice genotypes including upland NERICAs and deep water genotypes were among the component crops of the system. This model was also being tested on-farm with demonstration farmers in the north-central region. However, each farm field presents a different ecosystem in terms of water accessibility; therefore, cropping techniques should be adapted to individual farm water environment.

By diversifying the crops and appropriately matching them with the field microclimates, the new cropping system could provide insurance against total crop failure caused by irregular floods and droughts, and increase total productivity per unit land area. For the mixed crops, it was thought that rice could help the co-growing dryland cereals to withstand short-term flood stress through rhizosphere interaction, since the rice is adapted to wetland environment.

5. Flood stress mitigation for dryland cereals by mix-planting with wetland species

Although plants require water for growth and survival, excess water that causes submergence or waterlogging is detrimental or even fatal to species adapted to aerobic, upland ecosystems (Setter and Belford, 1990; Armstrong and Drew, 2002). 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 gas concentrations; reduction of aerobic and proliferation of anaerobic microbe populations; and accumulation of organic acids such as propionic and butyric acids and reduced phytotoxins such as Fe^{2+}, Mn^{2+}, and H_2S in the soil solution (Setter and Belford, 1990; Armstrong and Drew, 2002; Colmer and Voesenek, 2009). O_2 is a fundamental requirement for plant growth; plants that do not possess mechanisms for flood tolerance experience poor growth, or even die as a result of flood stress (Setter and Belford, 1990).

Rice is the only cereal crop that can grow in wetland environments because its roots possess an efficient internal aeration system and also release O_2 into the aqueous rhizosphere by radial O_2 loss, which are the mechanisms allowing rice roots to grow in flooded, anoxic soils (Joshi et al., 1973; Armstrong, 1979; Colmer, 2003; Kirk, 2003;

Shiono et al., 2011; Nishiuchi et al, 2012). Aerenchyma, continuous air channels formed in the cortex tissues, facilitate the transport of O_2 from well-aerated shoots to submerged roots. Longitudinal diffusion of O_2 towards the root apex is further enhanced by induction of a barrier to radial O_2 loss (ROL) at the root surface, minimizing loss of O_2 to the surrounding environment and hence maintaining adequate cellular respiration. This barrier also may impede diffusion of the soil-derived phytotoxins, and harmful organic acids and gases into the roots (Armstrong, 1979; Colmer 2003). Both upland and lowland rice species use these mechanisms under waterlogged conditions (Colmer, 2003; Nishiuchi et al., 2012).

Even though rice roots contain a barrier to ROL, such barrier is usually not developed in the newly formed, young meristem regions near the root tips, allowing the O_2 to be released into the aqueous rhizosphere (Armstrong, 1979; Colmer, 2003; Yamauchi et al., 2013). In the rhizosphere, O_2 is used by soil aerobic 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). However, unlike rice roots, most terrestrial plant roots do not form a barrier against ROL to ensure efficient internal aeration during soil flooding (Armstrong, 1979). Therefore, excess water causing O_2 deprivation in the soil environment can be detrimental to land plants including cultivated crops, thereby adversely affecting agricultural production by reducing crop yields (Armstrong and Drew, 2002). As stated earlier, irregular, high rainfall floods occurring in semi-arid regions often cause poor production of pearl millet and sorghum or even complete crop failure, thus subjecting local communities to food insecurity.

Mixed cropping or intercropping is known to offer diverse benefits to farmers though the practice also generally induces competition for resources. Mixed cropping is widely adopted in the subsistence agriculture of semi-arid Sub-Saharan Africa as a food security measure (McDonagh and Hillyer, 2003; Zegada-Lizarazu et al., 2005, 2007; Ogutu et al., 2012). Strategies toward crop security by this system include the creation of beneficial plant associations among component crops. Under mixed cropping conditions, the co-growing plants can improve the microclimate of their neighbours through rhizosphere interaction, thereby facilitating the growth of the neighbour (Brooker, 2006; Brooker et al., 2015). Therefore, 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 including cereals (Li et al., 1999; Xiao et al., 2004; Dahmardeh et al., 2010; Mucheru-Muna et al., 2010; Olujobi and Oyun, 2012, Ramirez-Garcia et al., 2015). Mixed cropping of cereals with legumes has often been practiced in many traditional systems because the nitrogen nutrient biologically fixed in the root nodules of the legumes would be used by the cereals for their nutrition. Similarly, cereals also enhance the uptake of mineral nutrients such as P, K, Fe and Zn by companion legumes (Zuo et al., 2000; Li et al., 2001, 2003, 2007; Inal et al., 2007; Zhang et al., 2013).

Besides nutritional interactions, current literature has indicated that wetland-adapted plant species could alleviate the adverse effects of soil flooding on susceptible species. Recently, we have reported that mix-planting pearl millet or sorghum with rice improved the photosynthetic rate, transpiration rate and biomass of pearl millet and sorghum seedlings grown in an O_2-deficient solution culture under glasshouse conditions (Iijima et al., 2016). Our previous study also demonstrated that rice has the potential to enhance flood stress tolerance of the co-growing dryland cereals by modifying their rhizosphere microenvironments via the O_2 released from its roots. The findings of the former study have significant implications for sustainable cereal production in semi-arid areas where pearl millet and sorghum production is affected by high-rainfall field flooding. The mixed-seedling cropping technique could serve as one of the agronomic countermeasures to ensure constant staple grain production under flood conditions (Iijima et al., 2016).

Despite agronomic implications of such findings, the solution culture experiments could only demonstrate the likely scenario; therefore there was a need to find out 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 owing to the presence of soil microorganisms and reduced phytotoxins. Moreover, the advantage of mixed crops or intercrops over sole crops is commonly assessed using the land equivalent ratio (LER), which is an expression of the land required for production of the same yield in the sole crops compared with the intercrop (Mead and Willey, 1980). If more land is required when plants are grown as sole crops, then the LER is > 1 and the mixed crop is advantageous.

6. Objective of the study

The overall objective of this study was to investigate whether mix-planting pearl millet or sorghum with rice under field flood conditions would improve the survival, growth and grain production of the dryland cereals.

Figure

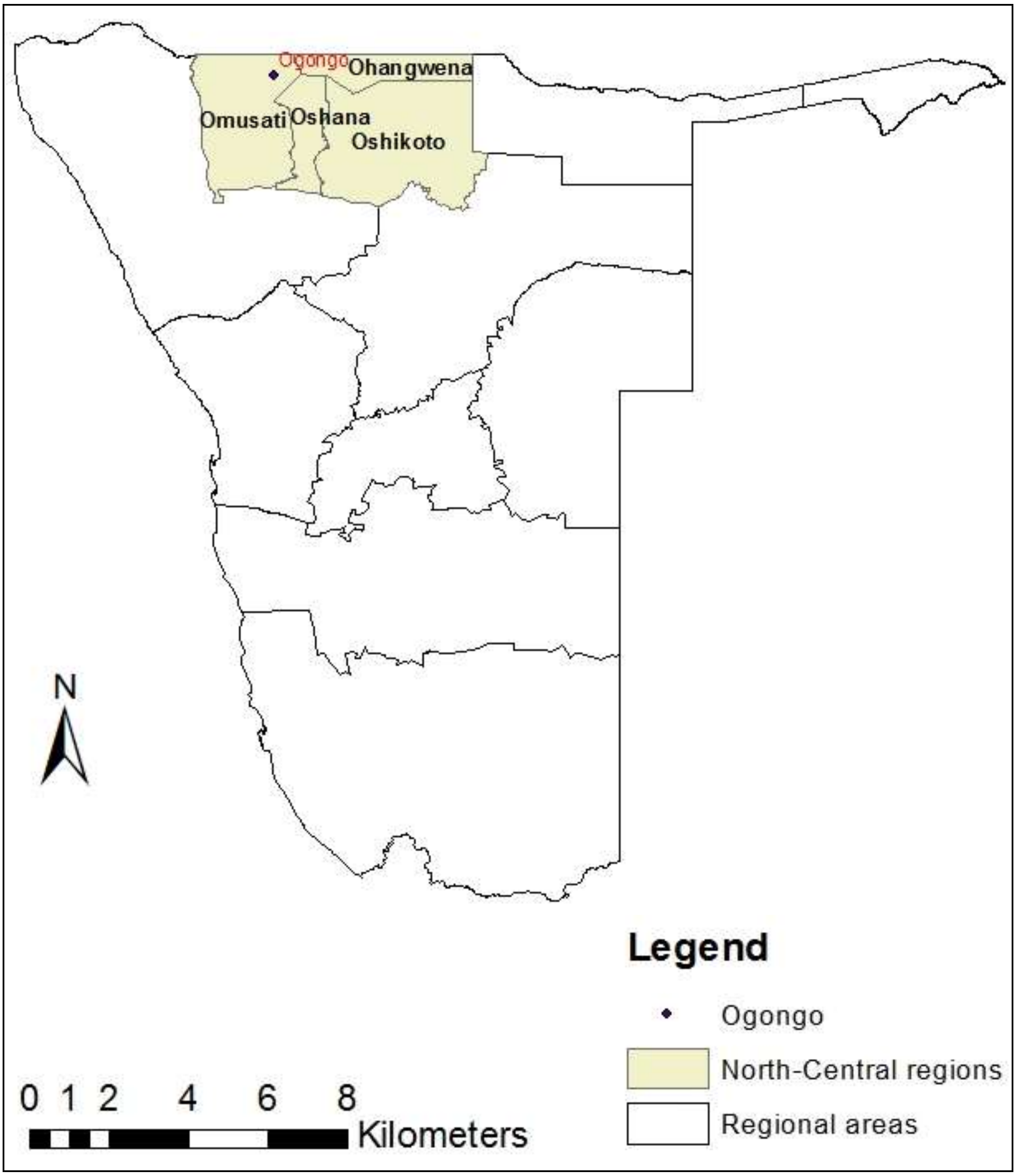

Figure 1-1. Study site—Ogongo Campus of University of Namibia, North-Central Namibia.

CHAPTER 2

FIELD EVALUATION OF MIXED-SEEDLINGS WITH RICE TO ALLEVIATE FLOOD STRESS FOR SEMI-ARID CEREALS

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; 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 2-1) 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 2-1). 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. 2-1) 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 to efficient O_2 transfer between the tangled roots of the two species. The pre-germinated seeds were sown in soil media in cell trays, i.e., one seed (for a single-species crop) or two seeds (for mixed species crops) were sown per cell (Fig. 2-1). For the mixed species crops, seeds of pearl millet and sorghum were relay-planted into cell compartments, containing 1-week-old rice seedlings. Therefore, the mixed-seedlings used in this experiment can be regarded as one of the mixed cropping techniques in the broadest sense. The seedlings of the two different species were in direct contact (Fig. 2-1), a precondition of close mixed planting. Hence, in this text, we define 'the mixed-seedling' as 'mixed cropping'.

The pre-germinated seeds were sown in Hygromix growing medium (90% v/v peat moss, 314 mg NO_3 L^{-1}, 174 mg PO_4 L^{-1} and 45 mg K L^{-1}; Hygrotech Pty, South Africa). The seedlings were cultivated in 137 L of solution culture, circulating in trays, with each overlying a hydroponic reservoir (1.43 × 0.60 × 0.30 m, $L \times W \times H$), in a greenhouse with natural lighting of approximately 12 h daily and with 56% solar radiation transmittance. A week after sowing the pearl millet and sorghum seeds, the cell trays were cut into individual cell compartments and placed in disposal dishes for the roots to entangle and form root mats (Iijima et al., 2016); thereafter, the seedlings were grown for 2 weeks before being transplanted to field plots. The culture medium was supplemented twice a week with Nitrospray Plus nutrient solution (Hygrotech Pty, South Africa), supplying 80.3 mg N L^{-1}, 32.8 mg P L^{-1}, 11.0 mg K L^{-1} and other mineral nutrients. The culture was renewed weekly and the pH was adjusted to 7.4, because the irrigation water was generally alkaline.

2.4. Field preparation

The fields were ploughed 15–20 cm deep using a tractor-drawn rotary tiller. Following general local recommendations, a basal fertilizer, at the rate of 30 kg N ha^{-1}, 45 kg P_2O_5 ha^{-1} and 30 kg K_2O ha^{-1}, was incorporated into the 15-cm soil layer by puddling with a light rotary tiller. After land preparations, the plots for the flood treatments were submerged and seedlings were transplanted into the plots. No top dressing was applied during the flood treatment.

2.5. Cropping system and experimental design

Five cropping systems namely, single-stand pearl millet, single-stand sorghum, single-stand rice, pearl millet mix-planted with rice and sorghum mix-planted with rice were tested in five different experiments to evaluate the mixed cropping concept (Table 2-1). Four of the experiments were conducted in 2014/2015 to test the survival and production analysis in a randomized complete block design with three replications. In the last experiment performed in 2015/2016 for grain production and analysis of land equivalent ratios, the cropping systems were tested under two flood treatments: non-flooded control (drained soil) and flood treatments, which were arranged in a split-plot design with eight replications, with the flood treatments being the main plots and cropping systems being the sub plots. In all the experiments, 3-week-old pearl millet and sorghum and 4-week-old rice seedlings were transplanted into field plots, at a soil depth of 5 cm with a constant spacing of 0.3 m × 0.3 m. In total, 10 and 18 hills per treatment were grown in the 2014/2015 and 2015/2016 experiments, respectively. Mixed cropping treatments had constant plant densities; the plant hills consisted of two plants, i.e. one pearl millet and one rice, and/or one sorghum and one rice but the control treatment had one plant per hill as sown in cell trays. The field size for each of the 2014/2015 experiments was 9 m × 7 m, while that for the 2015/2016 experiment was 32 m × 18 m. NERICA4 was transplanted as a border plant in each experiment. Moreover, before field transplanting compacted earth bands (0.5 m high × 1.0 m wide) were constructed around each experimental plot, and between main plot treatments in the last experiment to separate non-flooded control plots from the flooded treatment plots.

2.6. Flood treatments, irrigation management, and yield evaluation

Soil flooding was achieved by applying an amount of about 20−30 mm of irrigation water every one or two days during the flood treatments. In the 2014/2015a experiment, the seedlings were exposed to flood stress for 22 days at a mean water level of 9 cm above the soil surface; while in the other experiments, the seedlings were subjected to flood stress for 11 or 15 days at a mean water level of 5–7 cm. The mean pH value of water in the individual experiments was approximately 7.5; the mean values of soil redox potential (Eh) were −74 mV {7 days after flooding (DAF)}, −183 mV (14 DAF) and −153 mV (9 DAF) for the 2014/2015a, b and d experiments, respectively. In the 2015/2016 experiment, Eh value in waterlogged soil gradually decreased from approximately 338 mV at the beginning of the waterlogged treatment to approximately −64 mV at 14th day of the treatment (Fig. 2-2). The water pH and Eh were monitored one to three times in the 2014/2015 experiments, and six times in the 2015/2016 experiment, during the flood treatments using a pH (Twin pH, B-211, Horiba, Japan) and Eh metre (PRN-41, Fujiwara Co Ltd., Japan). Measurements for Eh were taken from 7.5 cm soil depth at the midpoint of the inter- and intra-row spacing, approximately 20 cm away from the adjacent plants.

Following the termination of the flood treatment until crop physiological maturity, plots in the production experiments were given supplemental irrigation during dry spells (Fig. 2-3). The 2014/2015a experiment was given supplemental irrigation by applying approximately 8 mm at 2−3 day intervals during the dry spells. In the 2014/2015b and 2015/2016 experiments, the amount of irrigation water was reduced due to poor dryland crop growth observed in the first experiment; therefore, each experiment received approximately 5 mm of water at 3−4 day intervals during the dry spells. In each experiment, top-dressing was done by band placement during the grain setting stage of pearl millet, about 55−60 days after sowing of pearl millet, at the rate of 3.9 g N m^{-2}, 5.9 g P_2O_5 m^{-2} and 3.9 g K_2O m^{-2}. No pesticide was applied during crop growth but insects and weeds were controlled manually. After field draining in the 2014/2015a experiment, soil water potential and volumetric soil water content were measured one day before each irrigation, using a tensiometer (DIK-3162, Rika Kogyo Co., Ltd., Japan) and neutron probe Delta-T PR1 (Delta-T Devices Ltd., Cambridge, UK), respectively. The tensiometer and neutron probe access tube were installed at the midpoint of the inter- and intra-row spacing. Soil water potential measured at 30 cm depth ranged from –14 to –45 kPa. Changes in volumetric soil water content within the 40 cm soil depth are shown in Fig. 2-4.

Plants were grown until maturity. Pearl millet was harvested between 90 and 100 days after sowing, while sorghum and rice were harvested between 115 and 132 days. Panicles were air-dried and threshed, and then the clean grains were weighed and the grain moisture content was measured by Grain Moisture Tester (PM-830-2, Kett, Japan). The grain weights were adjusted to 14% moisture content to obtain total yield per plot.

2.7. Evaluation of plant survival rates

In the four 2014/2015 experiments, the topmost youngest, fully expanded leaf, was used to determine the survival rates of pearl millet and sorghum during the flood treatments, because in most cases, the selected leaf was the last to turn brownish. In each plot all individual plants were assessed during the flood treatment to determine the extent to which the leaf tissue colour had changed, i.e. from green to brown, relative to total leaf area. The leaf was assigned a percentage score such that 0% represents a healthy green leaf denoting a fully live plant, 50% indicates half brown-half green leaf thus a plant withstanding stress, and 80–100% denotes nearly whole brown leaf area without chlorophylls hence considered as dead. In fact, plants did not recover after this condition (80–100% score).

2.8. Mixed crop productivity assessment

Using the grain yields from the 2015/2016 experiment, mixed cropping productivity was evaluated by the land equivalent ratio (LER), which compares yields / ha of monocrop- vs. mixed-species yields. The LERs for mixtures of pearl millet or sorghum (dryland cereal [d] and rice [r]) were determined following the method described by Mead and Willey (1980):

$$LER = LER_d + LER_r = (Y_{dm}/Y_{ds}) + (Y_{rm}/Y_{rs})$$

where, LER_d and LER_r represent partial LER of 'd' and 'r' crops, respectively, Y_{dm} and Y_{rm} represent the yields of 'd' and 'r' as mixed crops, respectively and Y_{ds} and Y_{rs} are the respective yields of 'd' and 'r' as single crops. An LER value of > 1 indicates a yield advantage, LER value = 1 indicates no advantage and LER value of < 1 indicates a disadvantage for mixed cropping.

2.9. Statistical analysis

Data were subjected to analysis of variance (ANOVA) using IBM SPSS Statistics, Version 21. For all the 2014/2015 experiments, an arcsine transformation was performed on survival rate percentage data, and single and mixed crop treatment mean values at each observation time were compared by independent samples *t*-test. Moreover, a two-way ANOVA was performed for grain yield data of the 2015/2016 experiment.

3. Results

3.1. Survival rates of mix-cropped pearl millet and sorghum

The survival rates of flood-stressed pearl millet and sorghum seedlings, grown as single stands and mixed plants with rice, were assessed in the 2014/2015a, b, c and d experiments (Fig. 2-5). The survival rate of pearl millet was generally unaffected by flood stress for nearly 5 days after flooding (DAF), irrespective of the cropping treatments; however, after this period the survival rate tended to decline rapidly though it remained relatively higher in the mixed plants than in the single-stand plants (Figs. 5a–d). At 13 DAF, the survival rates in the single-stand treatments were 40%, 3% and 20% (Fig. 2-5 Pearl millet a, b, c, respectively) compared with 57%, 23% and 33% in the corresponding mixed plant treatments. However, in all of these experiments, the survival rate generally dropped fast, and in the 2014/2015a experiment (Fig. 2-5a), all the plants were killed at 18 DAF. Moreover, the plants in the 2014/2015d experiment (Fig. 2-5d) remained alive for only about 11 days after flooding, whereas the plants in the other experiments (Fig. 2-5b and c) were still alive by the 15th day after flooding. With regards to sorghum, plant survival rate patterns were almost similar to pearl millet; in most cases, the survival rate was much higher in the mixed than in the single-stand plants. At 13 DAF, the survival rate of the sorghum mixed plants was 87%, 56% and 63% (Fig. 2-5 Sorghum a, c, d, respectively) as compared with 60%, 40% and 13% of their single-stand counterparts.

These results indicated that the impact of flood stress was much higher in pearl millet than in sorghum.

3.2. Grain production of mixed crops

Table 2 demonstrates the grain yields of pearl millet, sorghum and rice, as influenced by cropping systems and flood conditions. In the 2014/2015a experiment, in which the plants were exposed to 3 weeks flood stress, no yield was obtained from pearl millet because all of the plants were killed by flood stress. However, for sorghum, the mixed plants produced a yield of 29.9 g m^{-2}, whereas no yield was obtained from the single-stand plants due to poor filling. In the 2014/2015b experiment with two weeks of flood stress, pearl millet and sorghum in the mixed plant treatments produced 26% and 18% greater yields, respectively, than in the corresponding single-stand treatments. However, the yields of pearl millet were affected by flooding much more than that of sorghum, irrespective of the cropping treatments. In the 2015/16 experiment, the amount of irrigation water was reduced, and rainfall before heading was quite low (Fig. 2-3), which eventually caused partial grain-filling in the rice. In this experiment, the effects of flooding were significant ($P < 0.01$) on the grain yields of pearl millet, sorghum and rice. Cropping systems did not have a significant ($P > 0.05$) influence on grain production in all the crops. However, the interaction between the flood treatments and cropping systems was significant ($P < 0.05$) on the sorghum grain yields. Overall, flooding decreased the dryland cereal yields, but increased the rice yields. In the pearl millet, under flood conditions, the grain yield in the mixed plant treatment was 86% higher than that obtained from the single-stand treatment. In sorghum, under the non-flooded upland (control) condition, grain yield in the mixed plant treatment was 45% lower than that in the single-stand treatment; conversely, under flood conditions, the grain yield in the mixed plant treatment was 40% higher than that in the single-stand treatment.

3.3. Productivity of mixed crops

Table 2-3 demonstrates the productivity indices for pearl millet–rice and sorghum–rice mixtures, based on the grain yields from the 2015/2016 experiment. The value of the total LER for the pearl millet–rice system in the flood treatment was 2.55, which was two times higher than that in the non-flooded upland. This value exceeded the minimum value of 1, indicating a mixed cropping yield advantage over single-stand planting in the flood treatment. For the sorghum-rice system, the total LER in the flood treatment was also greater than the minimum value, being 2.14 and again displaying a mixed cropping advantage over single-stand planting for sorghum.

4. Discussion

4.1. Crop performance

The results of the present study demonstrated that the survival rates of pearl millet and sorghum plants mix-planted with rice, under the different flood treatments, were generally higher than that of their corresponding single-stand plants (Fig. 2-5a–d). The abrupt fall of all values at about 5 days after the imposition of flood stress indicates the time when the stress symptoms on plants became visible, which was the time when some of the plants were killed by flood stress. Soil flooding reduces tillering, plant height and dry matter in pearl millet (Sharma and Swarup, 1989; Zegada-Lizarazu and Iijima, 2005). Thus, the higher survival rate of the mix-planted pearl millet may be due to a slight root-zone anoxic condition, created by radial O_2 loss from rice roots into the aqueous rhizosphere. In our previous study, O_2 concentration of the mixed-seedlings was higher than that of single stand pearl millet under water culture experiment (Fig. 2-3 of Iijima et al. 2016). The O_2 released from the rice root system can ameliorate the adverse effects of low O_2 stress and reduce phytotoxins in the root zone; moreover, it can also facilitate plant nutrient uptake under submerged soil conditions (Armstrong, 1979; Colmer, 2003; Kirk and Kronzucker, 2005). The mixed cropping technique used in the present study was designed to enhance rice and pearl millet root entanglement or rhizosphere interaction, so that the roots of pearl millet would be exposed to the O_2 being lost radially from the rice roots. Hence, the oxygenated rhizosphere environment possibly caused improved root respiration of the mix-planted pearl millet during flooding, thus allowing the pearl millet plants to sustain growth. The results of this study are consistent with the findings of our previous laboratory study (Iijima et al., 2016). Also, the survived pearl millet tended to form aerial roots from the shoot base, which may help enhance plant survival under the submerged soil environment as these roots can supply O_2 to root tips to sustain water and nutrient absorption.

In the 2014/2015a experiment, all pearl millet and most sorghum plants in the single-stand treatment were killed by the 3-week flood stress (Fig. 2-5a), which may be attributed to the higher flood water level and/or longer duration of flooding than the other experiments. Moreover, environmental and/or meteorological conditions seemed to have affected the survival rates of pearl millet and sorghum. For example, plants in the 2014/2015c experiment, which were associated with a moist environment under higher mean relative humidity (Table 2-1), had better survival rates than plants in the 2014/2015a experiment (Fig. 2-5), which were exposed to hot and dry environments due to higher temperatures and lower relative humidity. Although sorghum tends to adapt to short-term flood conditions by forming root aerenchyma (Promkhambut et al., 2011), in this experiment (2014/2015a), grain yield was only realized from the mixed crop treatment (2014/2015a experiment), indicating that the mixed cropping technique was effective. The reduction in the yields of the mix-planted rice across the experiments (2014/2015a, b and 2015/2016) and the increase in the corresponding pearl millet yields (Table 2-2) seem to reflect the flood stress intensity, as well as rainfall distribution and supplemental irrigation in the respective experiments. High-rainfall flood events of variable duration have recently been experienced in semi-arid regions, such as Namibia (Mendelsohn et al., 2013; Mizuochi et al., 2014), causing yield losses of pearl millet and sorghum (Anthonj et al., 2015). Therefore, the new mixed cropping system of dryland cereals and rice appears to have the potential to prevent complete dryland-cereal grain losses under short-term field flood conditions (Table 2-2). Moreover, because rice is adapted to the flood conditions, in this cropping system, it is evident that rice would produce some grains when extended or when severe flood occurred and hence can compensate for the dryland-cereal yield losses (Table 2-2), ultimately, contributing to grain security in such regions.

Productivity analyses demonstrated high total LER values for the pearl millet–rice mixtures relative to single-stand cropping under short-term flood stress conditions (Table 2-3). The higher LER values indicate that mixed cropping created a yield advantage, which can be ascribed to the flood stress mitigation effects of rice on the dryland cereals. Co-growing plants can improve the microclimate of their neighbours through rhizosphere interaction (Brooker, 2006; Brooker et al., 2015). However, although there is a high land productivity due to mixed cropping effect, it may be important that such an advantage is considered in relation to the absolute yield, to determine whether the LER values represent appreciable grain quantities. For instance, Table 2-2 demonstrates that the yields of the mix-planted pearl millet subjected to flooding were higher than those of their single-stand counterparts, leading to the high total LER values (Table 2-3). However, when the absolute yield under the flood and non-flooded upland conditions were compared (Table 2-2), the yields under the flood condition were much smaller, indicating that mix-cropping did not substantially increase pearl millet and sorghum grain yields, despite the high LER values. Although no nutrient deficiency symptoms were observed during plant growth, interspecific competition during post-flooding growth may have masked the yield advantage of this cropping technique. Flood stress mitigation by this new cropping technique may be enhanced through judicious agronomic practices, including nutrient management, and through the selection of compatible cultivars that would reduce competition and enhance their complementarity.

4.2. Agronomical implications

Currently, the simultaneous occurrence of both floods and droughts in the same place has become common worldwide. Under such weather conditions, crop cultivation techniques that may accommodate both extremes of water abundance are required to stabilize cereal production. During the process of developing a mixed cropping system of flood-tolerant rice and drought-tolerant grain crops (Iijima, 2011), we found a new possibility in mixed cropping, by enhancement of the flood tolerance of upland crops. The new cultivation model to mitigate flood stress in semi-arid regions could be established by using mixed-seedlings that are introduced into the water fluctuation zone of a farm field (Fig. 2-6). Most of the upland food-crop fields, in resource-poor small-scale holder farms, have small ditches where stagnant water remains after heavy rain or short-term flash floods. The utilization of the wet portions of fields for upland farming would help stabilize food production, particularly in areas with significant rainfall fluctuation. During flooding (Fig. 2-6B), the survival rate of upland species could be enhanced by using the mixed-seedlings approach, which may contribute to the stable production of traditional drought-resistant cereals by local small-scale holder farmers in semi-arid regions. Furthermore, they could obtain a rice yield by using the mixed cropping system.

In the semi-arid regions of southern Africa, along the borders of Angola with Namibia, Botswana and Zambia, extensive seasonal wetlands are formed during the rainy season by floodwaters originating from the Angolan highlands (Mendelsohn et al., 2013). A rice introduction effort (Iijima, 2011; Suzuki et al., 2013) is on-going in the seasonal wetlands formed in semi-arid North Central Namibia because the pearl millet fields mostly contain small wetlands where rain-fed, lowland rice can be grown. Flash floods that have become common in this region often adversely affect the harvest of staple food crop, pearl millet. As a result, local farmers often practice mixed cropping of pearl millet and sorghum, which nowadays include mixed sowing within hills (Fig. 2-7), as a way of ensuring crop security since sorghum is relatively waterlogging tolerant than pearl millet. This is one of the benefits for local farmers when they practically adopted the mixed-seedling concept. However, in the near future, climate change would probably cause more frequent and considerably severe flooding in the semi-arid regions. Under such circumstances, the risk of complete crop failure of flood-susceptible cereals may significantly increase. Further research on the proposed mixed cropping technique, involving the use of mixed-seedlings (practical model; Fig. 2-6) could help increase the rice yield in small-scale wetlands and stabilize the yields of traditional drought-resistant staple grains produced by local subsistence farmers. Continuous research and development work are warranted to provide agronomic countermeasures in order to ensure constant staple food production under flood conditions occurring in semi-arid regions because of climate changes.

5. Conclusions

Mixed-seedlings of pearl millet and rice or sorghum and rice mitigated the effects of flooding on pearl millet and sorghum. Mixed-seedlings increased survival rates in pearl millet and sorghum, with the impact being much higher in sorghum. Moreover, although grain yields of both the pearl millet and sorghum were decreased by flood stress, in both the single-stand and mixed plant treatments as compared with the yields of the non-flooded upland fields, the yields were mostly higher in the mixed plants than in the single-stand plants under flood conditions. In contrast, the yields of rice were increased by flooding. Furthermore, under flood conditions, the LER values for both pearl millet–rice and sorghum–rice mixtures were > 1.0, indicating a mixed planting advantage over single-stand planting.

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.). 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 O_2 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 were evaluated on their survival, growth and grain yields, 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 flooding stress at the vegetative growth stage. Mixed planting increased seedling survival rates in both pearl millet and sorghum, but the impact was much higher in 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, thereby complementing the low yields of dryland cereals. Both pearl millet-rice and sorghum-rice mixtures demonstrated higher biological efficiency (land equivalent ratios > 1.0), 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. Further studies are warranted to improve the efficacy of this cropping concept on pearl millet and sorghum yields.

Tables and figures

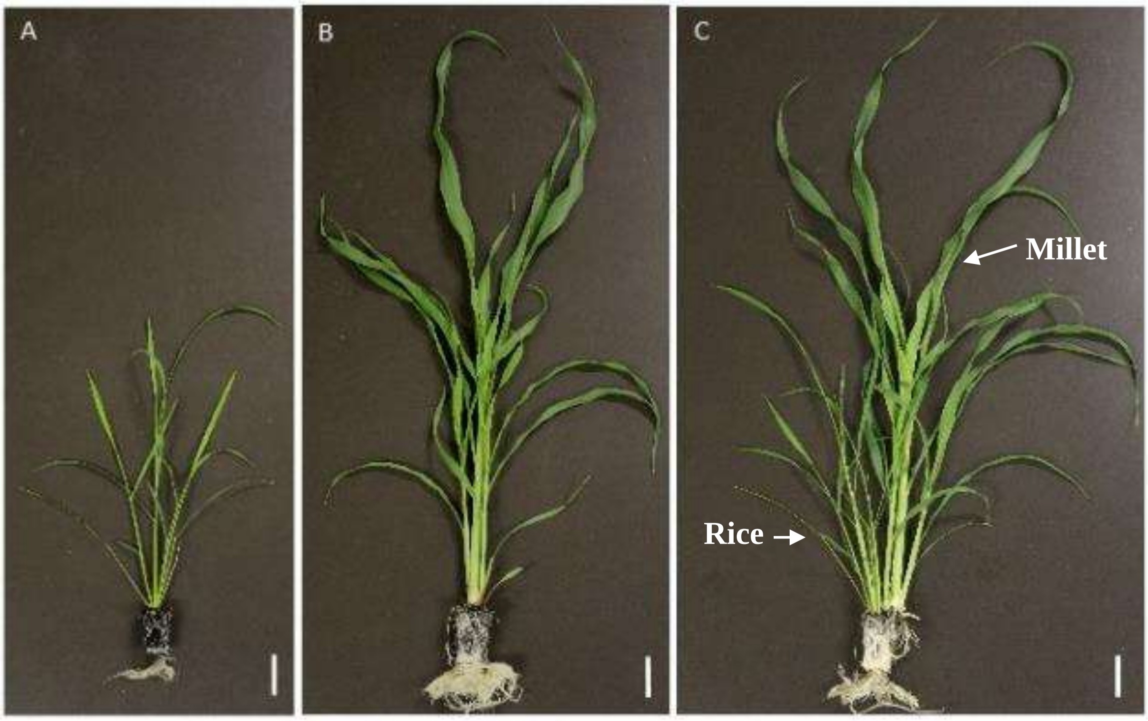

Fig. 2-1. Growth of pearl millet-rice mixed seedling in cell tray. A, single-stand rice; B, single-stand pearl millet; and C, pearl millet mix-planted with rice. Scale bar (lower right in each figure) = 50 mm.

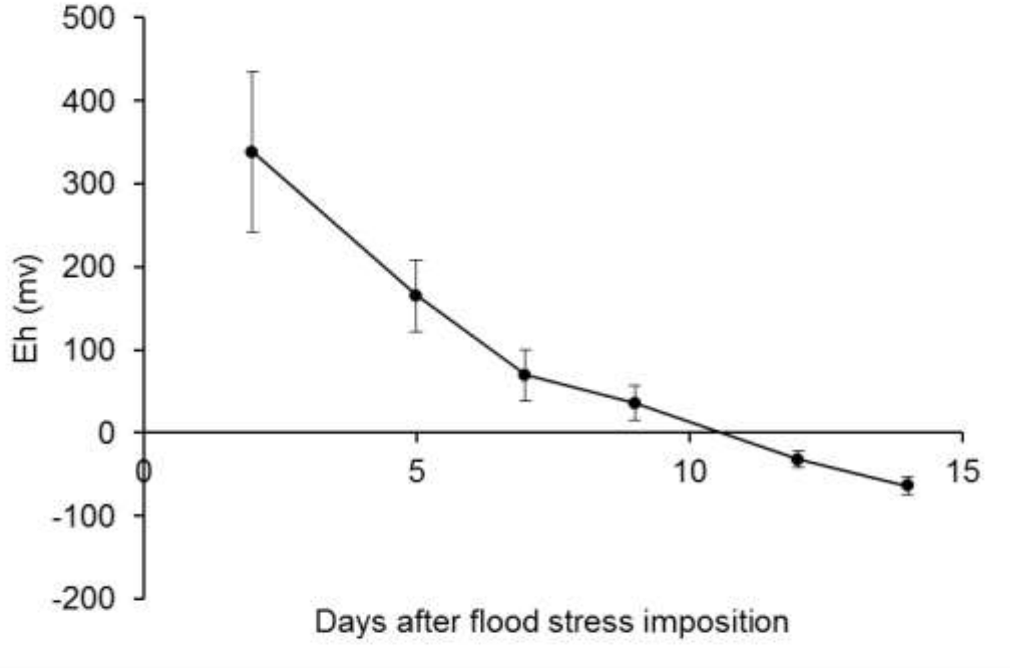

Fig. 2-2. Changes in the soil redox potential during the flood treatment in the 2015/2016 experiment. Vertical bars represent ± standard error of the mean (n = 5).

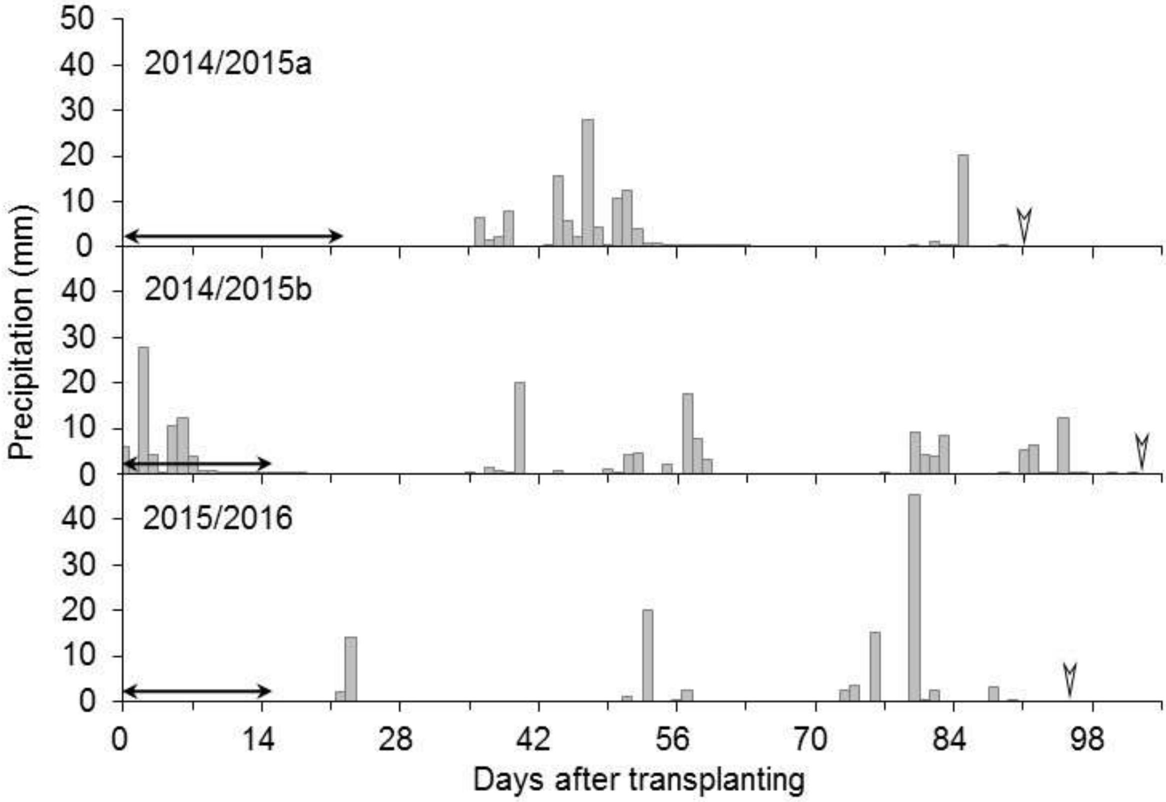

Fig. 2-3. Daily precipitation in the 2014/2015a, 2014/2015b and 2015/2016 experiments. Horizontal arrows, flood treatment period; arrow head, end of the experiment. Irrigation was done during the dry spell periods.

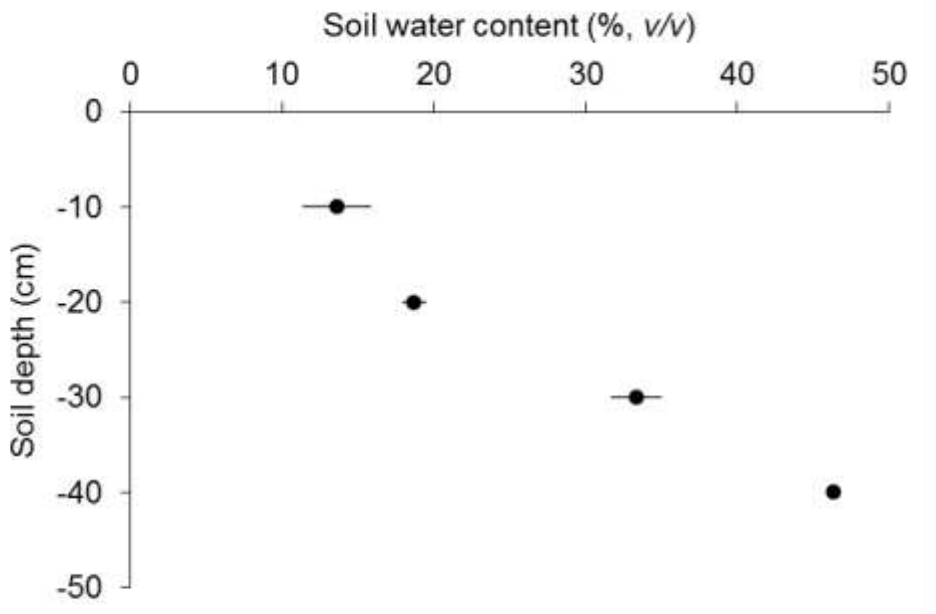

Fig. 2-4. Volumetric soil water content within the top 40 cm soil depth in the 2014/2015a experiment. Horizontal bars represent ± standard error of the mean (n = 7, 7, 5 and 2 at 10, 20, 30 and 40 cm depth, respectively). Measurements were taken one day before each irrigation application.

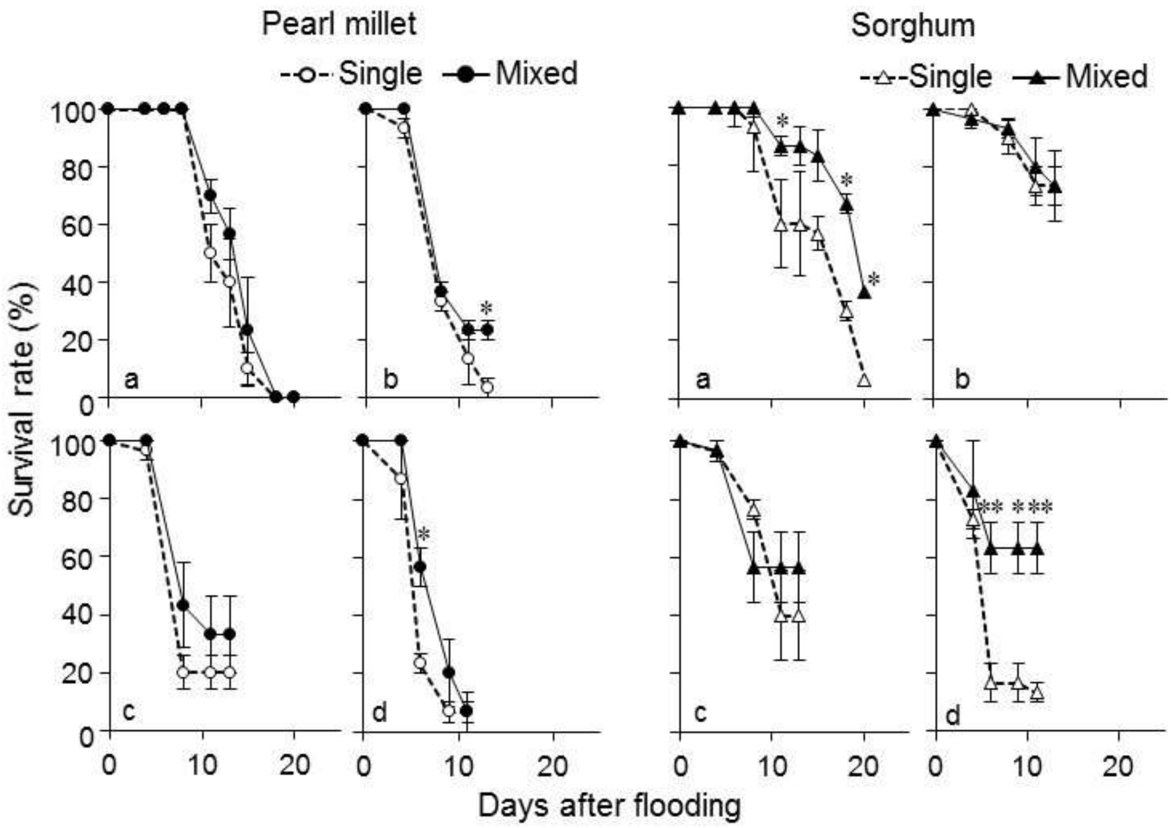

Fig. 2-5. Survival rates of pearl millet and sorghum mix-cropped with rice (cv. NERICA4) under flood stress conditions at the vegetative growth stage in the 2014/2015 experiments. Plants were subjected to flood stress from the day of transplanting (0 day). Vertical bars represent ± standard error of the mean (n = 3). a–d, 2014/2015a–d experiment (Table 2-1) respectively. **, and *, significant difference at $P < 0.01$ and $P < 0.05$, respectively.

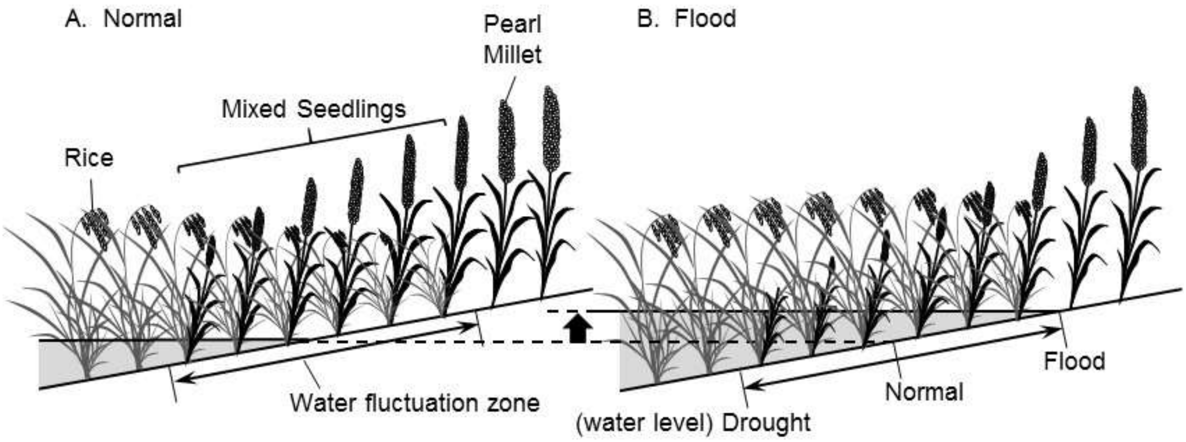

Fig. 2-6. Possible use of the pearl millet (or sorghum) and rice mixed-seedling system in flood-affected, rain-fed fields of smallholder farmers in semi-arid regions. This mixed cropping model could provide countermeasures to secure grain production under extreme weather conditions.

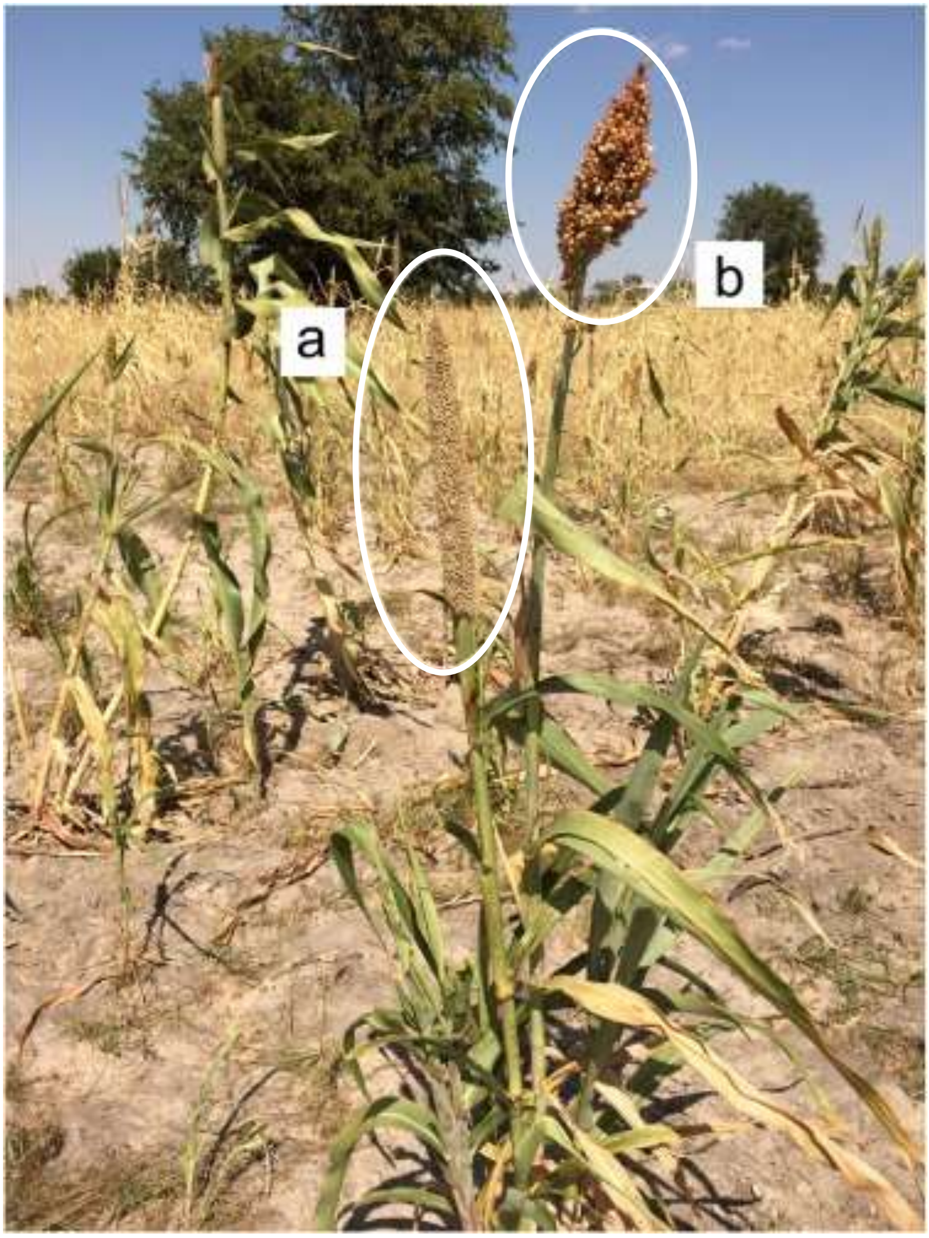

Fig. 2-7. Mixed plants of pearl millet (a) and sorghum (b) in a farmer's field in Onamundindi village, North-Central Namibia, 2015/2016 cropping season.

Table 2-1. Weather conditions during field experiments in 2014–2016

Experimental period				Temperature (ºC)			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.

Table 2-2. Grain yields of pearl millet and sorghum, mix-cropped with rice (NERICA4) under flood stress conditions at the vegetative growth stage

Experimental year	Flooding duration (days)	Treatment		Grain yield ($g\ m^{-2}$) Pearl millet Single	Pearl millet Mix	Sorghum Single	Sorghum Mix	Rice Single	Rice Mix (Pearl millet)	Rice Mix (Sorghum)
2014/2015a	22	Flooding		0	0	0	29.9	N/A	233.3	113.4
2014/2015b	15	Flooding		78.9	99.2	304.6	360.6	N/A	122	82.6
2015/2016	15	Upland		661.7	578.4	431.6	237.2	17.9	5.5	3.2
		Flooding		101.2	188.6	129.4	181.7	79.9	54.8	58.4
		Two-way ANOVA	Treatment	**		**		**		
			Cropping	n.s.		n.s.		n.s.		
			Interaction	n.s.		*		n.s.		

N/A, Rice-single not planted. ** and *, indicate significant difference at $P < 0.01$ and $P < 0.05$, respectively. n.s., not significant.

Table 2-3. Land equivalent ratio (LER) for mixtures of pearl millet, sorghum and rice in the 2015/2016 experiment

	Pearl millet			Sorghum		
	Partial LER		Total	Partial LER		Total
Treatment	Pearl millet	Rice	LER	Sorghum	Rice	LER
Upland	0.87	0.31	1.18	0.55	0.18	0.73
Flooding	1.86	0.69	2.55	1.4	0.73	2.14

CHAPTER 3

GENERAL DISCUSSION

1. Rice introduction process to the seasonal wetlands in North-Central Namibia

The objective of this study was to prove whether mix-planting dryland cereals of pearl millet (*Pennisetum glaucum* L.) or sorghum (*Sorghum bicolor* L.) with rice (*Oryza* spp.) would improve their performance under field flood conditions. In recent years, extreme weather conditions of flood and drought tend to occur frequently in same areas due to the effects of global climate change. These alternating episodes of contrasting weather phenomena are a typical characteristic of semi-arid, North-Central Namibia. Despite being generally a dry area, the north-central area receives floodwaters from Angolan highlands, where rainfall is higher, and this results in the formation of seasonal wetlands, *oshanas* in the region (Lindeque and Archibald, 1991; Mendelsohn et al., 2000; Iijima et al., 2013). Currently, the water resource of the seasonal wetlands is not utilized for cropping but mainly used for grazing and fishing (Mendelsohn et al., 2000). The 1st phase of rice (*Oryza* spp.) introduction to the seasonal wetlands, initiated in the early 2000s, focused on basic research and promotional activities that have been sustained ever since (Kanyomeka et al., 2008; Awala et al., 2009, 2010; Iijima et al., 2013; Suzuki et al., 2013, 2014).

It was initially thought that rice introduction harmonized with the cropping of local pearl millet, the staple food for North-Central Namibia, would not be difficult because of the presence of the *oshanas*' floodwaters during the cropping season. However, the quantity and existence of the floodwaters in most of the seasonal wetlands fluctuate significantly (Iijima et al., 2013; Mendelsohn et al., 2013; Hiyama et al., 2014; Mizuochi et al., 2014). Severe floods occurred during the 2008, 2009, and 2011 cropping season, and the water level used to rise by 10 cm/day and finally reached around 1 m high above the soil surface in an experimental rice field set up in a seasonal wetland inside the University of Namibia Ogongo Campus located situated in the central zone of the seasonal wetlands' network. The floodwaters were retained nearly for one month. Rice in the experimental field, in 2009, was completely killed by this flooding. In 2010, flood came late during the season. By contrary, in 2013 all local wetlands did not receive any floodwaters. This year was characterized by extreme drought, occurring for the first time in the last 30 years. The area was once again stricken by successive, severe droughts in 2015 and 2016.

Because of the fluctuation in the abundance and arrival of floodwaters in the *oshanas*, rice production in these ecosystems was highly unstable; as a result, rice production in the *oshanas* was finally not recommended. Therefore, during the 2nd phase of the rice introduction program, which ran from 2012–2017, the target area for rice introduction in North-Central Namibia was another type of seasonal wetland, *ondombe*, which is smaller and deeper than an *oshana* and widely found in most farm fields (Iijima et al., 2013). However, there was still a need to consider yearly or seasonal water fluctuations. The 2nd phase was funded by the Japan International Cooperation Agency (JICA) and Japan Science and Technology (JST) as one of the research programs of the "Science and Technology Research Partnership for Sustainable Development (SATREPS)".

2. Mixed cropping in the water fluctuation zone

During flood years, floodwaters in the *oondombe* can extend up to the middle of the dry land zone of a farm field where pearl millet is cultivated. Pearl millet is known as the drought resistant major cereal species in semi-arid regions, but it is intolerant of waterlogged condition (Sharma and Swarup, 1989; Zegada-Lizarazu and Iijima, 2005; Zegada-Lizarazu et al., 2007). The crop is usually killed by prolonged waterlogged soil condition caused by flooding. In contrast, during drought years, water may remain only at the deepest zone of the *oondombe*, and the pearl millet growing near these areas would survive the drought. Cultivation techniques adapted to both flood and drought environments may have to incorporate the mixed cropping of flood resistant rice and drought resistant pearl millet (Iijima et al., 2013). If the farmers can cultivate the wetland portion of their fields, rice cropping can easily be introduced to this area. Mixed cropping can then be introduced to the water fluctuation zone of the field. Mixed cropping of pearl millet-rice and sorghum-rice, as a way of mitigating the risk of production failure caused by drought and flood, was the major focus of the 2nd phase of rice introduction to the seasonal wetlands, and also the central theme of this study.

Solution culture studies (Iijima et al., 2016) indicated that rice can enhance flood stress tolerance of co-growing pearl millet and sorghum by modifying their rhizosphere microenvironments via the O_2 released from the rice roots. The results of the present study demonstrated that such phenomenon is expressed under field conditions (Chapter 2). Mix-planting pearl millet or sorghum with rice mitigated the effects of flooding on pearl millet and sorghum. The survival rates of pearl millet and sorghum seedlings were increased by close mixed planting, and the impact was much higher in sorghum than pearl millet. Concerning grain production, even though grain yields were generally decreased by flooding, the mix-cropped dryland cereals produced better yields than their single stande counter parts. Additionally, the yields of the rice crop component were increased by flooding, thereby complementing the low yields of pearl millet and sorghum under flood conditions. Mix-planting pearl millet or sorghum with rice also displayed higher biological efficiency in terms of land equivalent ratios, being > 1.0, indicating a mixed planting advantage under flood conditions. Overall, the new mixed cropping technique indicated the potential to enhance pearl millet and sorghum yields under short-term field flood conditions. Moreover, in cases of extended or severe flood, the rice yield could compensate for the dryland-cereal yield losses, thus serving as a buffer for grain security in flood years.

Currently, the alternate occurrence of floods and droughts in the same place has become common worldwide. Flash floods, erratically striking semi-arid regions adversely affect production of the food staples, pearl millet and sorghum. In the near future, climate change would probably cause more frequent and severe floods to these regions. Under such circumstances, the risk of complete failure of the drought-tolerant, dryland cereals may significantly increase. The new cropping system might be considered as an alternative to the conventional sole-cropping of dryland crops or simply mix-cropping of dryland crops in flood-prone semi-arid regions such as North-Central Namibia (Mendelsohn et al., 2009; Iijima et al., 2013; Mendelsohn et al., 2013; Mizuochi et al., 2014; Suzuki et al., 2014), where flood can cause significant crop losses (Anthonj et al., 2015). The utilization of the wet portion of a farm fields for upland crop farming would help stabilize food production, particularly in areas with significant rainfall fluctuation. The new cropping system has therefore been proposed for field zones that are prone to flooding, such as the water fluctuation zone of an *ondombe* (Iijima et al., 2013).

Continuous research and development work are warranted to provide agronomic countermeasures in order to ensure constant staple food production in flood-affected fields in semi-arid regions. However, the proposed cropping system may need to be considered in relation to specific cultivation methods that would enhance the mitigation effect of rice on the dryland cereals. These methods include, amongst others, ridge/furrow mixed cropping and sequential planting after rainfall early cessation during drought years as well as cultivar selection and fertilizer application.

3. Ridge/furrow mixed cropping

It is worth considering how the two crop species, the wetland and dryland species, can be mixed in the water fluctuation zone. There might be a need to adopt cultivation techniques resulting in differential soil moisture conditions to create field microenvironments conducive for each of the species. The concept of small-scale water harvesting by ridge/furrow tillage system could therefore be applied. Pearl millet is adapted to the drier region of the field thus should grow well on high ridges, which can quickly become dry after the recession of floodwaters. In contrast, rice is adapted to the wetter portion of the field, thus should grow well in furrows, which can harvest water from the ridges when water is limited. The Namibia-Japan Rice and Mahangu Project has introduced a drive-type disc plough that can easily make relatively higher ridges. By using this implement, the height difference between the ridge and furrow varies from 40–50 cm. This difference would offer wet and dry soil microenvironments favorable for rice and pearl millet, respectively, as proposed by our new mixed cropping concept (Iijima et al., 2013).

4. Sequential planting after rainfall early cessation during drought years

Severe droughts struck North-Central Namibia during the cropping seasons of 2012/2013 (Iijima et al., 2013; Mendelsohn et al., 2013) and 2014/2015. Floodwaters did not arrive to the seasonal rivers around the Ogongo Campus. The 2012/2013 drought was the most severe drought event experienced in the last 30 years as far as local farmers could remember. Water was available only at the lowest portion of some *oondombe* and used for livestock (cattle) drinking. In such a severe drought year, rice cropping seemed to be impossible because rice requires more water than pearl millet. In some farms, even pearl millet was completely killed by the drought, but the cowpea plants that were mix-planted with pearl millet survived. However, even in such a severe drought year, *oondombe* could be used for rice cropping since they can retain water for sometimes after the cessation of the rainy season.

Ground water level in this region may be quite shallow due to the continuous water supply by the seasonal wetlands of the Cunene Basin. Some farmers in this area had cultivated rice and the crop matured quite well. In one of the mixed cropping demonstration farms in Oshiteyatemo, a village near Okalongo town about 10 km south of the Angolan border, water existed even during the early March of 2013, the severe drought year. The water level of this wetland usually goes up to nearly 1 m during normal rainy seasons, according to the farm owner. Because of this high water level, the farmer thought that the place cannot be used for crop production. Deep water rice varieties which are adapted to high water level of 0.5–1 m can be introduced to such deep water ponds (*oondombe*) in the near future. The water level at the deepest point of this wetland ranged from 0.1–0.3 m as a result of the delayed rainfall during the severe drought year, suggesting that even during severe drought years, rice can still be grown using *oondombe*. We had tested whether transplanting rice seedlings in early March, which was more than a month later than the planting season in a normal rainfall year and hence considered as sequential planting. The rice crop finally matured well and grain yield was obtained from this wetland. Therefore, late transplanting in *oondombe* may be considered as one of the drought-adaptive cultivation techniques in near future.

5. Other potential cropping techniques and basic research trials

The water environment of a typical farm-crop field, wet-to-dry conditions up the slope, was modelled to simulate plant growth in the experimental sloped field in Ogongo

Campus (Iijima et al., 2013; Awala et al., 2013). The height difference was approximately 2 m between the lowest and the highest ends of the field, and the field was 160 m long from the wet to the dry region. A quarter of the area at the lower end of the field represented the wetland zone, which was used as a rice paddy where rice was grown under water stagnant conditions. Another quarter at the upper end of the field represented the upland zone, which was used for the conventional mixed cropping system of pearl millet and cowpea (McDonagh and Hillyer, 2003; Zegada-Lizarazu et al., 2005, 2006, 2007). The middle area, half of the field was the water fluctuation zone in which rice, pearl millet, sorghum, and cowpea were grown.

In order to introduce a viable rice and pearl millet mixed cropping system, various research studies, such as cultivar selection, fertilization techniques, planting methods, and many others, are necessary. During the project's 2nd phase, under which the present study was conducted, 38 individual paddy fields (48-50 m long × 25 m wide each) were established at the Ogongo Campus and used for various crop research and production activities. These fields included 12 experimental fields, 13 seed multiplication fields, and 13 production fields. Rice harvested from the production fields was milled and sold in the local market to create awareness about the rice introduction program. About 130 cultivars were tested in 2006 through the 1st phase of the rice introduction program (Awala et al., 2009). These cultivars have been continuously being tested to acquire basic information on their growth and potential yields under the semi-arid conditions of North-Central Namibia. Most of the cultivars were from West Africa, Philippines and Japan. Not only Asian rice (*Oryza sativa*) was tested, but African rice (*O. glaberrima*) and New Rice for Africa (interspecies of *O. sativa* and *O. glaberrima*, called NERICA; *Oryza* spp.) were also grown, insuring a high genetic diversity necessary for the selection of cultivars that would withstand both abiotic and biotic stresses in southern Africa. NERICA 1, NERICA 4 and NERICA 7 were the candidate cultivars to be introduced to the seasonal wetlands according to the experimental results obtained by the 2013/2014 wet season.

In the experimental paddy fields, fertilization dosages were tested to propose a sustainable cropping scheme that fully utilizes domestic organic manures from animal waste for both rice and pearl millet fields. Planting methods of direct seedling and transplanting were also tested. Broadcasting is a suitable seeding technique for saving labor but this method is associated with low yield potential. Line and random planting methods have also been tested to compare yield difference between the two practices. Weeding cost should also be considered to make future recommendations. Together with these basic research trials, selection of flood-tolerant lines of pearl millet, and pearl millet-rice mixed seedlings were tested as the initial attempt to determine whether rice can improve the performance of pearl millet under waterlogging conditions. Pearl millet has high variability for growth durations; therefore, pearl millet genotypes' flood resistance should vary significantly. Therefore, several field and water culture were conducted in both Namibia and Japan.

Furthermore, to fully utilize the broken rice resulting from the milling process, a mixture of rice and pearl millet flour was tested through the joint program of Japanese volunteers (JOCV; Japan Overseas Cooperation Volunteers). Demand for the flour showed great potential for market development for this product in North-Central Namibia. In fact, the first commodity displayed in August 2014 at the trade fair held in Ondangwa town was sold out within 10 minutes of display. Many consumers attributed their preference for the food product of this flour mixture to its more whitish colour as well as better texture and taste, compared with the conventional product of pearl millet flour. The high demand for the locally grown rice should serve as an incentive for both local producers and rice researchers.

6. Integrated joint study of the phase II rice introduction

As described above, efforts for the second phase of rice introduction in the seasonal wetlands in North-Central Namibia still continue. However, the mixed cropping system of rice and pearl millet in the water fluctuation zone developed initially should offer one answer to establishing sustainable agriculture that fully utilizes the seasonal wetlands without modification of the fragile water environment in semi-arid zones. The second phase comprised integrated studies of three different disciplines, Crop science, Hydrology, and Development study (Iijima et al., 2013). These are quite different fields of science; however, collaboration among these fields is necessary to develop a cropping system that can sustainably preserve water environment. Monitoring of both natural and social impacts is essential and should be considered to propose a mixed cropping system that is adapted to both flood and drought environments.

MAJOR CONCLUSIONS

Extreme climatic conditions of flood and drought tend to occur frequently in same areas due to the recent climate change. Semi-arid and arid regions are especially vulnerable to the effects of climate change and variability because of their fragile, marginal environments. Major grain crops cultivated in these regions are pearl millet and sorghum which are drought resistant but intolerant of flood stress. Therefore, during flood years the local resource-poor, smallholder farmers, who are the majority in these regions, often experience poor harvest or even complete crop failure, causing food insecurity among local communities. Cultivation techniques adapted to both flood and drought environments may therefore need to incorporate mixed cropping of flood-resistant rice and drought resistant pearl millet and sorghum to ensure stable grain production. This study assessed the effects of mix-planting of pearl millet and sorghum with rice under field flood conditions on the survival, growth and grain production of the dryland cereals. A series of mixed cropping experiments were conducted under field in semi-arid North-Central Namibia.

Mix-planting pearl millet or sorghum with rice alleviated the effects of flooding on both pearl millet and sorghum. Mixed planting increased seedling survival rates in pearl millet and sorghum, but the impact was much higher in sorghum. Moreover, although grain yields of both the pearl millet and sorghum were decreased by flooding, in both the single-stand and mixed plant treatments as compared with the yields of the non-flooded upland fields, the yields were mostly higher in the mixed plants than in the single-stand plants under flood conditions. However, the yields of rice were increased by flooding thus complementing the low yields of dryland cereals.

Furthermore, under flood conditions, the LER values for both pearl millet–rice and sorghum–rice mixtures were > 1.0, indicating a mixed planting advantage over single-stand planting. Sorghum yield demonstrated a minimal response to mixed planting, possibly due to post-flooding interspecific competition. Overall, the mixed planting technique tested indicated the potential to enhance pearl millet and sorghum yields under the short-term field flood conditions. Moreover, the results revealed that in cases of extended or severe flood, where the survival of the dryland cereals would be impossible, the rice yield could compensate for the dryland-cereal yield losses, thus serving as a buffer for grain security. Further research on the new mixed cropping technique, involving the use of mixed-seedlings, could help increase the rice yield ~~in~~ under the seasonal wetland conditions and stabilize the yields of traditional drought-resistant staple grains of pearl millet and sorghum. Continuous research and development work are warranted to provide agronomic countermeasures that would ensure constant staple food production in flood-affected semi-arid regions such as North-Central Namibia.

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LIST OF PUBLICATIONS

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