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Water Acquisition from the Seasonal Wetland and Root Development of Pearl Millet Intercropped with Cowpea in a Flooding Ecosystem of Northern Namibia

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Abstract : Seasonal wetlands, locally called *oshanas*, are characteristic of the densely populated northern Namibia, a desert country in southwest Africa. The formation of seasonal wetlands, which will sustain the water balance of a semiarid environment, was quite unstable depending entirely on the variable rainfall in the upper catchments of Angola. The objective of the present study was to evaluate the use of seasonal wetland water by pearl millet, the local staple food crop intercropped with cowpea, to discuss the water competition pattern of intercropped species. Root system development of the intercropped species was also evaluated together with the water source analysis. For this purpose, field experiments using pearl millet intercropped with cowpea in the seasonal wetland in Namibia University (Exp. 1) and monocropped pearl millet in the local farmers field (Exp. 2) were conducted in northern Namibia. Both pearl millet and cowpea developed deeper root systems as the distance from the seasonal wetland water increased. At flowering time, the δD value of intercropped cowpea was similar to that of wetland water, while that in pearl millet was much lower than those of both the wetland water and groundwater. This indicated that intercropped pearl millet did not have full access to the wetland water when there was competition with cowpea for water derived from various water sources. Under such circumstances, intercropped pearl millet probably relies more on the rainfall water, which is just sufficient to sustain its growth in a semiarid environment. By contrast, intercropped cowpea wins in the competition with pearl millet and can acquire water from the existing stored wetland water.

Key words : Deuterium, δD, Drought, Heavy water, Intercropping, Stable isotope, Water stress, Water uptake.

Although Namibia is an arid country, the north central region is characterized by seasonal floodplains, which are locally called *oshanas*. About a quarter of Namibia's population lives in this part of the country. The dense population of this region is attributed to the easy access to shallow well water, which occurs because of the high groundwater level derived from the local flooding of *oshanas*. The *oshanas* (wetland) are a result of a complex endorheic system and shallow basin topography. During the wet season, water from the upper catchments in Angola contributes to the flow of the wetland drainage system (Mendelsohn et al., 2002). The duration and amount of water stored in the wetland are unpredictable and depend entirely on the variable rainfall in the area of upper catchments approximately 37,000 km^2 apart (Lindeque and Archibald, 1991). Local rainfall in north-central Namibia is not likely to contribute to the duration or severity of floods because of the low annual precipitation (200-400 mm yr^{-1}), high evaporation rates (as high as 3,700 mm), and high infiltration rate of the sandy soils that lead to minimal run-off (Lindeque and Archibald, 1991; Heyns, 1991). However, the role of groundwater and subsurface flow as hydrological input to the wetland has not been studied.

The formation of seasonal wetland is the common phenomenon observed widely in the world, and the characteristics of the wetland in Namibia are similar to those of other wetlands in other semiarid parts of the world (Breen, 1991). The seasonal wetland in Namibia acts as a reservoir, storing water during the rainy season and releasing it slowly at later stages. Moreover, from the waterlogged center of the wetland towards the dry uplands, there is a moisture gradient with more favorable moisture conditions for crop production. In the semiarid Sahelian environment (an almost identical environment to that in northern Namibia), the yield of pearl millet increased when it was planted towards the lower and wetter slopes (Rockström and de Rouw, 1997). The large amounts of water accumulated in deep layers of lower slopes or lowlands may contribute to these yield gradients.

In north-central Namibia, more than 90% of the farmers cultivate pearl millet as a staple food

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Abbreviations: ANOVA, analysis of variance; DAS, days after sowing.

Table 1. Soil characteristics of the topsoil and subsoil at the University of Namibia, Ogongo Campus (Exp. 1) and Olyavahenge (Exp. 2). N - Kjeidahl acid digestion. P - Olsen method. K - Atomic absorption spectroscopy. #Organic matter. Soil analysis was done by the National Soil Science Laboratory, Namibia. Values are means of three replications.

	Soil depth (cm)	N (%)	P (ppm)	K (ppm)	pH (H_2O)	OM# (%)	Sand (%)	Clay (%)	Silt (%)
Exp. 1	0-30	0.03	4.13	128	5.6	1.23	89.4	7.3	3.3
	30-75	0.01	0.20	181	7.6	0.28	76.9	20.9	2.2
Exp. 2	0-45	0.02	0.74	154	7.3	0.89	83.0	11.7	5.3

(McDonagh and Hillyer, 2003) because this is the best cereal crop that can survive under natural rainfall in the semiarid environment of northern Namibia. Although data on the yield of pearl millet in these areas is lacking, the average was 225 kg ha^{-1} from 1990 to 1993 (Matanyaire, 1998). This low yield is a major concern for subsistence farmers who need to at least double this level to become self-sufficient pearl millet producers (Matanyaire, 1998). As a measure to stabilize crop productivity and to reduce the high risk of crop failure, cowpea is usually intercropped with pearl millet in north central Namibia (McDonagh and Hillyer, 2003). However, the chances of crop failure due to drought remain high; moreover, the effects of intercropped cowpea on pearl millet are complicated and greatly vary with the soil moisture and plant density.

The wetlands are estimated to cover an area of approximately 7,000 to 11,550 km^2 (Hochobeb, 2002), 85% of which is used communally (Schrader, 1991). At present, the wetlands are mainly used for small-scale livestock grazing, but the livestock farmers often grow pearl millet as their staple food crop. Livestock farmers and small-scale subsistence farmers often utilize the wetland as the grazing field for their animals and higher portions adjacent to wetland are the potential pearl millet fields, although there is a risk to fail the cropping due to the uncertainty of flooding timing and duration. When the precipitation is more than 300 to 350 mm (Latha et al., 2004), pearl millet can grow well without significant reduction of the yield. However, due to the scarce and unreliable rainfall distribution, the probability of the occurrence of a drought in any given year is 50% in Namibia (McDonagh and Hillyer, 2003). Previously, we found a significant suppressive effect of cowpea on the ability of pearl millet to extract stored soil water when subjected to drought (Zegada-Lizarazu et al., 2005, 2006a, b). Therefore, the water uptake trend of pearl millet intercropped with cowpea in the areas of better soil moisture conditions adjacent to the wetland should be fully studied to stabilize pearl millet productivity and secure food production in the subsistence farming system.

To our knowledge, the trend of crop water uptake along the moisture gradients in a wetland ecosystem has not been studied previously. The naturally occurring stable isotope of water, deuterium, can be used to trace the ability of pearl millet and cowpea to extract water from a wetland. No isotopic fractionation occurs during the movement of water from the roots to the shoot base of a plant. Therefore, the stable isotope ratio (deuterium/hydrogen) in xylem sap water at the shoot base should reflect the water sources of a plant at the time of analysis (Dawson and Ehleringer, 1991). This technique has been used to determine the sources of water used by tree/shrub communities (Ehleringer et al., 1991; Dawson, 1993) and annual crops (Zegada-Lizarazu and Iijima, 2004; Araki and Iijima, 2005; Iijima et al., 2005; Zegada-Lizarazu and Iijima, 2005; Zegada-Lizarazu et al., 2005, 2006a, b). The objective of the present study was to determine the water sources used by pearl millet intercropped with cowpea when planted at different distances from the seasonal wetland water, in Namibia. Root development along the water gradient was also analyzed together with the water source analysis.

Materials and Methods

1. Study sites

The growth of pearl millet monocropped and intercropped with cowpea and the source of water used by both crops were evaluated at two locations with different soil and environmental conditions. The intercropping experiment (Exp. 1) was conducted at the University of Namibia, Ogongo Campus (latitude 17°43'S, longitude 15°15'E). The monocropped experiment (Exp. 2) was conducted on a farm field at Olyavahenge, a village located 50 km NE of the Ogongo Campus (latitude 17°26'S, longitude 15°25' E). Discussions were held with the farmer to obtain her agreement to carry out the research in her field. At the Ogongo Campus, rainfall for the 2005 cropping season (Jan.-Mar.) was unevenly distributed, with a total of 192 mm (42 mm below the 5-year average). Between the 1st and 11th of January (before sowing of Exp. 1) 27.6 mm of rainfall was recorded. The mean ambient temperature in north central Namibia between January and February was 26°C. The temperature in March 2005 was not recorded, but the historic average (1902-1985) for this month is 23.1°C (National Meteorological Centre, Windhoek, Namibia). In Exp. 1, the topsoil (0-30 cm) in the field was sand, while the subsoil (30-75 cm) was sandy clay loam. In Exp. 2,

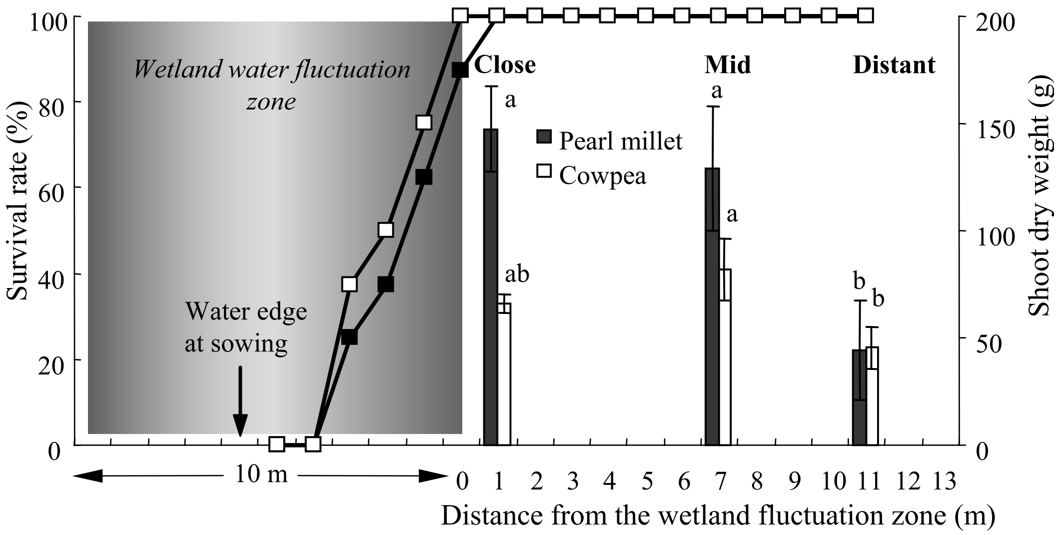

Fig. 1. Shoot dry weight (bars) and survival rate (solid lines) of intercrops at various distances from the wetland water. The seventh row from the water edge at sowing (arrow), where all plants survived, was regarded as the first sampling distance (close site) from the wetland water fluctuation zone. At sampling, the water edge had receded 11 m from the first sampling distance. Different letters within each species indicate significant differences (P<0.05) of shoot dry weight among the distances from the wetland water (Duncan's multiple range test). Values are means of six replications ± SE.

the topsoil was characterized as loamy sand. Further information about the soil characteristics in both experiments is presented in Table 1. The soil fertility at different distances from the wetland water was not measured in either experiment.

2. Treatments and field management

In Exp. 1, crop performance and the source of water used along the slope were studied at three distances relative to the wetland starting from the nearest one, at which all plants survived from the flooding during the experimental period. These distances were regarded as the treatments and are described as follows: close distance (at 1 m), mid-distance (at 7 m), and distant site (at 11 m). Six plants per species at each distance, along a straight row parallel to the wetland borderline, were sampled to make the replications for the statistical analysis; this type of statistical analysis is widely conducted (Onyewotu et al., 1994; Wezel, 2000; Bayala et al., 2002). All the plants in the first row from the original border of wetland at sowing (−5 m in Fig. 1) could not survive due to the flooding during the plant establishment (see Fig. 1 of survival rates). As the wet season progressed, the water level gradually increased, and finally reached the fifth to sixth row, affecting significantly the survival rate of both crops. Therefore, the seventh row from the original wetland border at sowing, where all plants survived was regarded as the first sampling distance (close site) from the wetland water fluctuation zone where wetland border changes during the experiment. At sampling, the border of the wetland water had receded 11 m from the first sampling distance (close site). One day before sowing, the land was prepared and leveled with a rotary plough to a depth of 15-20 cm. Before sowing, 45 kg ha^{-1} each of N, P, and K was broadcast and raked into the soil. No top dressing was applied. Pearl millet cv. Okashana-1 (*Pennisetum glaucum*) and cowpea cv. Nakale (*Vigna unguiculata*) were sown in rows in an alternating pattern within the same row (pearl millet-cowpea). Each row consisted of 16 plants (eight per species). A total of 19 rows were sown, with the closest (lowermost) one located −6 m from the first sampling distance (close site) and the farthest row (uppermost) located 13 m from it. The experimental plot was 16 m wide by 20 m long, and the total planting area was 320 m^2. Both crops were sown on January 11, 2005, with a between and within row spacing of 1 × 1 m by an additive design of intercropping, i.e., the planting density was 20,000 plants per ha. Thinning was done (following the local practice) to 2-3 and 1-2 plants $hill^{-1}$ for pearl millet and cowpea, respectively, at about 20 days after sowing (DAS). Weeding was carried out manually between 20 and 25 DAS. Pest management was not conducted, since none appeared during plant growth.

In Exp. 2, three distances from the wetland were designated for sampling: close (at 1 m); distant (at 11 m), and extremely distant (at 18 m) from the wetland water fluctuation zone (same concept as Exp. 1.). At each distance, eight plants growing along a straight row parallel to the water fluctuation border were sampled to make the replications for the statistical analysis. In this experiment, pearl millet was grown as a monocrop, following the landowner's willingness. In Namibia intercropping/mixed cropping with cowpea

Table 2. Shoot biomass, leaf physiological parameters, and soil water content at various distances from the wetland (Exp. 2). Different letters within columns indicate significant differences (P<0.05) among the distances from the wetland (Duncan's multiple range test). Crop parameter values are means of eight replications and soil water content values are means of three replications.

Distance from the wetland	Shoot dry weight (g)	Photosynthetic rate (μmol m^{-2} s^{-1})	Transpiration rate (mmol m^{-2} s^{-1})	Soil water content (%, w/w)
Pearl millet (PM)				
1 m	98.63 a	32.97 a	6.96 a	8.70 a
11 m	31.90 b	12.06 c	3.14 b	4.64 b
18 m	10.26 b	19.67 b	6.30 a	4.17 b

was practiced in approximately 45% of pearl millet field (Matanyaire, 1998). Soil was prepared by hand with a hoe to an approximate depth of 10-15 cm. Neither chemical nor organic fertilizers were applied. The local pearl millet landrace used in the region (cv. Omahangu) was sown during the second week of November, 2004. Sowing was done randomly in small pockets; 6～10 seeds were placed in each pocket. Thinning was done to 2-3 plants hill^{-1}, at 20-25 DAS. Weeding was carried out manually only once with a hoe. Pest management was not conducted. From plant counts, we estimated pearl millet density to be 20,000 hills ha^{-1}. On average, hills were 0.7 m apart. At sowing time, the front row of pearl millet plants facing the wetland was located 3 m from the edge. At flowering, the border of the wetland water had receded 15 m from the first row sowed.

3. Crop measurements

In Exp.1, at 50 DAS, six pearl millet and six cowpea plants at each sampling distance were harvested, and their shoot dry biomass was determined after oven-drying at 80°C for three days. Due to the limited size of experimental field, the seed production of pearl millet was not measured. Root samples were collected immediately after shoot sampling. A trench measuring approximately 12 m in length, 0.8 m in width, and 0.9 m in depth was dug at each sampling distance. Root samples were collected just below the plant canopy from the following depths: 2.5, 10, 20, 30, 50, and 75 cm with a stainless core sampler (volume 100 cm^3). Roots in the cores were washed out with water over a sieve and separated from other organic debris. After removing all debris, the root fresh weight was measured, and the root weight density (root weight soil volume^{-1}) was calculated. The representative data of the surface, intermediate, and deep layers are presented in the results section (at depths of 2.5, 30, and 75 cm, respectively). At the time of root sampling, another set of soil cores was taken at the same depth intervals, starting at a depth of 10 cm, for soil water content analysis (w/w). The survival rate (number of living plants per row) of pearl millet and cowpea was also determined.

In Exp. 2, eight plants per sampling distance were harvested at flowering (110 DAS). Just before plant harvesting, the photosynthetic and transpiration rates were measured with a portable photosynthesis analyzer (LCi, ADC BioScientific, Ltd., UK) using the first fully expanded leaf from the top. During the measurements, the ambient relative humidity at 09:00 h was 30% and at 10:00 h it decreased to 22%. The minimum and maximum temperatures on the sampling day were 21 and 35°C, respectively, and the average light intensity was 1548 μmol m^{-2}s^{-1}. The shoot dry weight was determined in the same way as described in Exp. 1. The soil water content (w/w) was determined from bulk soil samples taken from the top 45 cm of the soil profile.

4. Stable isotope analysis

In Exp. 1, water samples were collected from plant stems, wetland water, rainfall, and groundwater. At flowering time, about seven hours after 5.2 mm rain fall, xylem sap of intercrops was sampled from the cut end of the stems, placing cotton puffs on the cut end of the stumps and wrapping them in thin polyethylene film, following the method described in Zegada-Lizarazu and Iijima (2004). Because of the dry weather, xylem sap was sampled just after rainfall to acquire enough quantities of sap samples to analyze the deuterium concentration. At the time of xylem sap sampling, however, surface layer of the well-drained sandy soil had already been quite dry because of no rain for 13 days before the rainfall. Water samples from the wetland were taken at 10 cm from the surface of the remaining impounded water adjacent to the experimental field and groundwater from a well located in the proximity of the experimental area. The groundwater level in the region fluctuated between 2 and 3 m depth. There was rainfall at around 0 to 2 AM. The rainfall samples in the study area could not be collected due to the danger of going outside at night; therefore, the samples collected at the beginning of the rainy season (December) in South Africa were used as a reference. All samples were stored at −30°C before deuterium analysis. The deuterium abundance in xylem sap, wetland water, groundwater, and rainfall were measured by mass spectrometry (DELTA^{plus},

Table 3. Root weight density[#] (kg m^{-3}) and soil water content (%) at various distances from the wetland (Exp. 1). [#]Root fresh weight. [$]Soil water content was measured at 10 cm depth. [&]Mean value of two replicates. Different letters within columns indicate significant differences (P<0.05) among the distances from the wetland (Duncan's multiple range test). Root parameters are means of four to six replications and soil water content values are means of three replications.

Distance from the wetland	Depth (cm)		
	2.5[$]	30	75
Pearl millet (PM)[#]			
1 m	27.27 ab	0.27 b	0.07 b
7 m	53.17 a	0.47 ab	0.04 b
11 m	21.11 b	0.67 a	0.45 a
Cowpea (CP)[#]			
1 m	36.23 a	0.20 b	0.01 [&]
7 m	32.01 a	0.63 ab	0.27 b
11 m	8.45 b	1.00 a	0.37 a
Soil water content (*w/w*)			
1 m	6.15 a	12.14 a	16.04 a
7 m	2.37 b	9.74 a	14.80 a
11 m	3.34 b	11.87 a	16.37 a

Finnigan Mat Instruments, Inc., Germany). The δD values were expressed as $\delta D = [(R_{sample}/R_{V\text{-}SMOW})\text{-}1]*1000$ ‰, where R is the molar ratio of heavy to light isotope (D/H), with D being deuterium and H, hydrogen.

5. Statistical analysis

In both experiments, a one-way analysis of variance (ANOVA) and Duncan's multiple range tests were used to compare all the parameters measured between distance treatments within each species. The number of replicates used for each analysis is indicated in the respective figures and tables.

Results

1. Shoot dry weight, photosynthesis and transpiration

Figure 1 shows the survival rates and biomass production of intercrops at various distances from the wetland. Biomass production of pearl millet and cowpea was similarly affected by the distance from the wetland. Higher dry matter production was obtained at both close and mid-distance sites, and the lowest values at the distant site (Fig. 1). This implies that the wetland water would not be utilized at the distant site, in other words, it was useful at mid-distance by the fluctuation of wetland borders during the crop growth period although the soil water contents was not high at mid-distance at the time of plant sampling (Table 3). The biomass reduction at the distant site was greater in pearl millet than in cowpea. In Exp. 2, the monocropped pearl millet at the close site had higher biomass production than at the distant and extremely distant sites (Table 2). In fact, shoot growth at both distances was very poor. The changes in biomass production along the distance followed the gradient in soil water content closely; significantly higher soil water content was observed at the close site than at the other distances (Table 2). The transpiration and photosynthetic rates of pearl millet in Exp. 2 were also affected by distance from the wetland. Although the transpiration rate inside the gas exchange chamber will not be equal to the transpiration in the open air, the value would indicate the relative trend among the treatments. At the close site, the transpiration and photosynthetic rates were 2.2 and 2.7 times higher, respectively, than those at the distant site. The value at the extremely distant site from the wetland water (at 18 m) was even higher than the distant site (at 11 m), but the soil water and/or nutrient status of the farm field at the time of measurement were unknown.

2. Root growth

The effect of distance from the wetland on the root system development of intercrops (Exp. 1) is summarized in Table 3. At mid-distance, the root weight density of pearl millet was higher than that at either at the close or distant sites in the top 2.5 cm layer. The plants at the close site had 1.3 times more roots than those at the distant site, but the difference was not significant. As for cowpea, the surface root weight density at the close site and mid-distances was significantly higher than that at the distant site. Conversely, a significant improvement in root growth was observed for both crops grown at the distant site at depths of 30 cm or more. Pearl millet at depths of 30 and 75 cm had 2.5 and 6.4 times more roots, respectively, at the distant site than at the close site, while cowpea had 5 and 37 times more roots at the respective depth and distance. The trend of changes in root distribution relative to distance from the wetland can be explained by differences in the content of soil water near the soil surface. In the top 10 cm of the soil, the soil water content was higher at the close site than it was at mid-distance or distant site, but at depths of 30 cm or more, no significant differences were observed between the three distances.

3. Source of water for the crops

Figure 2 shows the water source for the crops at various distances from the wetland (Exp. 1). The wetland water had a δD value of 53.0‰, and the groundwater value was 2.1‰. Rainfall collected in December in Johannesburg (latitude 26°08'S, longitude 27°54'E), about 1,600 km from the study site, had a δD value of −39.1‰, while rainfall values during the mid rainy season in Zimbabwe ranged from −30 to −90‰ (McCartney et al., 1998). Little variation was found in the δD values of pearl millet

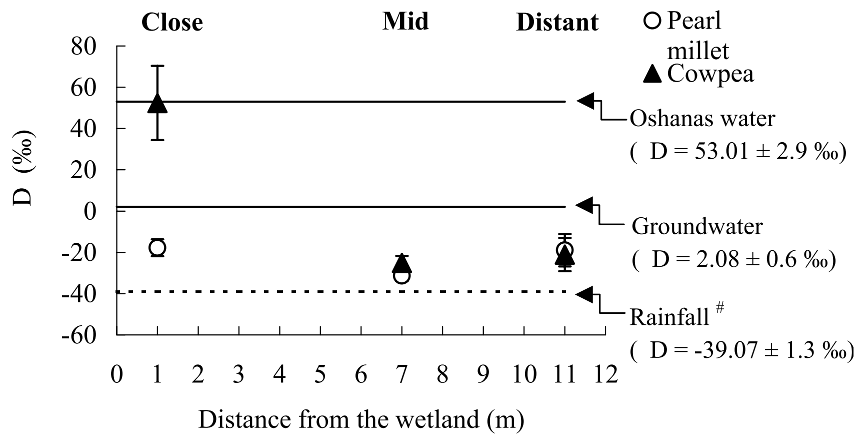

Fig. 2. Deuterium values in xylem sap of intercrops and in different water sources. Values are means of three to six replications ± SE. *Deuterium values in December's rainfall (2004) in South Africa.

at the three distances from the wetland water; these values ranged from −31.3 to −17.8‰, indicating that pearl millet at flowering time did not have full access to the wetland water when there is water competition with cowpea for various water sources. Under such circumstances, pearl millet probably relied strongly on rainfall water or on a mixture of groundwater and rainfall. On the other hand, cowpea at the close site had a similar δD value (52.4‰) to that of the wetland water, indicating that, at this distance, cowpea uses mainly the wetland water. The δD values in cowpea at mid-distance and distant sites, −25.1 and −21.2‰, respectively, were between the δD values of rainfall and groundwater, indicating that the water taken up by cowpea at these distances is derived from the range of the two sources. The water content of the surface soil at these distances was not as high as that at the close site (Table 3). This indicates that only the close site received water derived from the wetland at the time of xylem sap sampling; i.e., the wetland water may be not accessible for crop species in both mid-distance and distant sites. This may be why the δD values in both pearl millet and cowpea were similar at these distances.

Discussion

The water source of intercropped pearl millet grown in the areas bordering the seasonal wetland in the densely populated north central Namibia was identified by the naturally occurring stable isotope of hydrogen. Moreover, deep root development was evaluated in relation to the distance from the seasonal wetland water.

1. Water sources

Intercropped pearl millet did not have full access to the wetland water at any distance analyzed when the xylem sap was sampled about seven hours after 5.2 mm rainfall (Fig. 2). By contrast, intercropped cowpea had full access to the wetland water when grown near the wetland water. These results, however, do not imply that pearl millet does not utilize the wetland water. As indicated by the difference in crop growth along the wetland water (Fig.1), pearl millet may rely much on the wetland water than cowpea for the biomass production. Under the water-competing intercropping situation, pearl millet was most probably strongly dependent to the rainfall water supplied several hours before the plant harvesting, because the xylem sap δD value was significantly lower than those of both wetland and groundwater. In fact, the rainfall water collected from the neighboring countries, i.e. South Africa and Zimbabwe, were nearer to the xylem sap δD value of pearl millet, although we failed to collect the previous nighttime rainfall due to the danger to go outside during the nighttime. The δD value of the previous nighttime rainfall may be even lower than those from neighboring countries.

The study area belongs to the semi-arid regions, and has only 300 – 350 mm annual rainfall on average mainly during five to six months of rainy season. Therefore, long term no rain even during mid rainy season is quite common in this region. Xylem sap collection for the analysis of plant water source under such circumstances was depending on the rainfall event to fill soil water enough to supply adequate quantity of xylem saps by the root pressure of the plants. In other words, the analysis of plant water source by using the difference in deuterium natural abundance ratio among the water sources was not possible without sufficient rainfall supply before the collection of plant xylem sap. Although 5.2 mm rainfall is not a small quantity, i.e., approximately 2.6 liters of water per crop can be supplied theoretically if all the rainfall was captured by the crops, the prolonged dry weather for 13 days in the well-drained sandy soil region caused the surface soil to dry completely within several hours after the rainfall. The impact of rainfall on the crop physiological state cannot be discussed further at present except for the water source estimation. We need detailed information on the water movement in the loamy sand soil of the study area, such as surface runoff, unsaturated hydraulic conductivity, intensity of rainfall, extent of root development, and so on, for further analysis of rainfall water use by the crops.

The present results suggested that intercropped pearl millet could not fully utilize the wetland water stored over a long period, i.e., wetland-derived water, due to the competition with cowpea. Stagnant and long existing wetland water will mix with the soil water and may become relatively inaccessible water for intercropped pearl millet due to the lower soil water potential of dry sandy soil as compared with recently supplied rainfall, which is easy for pearl millet to acquire due to its higher water potential. As indicated by its xylem sap δD value (Fig. 2), cowpea successfully utilized wetland water when it was grown near the wetland. Cowpea had a higher ability to acquire existing water in the dry soil, which was not easy to access for pearl millet when they were grown under competitive intercropping condition. The water derived from rainfall would be accessible by plants only just after the rainfall in the semiarid regions like the study area, and the amount may be limited as compared with the long- term existing wetland-derived water. If the water acquisition abilities to the easily accessible higher water potential water are similar in both crop species, cowpea would always have higher access to the wetland-derived water. The present results agreed with those obtained in our previous studies on water sources of intercropped pearl millet using deuterated irrigation water to the pot (Zegada-Lizarazu et al., 2005) and field soils (Zegada-Lizarazu et al., 2006a, b). In this study, we demonstrated the species- specific differences in the water sources of intercropped pearl millet and cowpea when they were grown near the seasonal wetland water in the desert country of Namibia.

2. Biomass production

Pearl milled showed higher biomass production when it was grown closer to the wetland than far away (Fig. 1 and Table 2). This could be attributed to the relatively higher soil water content near the wetland (Tables 2 and 3). Pearl millet must have utilized the wetland water during its growth period, although the main water source for intercropped pearl millet would be the rainfall water. The total rainfall during the pearl millet growth period from sowing to heading was 192 mm, which was sufficient to sustain the drought-resistant local pearl millet cultivars. The excess soil water derived from stagnant wetland water would be highly valuable for increasing the biomass production in both crops. The biomass reduction at the distant site was greater in pearl millet than in cowpea (Fig. 1), which indicates the presence of competition between the two species; cowpea could utilize the limited water at the distant site while pearl millet could not fully utilize it due to the competition with cowpea. In the single planted pearl millet (Table 2), the ratio of biomass production at the close site to that at the distant site was quite similar to that in intercropped pearl millet (Fig. 1). The similar reduction could not explain the difference in water competition between the two different field experiments.

3. Deep root development

Deep rooting of annual food crop species has been extensively studied (Araki and Iijima, 1998, 2001; Araki et al., 2000). Vertical deep root penetration often helps plants to overcome drought stress (Araki and Iijima, 2001). Furthermore, water uptake is a function of root density and distribution in relation to available soil moisture. The changes in root distribution relative to distance from the wetland is quite close to the differences in soil water content near the soil surface; in the upper 2.5 cm of soil, more roots were observed at sites wetter and closer to the wetland than at drier and distant sites (Table 3). This root distribution pattern indicates that the shallower root system of pearl millet at the close site may enhance the absorption of rainfall water. By contrast, at the site distant from the wetland water more photosynthates were allocated to the deep roots (Table 3). Even though more roots could reach the deeper wetter layers at this position, the root density would be insufficient to make a significant contribution to the transpirational requirements of the plant because water uptake efficiency of deep roots in pearl millet will not be enhanced in the wet soil layer (Zegada-Lizarazu and Iijima, 2005). These findings are in accord with those of reduced shoot biomass production and lower soil water content observed in the upper layers at the distant site (Fig. 1; Table 2).

In conclusion, intercropped pearl millet planted near the seasonal wetland did not have full access to the wetland water when there is competition with cowpea for various water sources. Under such circumstances, pearl millet most probably relied more on rainfall water, which was just sufficient to sustain its growth in the semiarid environment. By contrast, intercropped cowpea obtained much more water from the wetland water due to the strong ability to acquire the existing stored soil water in comparison with pearl millet. The biomass production, which is a testimony to the soil conditions during the entire growing period, shows that it is beneficial to grow pearl millet and cowpea in the areas adjacent to the wetland water. However, at the same time, the survival rate indicates that growing both crops too close to the wetland water is detrimental because of the periodic inundations and high susceptibility of pearl millet and cowpea to waterlogging. The use of the seasonal wetland as the crop field may be beneficial for the subsistence farmers in this region. For this purpose, we have started a scientific project to introduce the rice paddy cultivars, which suit the local wetland environment, taking into consideration the harmonization of the pearl millet cropping system. Rice cropping in wetland and pearl millet production in the vicinity of the wetland may be introduced to this region in future.

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