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学位論文全文に代わる要約
Extended Summary in Lieu of Dissertation

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学位論文題目：
Title of Dissertation

Development of temporal and spatial sowing methods for increasing soil moisture and yield of upland rice under rainfed conditions in Benin, West Africa
（西アフリカ・ベナンの天水条件下における陸稲の土壌水分および収量増加を目指した時間的・空間的播種技術の開発）

学位論文要約：
Dissertation Summary

Introduction

Rice is an important staple and economical crop in West Africa. However, most of the rice is cultivated in the rainfed environment, where rice yields are low and variable due to various constraints, such as adverse climate conditions and poor water management. Therefore, it is necessary to identify the conditions that cause low yields in rainfed regions and find methods that efficiently utilize the limited rainwater to improve production. The objectives of this study are to (1) identify the differences between low yielding and high yielding farmers in rainfed regions, (2) verify the temporal effects of sowing date adjustment on soil moisture and yield, and (3) verify the spatial effects of furrow sowing on soil moisture, seedling establishment and on (4) yield, for improving productivity in rainfed rice.

Site description

The study took place in a rural farming village of Kpakpazoumé (7°55’N 2°15’E), located in the commune of Glazoué, Collines Department, Benin. This area lies in the tropical Sudano-Guinean climate with a bimodal rainfall pattern. The mean annual temperature of this area is 27°C and the mean annual rainfall in this region is 1109 mm, with a range between 754–1498 mm (Fig. 1). Most of the rain events take place during the rainy season which generally begins around the end of May and terminates in November.

Kpakpazoumé is characterized by gentle sloping lands where various crops such as rice, maize, cowpea, soybean, groundnut and cotton are cultivated under rainfed conditions in variable

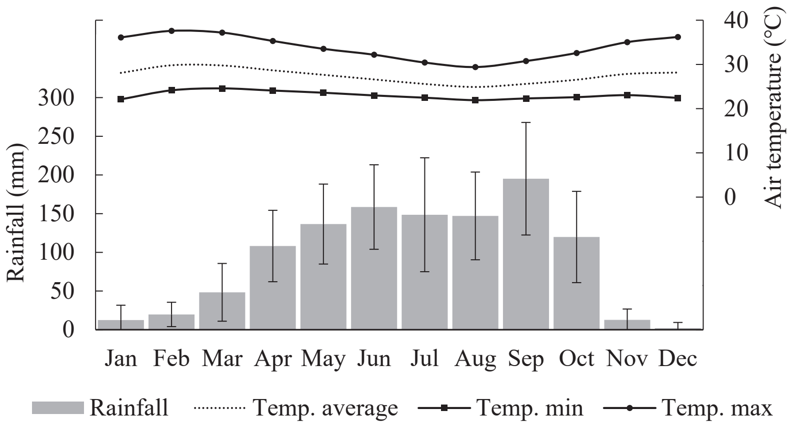

Fig. 1. Average monthly rainfall and temperature during 2001–2014 for the Savè station.
Error bars indicate standard deviation.

field ecologies, from the uplands with freely draining soil, to the valley bottom with shallow groundwater levels. After several rainfall events at the beginning of the rainy season, farmers plow the adequately moistened field by hand or with the help of a bull, then create ridges for planting crops such as cowpea and maize. For rice cultivation, the plowed field is leveled flat with a manual hoe before seeds are directly sown by hand. Rice is typically sown in June–July and harvested in November, when the rainy season ends. The soil type in Kpakpazoumé has been reported as Plinthic Luvisol with a sandy loam texture.

(1) Farmer interview

Farmer interviews were conducted between 2015–2016 in Kpakpazoumé, with 12 randomly selected farmers on management practices such as crop cultivation area, yield and sowing date. Results showed that rice yields positively corresponded with the seasonal rainfall, and the average rice cultivation area of the farmers decreased 89% over 4 years, from 1.2 ha in 2013 to 0.13 ha in 2016 (Table 1). The rice area percentage significantly decreased from 11.1% in 2015 to 3.6% in 2016.

Table 1. Rainfall data and rice cultivation data per farmer (2013–2016).

Year	Rainfall (mm) [1)]	Yield (t ha^{-1})	Rice area (ha)	Rice area to total farming area (%) [2)]
2013 (n=4)	422	1.1 ab	1.20 a	14.3 a
2014 (n=12)	658	1.8 a	0.58 ab	12.2 a
2015 (n=12)	347	0.3 b	0.48 ab	11.1 a
2016 (n=12)	589	–	0.13 b	3.6 b

[1)] Sum of rainfall during the rice cropping season (June 1st–November 31st , Savè station data). [2)] The percentage was analyzed after arcsine conversion. n, number of farmers; –, data not available and not used for statistical analysis. Values followed by different letters in a column are significantly different at $P < 0.05$ by Tukey's HSD test.

Regarding individual farmers, the rice area from 2015 to 2016 greatly decreased with farmers who yielded less than 2 t ha^{-1} in 2014 (LYF, low-yield farmer), in comparison to farmers who yielded 2 t ha^{-1} or more in 2014 (HYF, high-yield farmer) (Fig. 2). Statistically, LYFs significantly reduced their rice area to total farming area (%) in comparison to HYFs, especially after a dry cropping season. These results suggest that farmers with fields that can yield 2 t ha^{-1} or more in a regular cropping season are more likely to continue rice cultivation even after drought years, while farmers with lower yielding fields tend to decrease or halt rice cultivation after experiencing a drought year. In addition, LYFs also sowed rice and other crops such as maize, cowpea and soybean significantly later than the HYFs by 18, 19, 10 and 23 days, respectively. The field water status was also assumed to be another important factor affecting sowing time, as adequate moisture in the soil is required before land preparation.

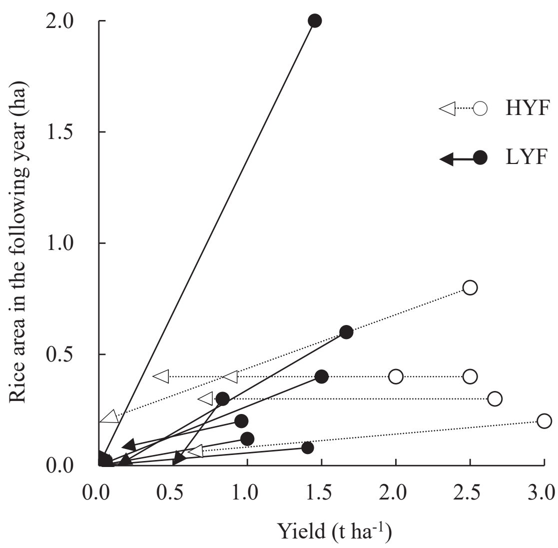

Fig. 2. Impact of yield on rice area in the following year. Circle indicates 2014 yield and 2015 area; arrow point indicates 2015 yield and 2016 area. High-yield farmer (HYF), yielded ≥ 2 t ha^{-1} in 2014; low-yield farmer (LYF), yielded < 2 t ha^{-1} in 2014.

(2) Effect of sowing date on yield

To verify the effect of sowing dates on yield and soil moisture, a field experiment was conducted with 4 different sowing dates on a LYF and a HYF field in 2015. Rice was sown at 3-week intervals on the following dates as treatments: 21 May (Date 1), 11 June (Date 2), 2 July (Date 3) and 23 July (Date 4). Date 3 is the approximate conventional sowing date of rice in this area.

The cropping season in 2015 was very dry, with the lowest cumulative rainfall over the past 16 years. Total rainfall during the experiment was 469 mm, which consisted of 52 days of rainfall events and 8 dry spells lasting from 5–16 days (Fig. 3). Throughout the experiment, soil moisture content was consistently lower in the LYF field than in the HYF field by an average value of 6%. The difference in soil moisture between the fields may be due to the topographic location of the fields, as the HYF field was located on the lower end of a slope and the LYF field on the upper part of a slope. In regard to sowing dates, the average soil moisture was higher in Date 1 and 2 than in Date 3 and 4. The soil moisture difference was especially significant during heading–maturity, where Date 3 and 4 had approximately 10% lower soil moisture than the earlier sowing dates, mainly due to the lack of rainfall at the end of the cropping season in October.

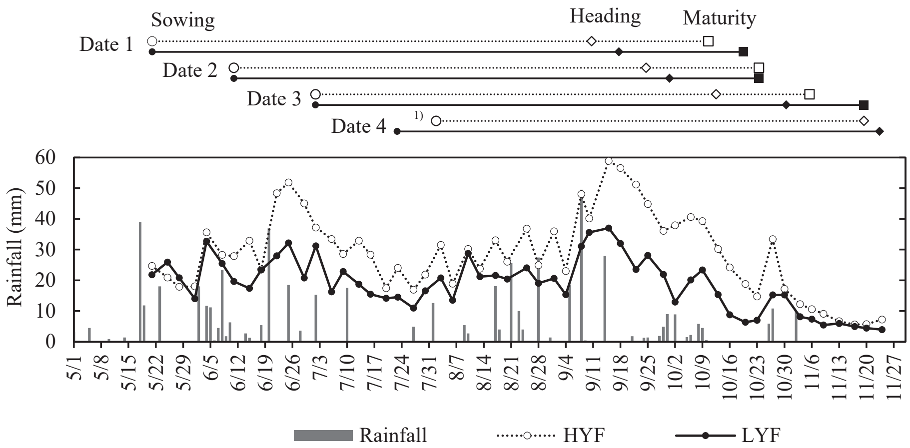

Fig. 3. Rainfall and soil moisture comparison between high-yield farmer's field (HYF) and low-yield farmer's field (LYF), with cropping stages in Kpakpazoumé (2015).
1) HYF field was resowed due to animal damage. Soil moistures indicate the average value of the different sowing dates.

The number of days to heading significantly increased under low soil moisture conditions and was significantly higher in the LYF field than in the HYF field by an average of 11 days, irrespective of the sowing date. On the other hand, the number of days from heading to maturity significantly decreased in correspondence with later sowing dates and lower soil moistures. The decrease of days during the reproductive period may be related to the acceleration of the senescence in the plants, induced by late season drought.

Average yields were significantly lower in Date 3 and 4 (0–0.7 t ha^{-1}), than in Date 1 and 2 (2.8 t ha^{-1}) (Table 2). The low yield of Date 3 and 4 were due to low filled grain percentage and crop failure, caused by low soil moistures at the end of the season when rice is most sensitive to water stress. The average yield in the LYF field was significantly 1.2 t ha^{-1} lower than the HYF field. Lower yields in the LYF field were attributed to the low number of spikelets (m^{-2}) and filled grain percentage for Date 1 and 2, respectively. The low number of spikelets (m^{-2}) may have been due to the large soil moisture difference between the two fields before the period of heading. The reduced percentage of filled grains in the LYF field was due to the significantly lower soil moisture during heading–maturity. These results suggest that yield is strongly related to soil moisture, and soil moisture can be improved by sowing earlier than the conventional date, as plants can reach maturity before terminal drought. Higher yield due to early sowing may act as an incentive for LYFs to continue rice production in the rainfed areas, even after a drought year with low yields.

Table 2. Yield and yield components of rice grown on HYF and LYF's field under 4 sowing dates.

Date of sow	Field [1]	No. of panicles (m^{-2})	No. of spikelets ($panicle^{-1}$)	No. of spikelets (m^{-2})	Filled grain (%)	1000-grain weight (g)	Yield ($t\ ha^{-1}$)
1 (May 21)	HYF	296 a	55 a	16014 a	76 a	28.2 a	3.4 a
	LYF	331 a	40 b	12971 b	65 a	26.4 a	2.2 b
2 (June 11)	HYF	306 a	67 a	20242 a	64 a	29.1 a	3.8 a
	LYF	293 a	56 a	15552 b	45 b	27.0 b	1.9 b
3 (July 2) conventional	HYF	249 a	80	18779	30	26.2	1.5 a
	LYF	106 b [2]	–	–	–	–	0 b
4 (July 23)	HYF	39 a [2]	–	–	–	–	0
	LYF	8 b [2]	–	–	–	–	0
Date of sow (D)	1	313 A	47 B	14492 B	70 A	27.3 A	2.8 A
	2	300 A	62 A	17897 A	55 B	28.0 A	2.8 A
	3	178 B	–	–	–	–	0.7 B
	4	23 C	–	–	–	–	0 C
Field (F)	HYF	222 A	61 A	18128 A	70 A	28.6 A	2.2 A
	LYF	184 B	48 B	14261 B	55 B	26.7 A	1.0 B
Slope (S)	Upper	187 B	52 A	14855 B	63 A	27.2 A	1.3 B
	Lower	219 A	57 A	17534 A	62 A	28.2 A	1.9 A
D		***	**	***	***	ns	***
F		*	*	***	***	ns	***
S		*	ns	**	ns	ns	***
D × F		***	ns	ns	ns	ns	***
D × S		ns	ns	ns	ns	ns	**
F × S		ns	ns	**	ns	ns	***
D × F × S		ns	ns	ns	ns	ns	ns

[1] High-yield farmers (HYF), yielded ≥ 2 $t\ ha^{-1}$ in 2014; low-yield farmers (LYF), yielded < 2 $t\ ha^{-1}$ in 2014.

[2] Panicle number at heading was used as plants died before maturity. *, **, ***; significant at the 0.05, 0.01 and 0.001 probability levels, respectively. ns, not significant at the 0.05 probability level. –, data not available and not used for statistical analysis. Values followed by different letters in a column are significantly different at $P < 0.05$. Lowercase letters indicate Student's t-test with a two-way analysis of farmer groups and slopes in each sowing date. Uppercase letters indicate Tukey's HSD test for sowing dates, Student's t-test for fields and slopes, with a three-way analysis of sowing dates, fields and slopes.

(3) Furrow sowing on soil moisture and seedling establishment

As a method to retain soil moisture in the plant-root zone, the effect of furrow sowing on emergence and early plant establishment was verified with narrow (width 3 cm, depth 7 cm) and wide (width 10 cm, depth 7 cm) furrows compared to conventional sowing under dry and wet conditions on 7–9 fields during April– June 2015 (Fig. 4).

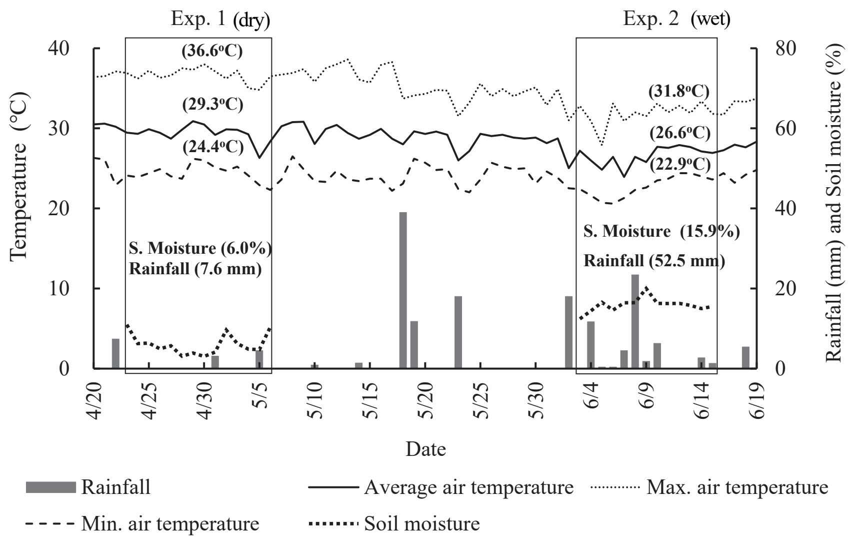

Fig. 4. Daily temperature, soil moisture and rainfall data for Exps. 1 and 2.
Numbers in brackets represent average temperatures, average soil moisture for control and total rainfall in each experiment.

In Exp. 1 under dry conditions, the average soil moisture in both furrows was significantly 2.5% higher than in the control plots. The emergence rate was significantly 15.9–24.6% higher in the furrows and the emergence rate positively correlated with the soil moisture ($r = 0.608$, $p < 0.01$). The time to 50% emergence (T_{50}) was earlier in the narrow furrow than the wide or control. T_{50} negatively correlated with shoot length ($r = -0.832$, $p < 0.001$) and leaf age ($r = -0.751$, $p < 0.001$), indicating that the speed of emergence was associated with seedling growth.

In Exp. 2 under wet conditions, the average soil moisture in both furrows was significantly about 5% higher than in the control plots. The emergence rate was highest in the wide furrow, followed by control and the narrow furrow. T_{50} was significantly earlier in the wide furrow and control than in the narrow furrow. Shoot length was high in the narrow furrow, though it tended to delay the leaf age development under wet conditions, indicating spindly growth.

From the results obtained in these 2 experiments, the relationship between the average soil moisture and emergence rate is shown in Fig. 5. As an overall trend, emergence rate increased as soil moisture increased, up to around 10% soil moisture where the emergence rate reached a saturation plateau. This indicates that up to around 10% of soil moisture, water is the limiting factor for emergence, and furrows effectively increased this due to its moisture-retaining properties. At soil moistures greater than 10%, water deficiency was no longer the limiting factor for emergence and the effect of this on emergence differed between the two furrows. The decrease in emergence in the narrow furrow may be due to soil infill and high moisture, caused by frequent rainfall during Exp. 2. In contrast, emergence rates increased in the wide furrow, despite high soil moisture, indicating that the wide furrow had a greater adaptability to different soil water conditions.

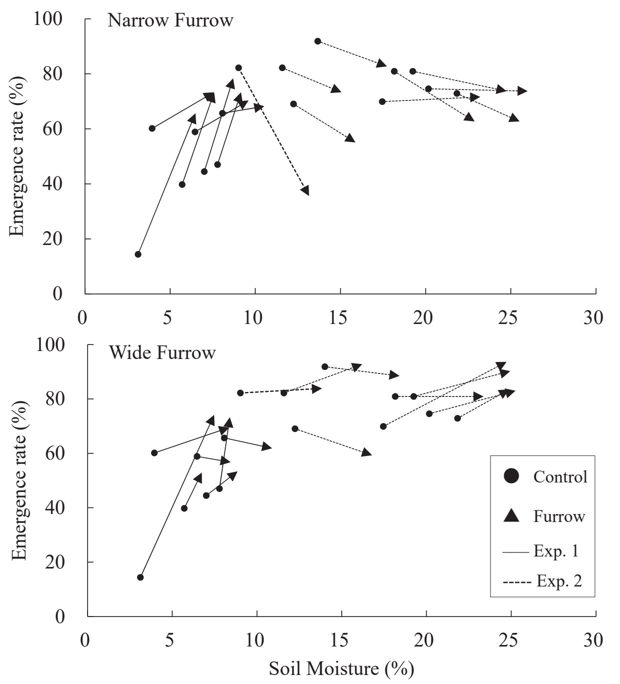

Fig. 5. The effects of furrow sowing on soil moisture and emergence rate in the narrow furrow (upper) and wide furrow (lower) for Exps. 1 and 2.
Circles to arrows show the change from control to furrow treatment in each field.

For improved crop establishment in rainfed fields, the width of the furrow should be chosen according to the expected rain and soil moisture conditions. In dry regions where little rain is expected at the beginning of the season, narrow furrows can be used to hasten emergence and seedling establishment in fields with average soil moistures below 10%. In areas where rainfall is uncertain or erratic, wide furrows can be used as they are more adaptable to different rainfall or moisture conditions and have greater potential in enhancing early growth than control or narrow furrows.

(4) Furrow sowing on soil moisture and yield

The effect of furrow sowing within a ridge-furrow system on yield and soil moisture was verified in 6 upland fields during May–September 2016. During the first 15 days after sow, average soil moisture content was significantly higher than control and the emergence rate increased by 8%.

Throughout the experiment, the average soil moisture content was significantly 1.6% higher in the furrow than in the control plots with a range of 0.1–2.9%. The average total dry weight at heading was significantly 22% higher in the furrow than in the control plots and the average panicle dry weight at maturity was significantly 5% higher in the furrow than in control.

The average yield (t ha^{-1}) was significantly 11% higher in the furrow than in the control, due to a 3% increase in the number of hills (m^{-2}) and an 8% increase in yield (g $hill^{-1}$). The higher yield (g $hill^{-1}$) was attributed to a 2% increase in 1000-grain weight and a 4% increase in filled-grain rate.

Significant improvements in crop establishment and yield components corresponded with significant soil moisture increases during their respective growth periods in each field. Therefore, it was indicated that the main effect of furrow was in increasing soil moisture content.

General discussion

These experiment results suggest that soil moisture is an important yield-limiting factor in rainfed upland rice, and we demonstrated that soil moisture and yields can be significantly improved by temporal and spatial sowing adjustment methods (Fig. 6). Sowing earlier in June could be a good strategy for rice farmers in this region, as the risk of terminal drought can be reduced, and also because of the lower rainfall variability in June than in the later months. Furrow sowing improved soil moisture, resulting in increased number of hills and yield. However, the soil moisture increasing effect was variable between fields and therefore requires further investigation to clarify the field conditions most effective for this method.

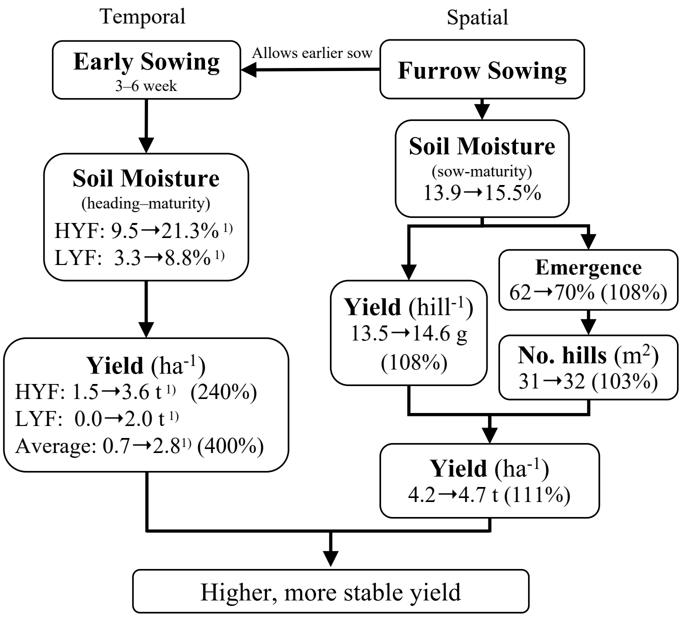

Fig. 6. Schematic description of major findings in the early sowing and furrow sowing experiments.
1) Incresase between date 1 and 2.

Furrow sowing can also be used to facilitate early sowing of rice. Many farmers cultivated cowpea or maize on ridges earlier in the rainy season. If these crops can be harvested before the rice cropping season, the ridge-furrow system can be immediately used for furrow sowing. This could reduce the time and labor normally required for field preparation and allow farmers to sow earlier. Singular or combined use of these sowing methods would be especially beneficial for LYFs, as it may reduce the risks of yield loss due to soil moisture stress caused by late season drought or by their sub-optimal field-water conditions.

References

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