Oxygen Demand Characteristics of Soybean Root System Relevant to Crop Diversification in Paddy Fields

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Since the last decade, crop diversification has been introduced into paddy fields in Japan. Among the field crops employed for the crop diversification, soybean, well-known as a row material for Japanese traditional foods, occupies the widest planted area. Marsh plants, for example, rice plants, have an internal pathway in which atmospheric oxygen diffuses through leaves and stems to roots in order to make them adaptable to marshy soil environment. On the contrary, soybean plants growing under strongly reduced soil conditions wilt to die very rapidly.[14]

Bond[3] reported that evolution of carbon dioxide from the surface of soil in which leguminous plants were growing was appreciably higher than that from the soil carrying other plants, as indicated by oxygen intake or carbon dioxide output; clover=0.558, rye=0.285, seradella=0.305 and mustard=0.218 g CO_2/m^2,h. This difference was caused by the presence of root nodules, a center of active metabolism, in legumes. Therefore, well-nodulated leguminous plants need more oxygen supply to their rhizosphere as compared with cereal crops.

To find out suitable soil management for soybean culture in paddy fields, physiological properties related to oxygen demand of root system and effects of fertilizer nitrogen on growth were investigated. Sorghum was used for comparison. Differential influences of soil physical properties of various soil types on growth of soybean plants were also examined.

Comparison of oxygen uptake by root systems of soybean and sorghum

Soybean, corn, sorghum and Job's tears were grown in pots for one month. Oxygen uptake by root tissues of these plants was measured. As shown in Table 1, detached root nodules consumed 5 times more oxygen than nodule-removed root tissues on fresh weight basis (detached nodules; 30 μl O_2/g,min, nodule-removed roots; 4.3 μl O_2/g,min at 30°C). Rate of oxygen uptake by root tissues of other three crops was much lower (0.8–2.4 μl O_2/g,min at 20–30°C) than that of soybean roots.

Changes in O_2 uptake rate of subterranean parts of soybean and sorghum by growing stages are shown in Fig. 1. In soybean, oxygen uptake increased sharply from the flowering stage (Aug. 15), reaching the maximum at the ripening stage (11.3 ml O_2/h,pot). In sorghum, O_2 uptake reached the maximum at the young-panicle formation stage (Aug. 15) but the value was much lower (2.25 ml O_2/h,pot) than that of soybean, and from this stage it declined gradually toward the ripening stage.

O_2 uptake by the soybean root system from which the nodules were detached was measured. At the ripening stage, O_2 uptake by nodule-

Table 1. Oxygen uptake rate* of subterranean part of four kinds of crop**

Plants		O_2 uptake rate at 20～30°C		
		Subterranean parts (μl-O_2/g-min)	Subterranean parts (μl-O_2/pot-min)	Terrestrial parts (μl-O_2/g-min)
Soybean	roots	2 ～ 4.3	94～250	1.6～4.2
	nodules	10 ～30		
Corn		0.8～ 1.8	97～216	0.5～1.2
Sorghum		1.4～ 2.4	93～156	0.8～1.5
Job's tears		1.6～ 2.8	35～ 62	0.6～1.1

* Fresh weight basis
** These plants were grown in pots for about one month.

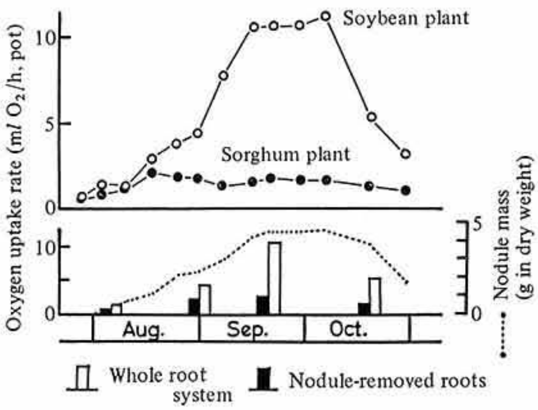

Fig. 1. Oxygen uptake by whole root system of soybean and sorghum plants, and nodule-removed roots of soybean plant

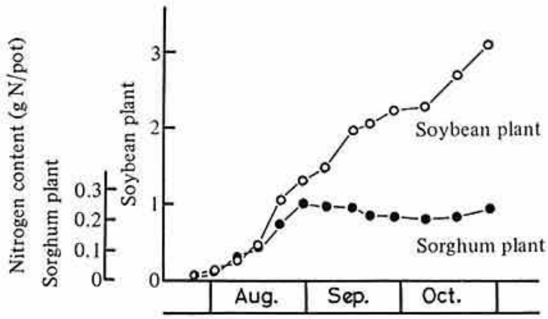

Fig. 2. Nitrogen content of terrestrial part of soybean and sorghum plants
Soybean and sorghum plants were cultivated in pots (1/5,000a) with the application of 0.2 and 3.0 kgN/a, respectively.

removed roots was only one fourth that of nodulated root system. O_2 uptake by whole root system was significantly correlated with dry weight of nodule mass (r=0.953***). These results indicated a high oxygen demand of root nodules.

Nitrogen content of terrestrial part of the both plants at various growing stages was analysed (Fig. 2). Nitrogen content of soybean plants increased sharply at the flowering-early podding stage with the increase in O_2 uptake by root systems and continued to increase toward the maturity stage. In sorghum, however, nitrogen content became maximum at the young-panicle formation stage and kept nearly constant afterwards.

These results show 1) a very close relationship between nitrogen content of plants and respiration of their root systems, which coincides with the result reported by Bond[4] and Mahon,[8] and 2) a strong association between nitrogen fixation and O_2 consumption in soybean root systems.

Effects of O_2 partial pressure on respiration of soybean root systems

Under poor aeration, decrease in O_2 content of soil air is generally greater than increase in CO_2 content, because CO_2 diffuses more rapidly through water films, due to greater solubility of CO_2 in water.[6]

In paddy fields with high water table or upland fields after rainfall, soil air permeability is poor. O_2 content in surface soil (5–10 cm in depth) after rainfall decreased to 14–17%[10] and that in the soil with water table set below 22 cm depth was 2–6%.[11]

In fields with high moisture content, O_2 content of soybean rhizosphere might rapidly decrease due to high O_2 consumption by soybean root system. Effects of partial pressure of O_2 on respiration and nitrogen fixation of the root system were examined (Fig. 3). In this experiment, gas metabolism of nodules and root tissues was measured by the method proposed by Ae and Nishi[1] which employs a new respirometer.

Amount of O_2 uptake and N_2 uptake (nitrogen fixation) of the root nodules increased as oxygen

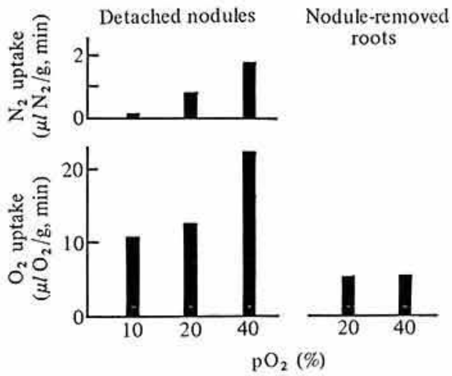

Fig. 3. Effect of partial pressure of O_2 on respiration and nitrogen fixation of root nodules (fresh weight basis, 30°C, at the early-podding stage)

Table 2. **Effects of basal nitrogen application on growth of soybean root systems at and after the flowering stage**

Growing stage	Nitrogen fertilizer (kg N/a)	Shoots (g/pot)	Roots (g/pot)	Nodules Mass (g/pot)	Nodules Number (/pot)
Aug. 20 (Flowering)	0.2	49.4*(11.7)**	20.2 (2.37)	4.94 (1.07)	380
	3.0	64.7 (14.1)	23.9 (2.35)	0.51 (0.07)	226
Aug. 27	0.2	81.7 (17.5)	28.3 (3.10)	6.67 (1.46)	447
	3.0	106.4 (25.2)	39.5 (4.24)	6.40 (1.03)	575
Sept. 10 (Podding)	0.2	123.7 (30.0)	27.3 (4.00)	10.31 (2.17)	545
	3.0	140.2 (34.0)	38.0 (5.25)	12.03 (2.26)	696

* Fresh weight
** Figures in parentheses indicate dry weight.

increased from 10 to 40% by pO_2. But, oxygen uptake by nodule-removed roots was kept constant as far as O_2 pressure was more than 20%-pO_2. Tjepkema and Yocum[13] reported that respiration of nodule-removed roots shows oxygen saturation at 10%-pO_2. Obviously, nitrogen fixation and respiration of nodules are quite sensitive to pO_2 in the soil.

Effect of nitrogen fertilizer on growth and nutrient uptake of soybean roots

Soybean plants were grown in pots (1/5,000a) at three nitrogen levels (0.2, 1.0 and 3.0 kg N/a by ammonium sulfate). Dry weight of nodules, roots and terrestrial parts were measured from the seedling stage to the early-podding stage.

High correlation coefficients were obtained between nodule-removed roots and terrestrial parts at the nitrogen level of 0.2–1.0 kg N/a (r= 0.878***) and 3.0 kg N/a (r=0.796***) as shown in Fig. 4–a. High dose of nitrogen (3.0 kg N/a) produced much more roots from the seedling stage as compared with low dose (0.2–1.0 kg N/a) and this effect was observed until the ripening stage (Fig. 4–c).

Production of root nodules was increased proportionally with the production of terrestrial part by the equation; $Y=a+bX$ (Y: dry weight of nodules, X: dry weight of terrestrial part) (Fig. 4–b).

1) At low nitrogen level
$Y=0.248+0.067X$ (r=0.935***)

Table 3. **Nutrient absorption by root system of soybean plant***

Nitrogen application (kg N/a)	P (ppm)** 0 hr	P (ppm)** 5 hr	NH_4-N** (ppm) 0 hr	NH_4-N** (ppm) 5 hr	NO_3-N** (ppm) 0 hr	NO_3-N** (ppm) 5 hr
0.2	0.25	0.23	3.33	1.31	3.57	2.37
3.0		0.06		0.99		1.15

* Separated root system was soaked in a diluted culture medium for 5 hr.
** Concentration of the culture medium

2) At high nitrogen level
$Y=-1.145+0.099X$ (r=0.944***)

High dose of nitrogen suppressed the growth of *Rhizobium japonicum* on the rhizoplane from the seedling stage to the flowering stage. It is known that nitrate nitrogen prevents nodulation.[5]

It is noteworthy that in Fig. 4–b two regression lines of equation 1) and 2) cross each other at about 40 g of dry weight of terrestrial part which corresponds to the growth at the flowering stage. At the high nitrogen level, the nodulation may continue at the higher rate than that of the low nitrogen level after the flowering stage. This assumption was confirmed by the fact that much more nodulation was actually observed in the high nitrogen level plot (Table 2).

Nutrient absorption from a culture medium by root systems detached from plants grown at two different basal nitrogen levels was measured (Table 3). The greater root system, produced at the high nitrogen level, was able to uptake more P, NO_3–N and NH_4–N than the small one produced at the low nitrogen level.

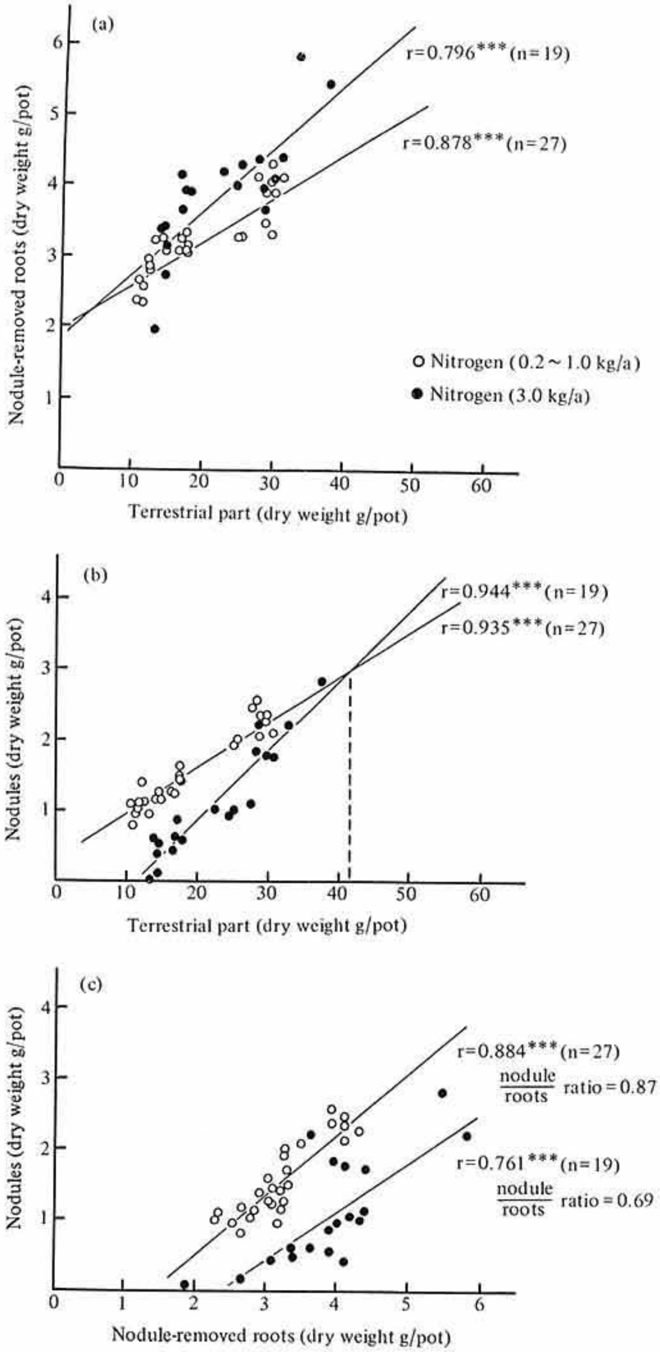

Fig. 4. Relationships among root growth, nodule formation, and growth of terrestrial part of potted soybean plants at two levels of nitrogen application (0.2–1.0 and 3.0 kg-N/a)

(a) Correlation between nodule-removed roots and terrestrial parts
(b) Correlation between nodules and terrestrial parts
(c) Correlation between nodules and nodule-removed roots

Table 4. Physical and chemical properties of paddy soils used in the experiment*

Soil type	Soil texture	pH (H_2O)	T-C (%)	T-N (%)	CEC (me/100g)	Base saturation (%)	Rice plant cultivation without nitrogen fertilizer	
							Grain yield (g/m^2)	Nitrogen uptake (g/m^2)
Strong-gley soil	SCL	5.1	2.31	0.24	18.1	44.6	416	8.6
Gley soil	CL	5.3	2.61	0.25	13.7	70.4	526	12.1
Gray Lowland soil (gray type)	L	6.9	1.02	0.10	13.3	81.8	341	5.8
Gray Lowland soil (grayish brown type)	SiCL	5.3	1.73	0.17	11.8	58.6	369	6.5
Yellow soil	SiCL	5.4	1.84	0.18	16.9	62.9	417	7.7
Andosol	L	5.5	10.3	0.61	32.8	20.3	470	10.5

* Grain yields and nitrogen uptake of rice plants are shown by the average of data from 1970 to 1979.

As for the effect of nitrogen level in basal application on soybean yield in a field experiment, much high yield was obtained by high nitrogen application (0.2 kg N/a; 288 g/m^2, 3.0 kg N/a; 386 g/m^2). Nantakorn et al.,[9] who studied correlations among nodule mass, nodule number, plant dry weight, plant height, seed size and seed yield, found out a good correlation between $N_2(C_2H_4)$-fixation rate and seed yield or between nodule mass and seed yield. Basal application of nitrogen is effective in increasing nodule mass, in maintaining favorable nutrient uptake by root system in the late growing period, and consequently in getting high yields.

As the activity of nitrogen fixation declines in the late ripening stage, many experiments on top-dressing of nitrogen have been carried out in Japan. The author considers that more attention should be focused on the whole root system than on the nodule itself in analyzing the effect of top-dressing. It is doubtful that the top-dressing is fully effective for nutrient uptake of soybean plants with inferior root growth caused by low rates of basal application of nitrogen.

Effects of physical properties of paddy soils on soybean yields

In order to evaluate rice productivity as related to several soil types of paddy fields distributed in Chugoku district in Japan, a lysimeter experiment has been carried out since 1970. Physical and chemical properties of the soils and rice yields obtained without nitrogen application were listed in Table 4.

The Gley soil was characterilized by releasing soil nitrogen at the highest level throughout the rice growing period and gave the highest yield. On the other hand, the grayish soil showed the lowest nitrogen supply of the soils used. The rice yields were significantly correlated with the amount of available soil nitrogen.[2]

In 1979, soybean was grown on the lysimeter under a high soil moisture condition (constant water table; 20 cm). Bulk density, hydraulic conductivity, air space at pF 1.5 and O.D.R. (oxygen diffusion rate) were measured during the soybean growing period. Effects of these physical properties of the soil on the growth of soybean plants were examined statistically Table 5).

No correlation was found between nitrogen uptake and soybean yields, unlike the case of rice yields; $r=0.576$ for soybean and $r=0.988$*** for rice. Although bulk density, hydraulic conductivity and air space at pF 1.5 varied considerably according to soil types, there was no correlation between these physical properties and soybean yields. However, the yields were significantly correlated with O.D.R.

Stolzy and Letey[12] demonstrated that root growth was closely related to O.D.R. values. Lippe and Fox[7] found out how quickly oxygen content of soil atmosphere in a lucern field was altered by root respiration. The dependence of soybean yields on O.D.R. of soils can be explained by the fact that nitrogen fixation and respiration of root nodules depend on oxygen concentration of soil air. As for the differences of soil types, volcanic ash soil (andosol) had specifically low

Table 5. Effects of physical properties of soils on soybean yields

Soil type	Bulk density	Solid volume (%)	Air space at pF 1.5 (%)	Aug. 30 Air volume (%)	Aug. 30 Hydraulic conductivity (ml/cm^2-sec)	Aug. 30 O.D.R. ($10^{-8}/cm^2$-min)	Oct. 3 Mn^{++} (mg/100g)	Soybean cultivation* Seed yield (g/m^2)	Soybean cultivation* Nitrogen uptake (g/m^2)
Strong-gley soil	1.19	46.0	9.3	18.1	5.11×10^{-3}	10.95	0.79	423	35.6
Gley soil	1.20	46.5	7.3	6.5	3.28×10^{-5}	10.52	0.65	397	39.1
Gray Lowland soil (gray type)	1.27	48.4	11.3	17.4	2.99×10^{-3}	15.61	0.70	418	30.8
Gray Lowland soil (grayish brown type)	1.18	45.0	8.6	14.2	3.40×10^{-3}	11.45	0.72	407	42.7
Yellow soil	1.19	45.9	5.7	12.8	5.40×10^{-4}	17.13	0.91	478	44.2
Andosol	0.67	28.4	4.9	6.8	2.91×10^{-4}	4.34	1.82	363	32.4
Seed yield correlation (r=)	0.664	0.646	0.103	0.494	0.126	0.888*	—	1.000	0.567

* The soils were adjusted to pH 6.5 by $CaCO_3$ before seeding soybean. Soybean plants were grown with application of 0.2 kg N/a under wet soil condition with water table at 20 cm depth.

O.D.R. It was also estimated that redox-potential of this soil under the soybean cultivation was low, judging from a high Mn^{++} content. These results strongly suggest that andosol possesses unfavorable physical properties for soybean croppin g. This may b one of the reasons for poor soybean production on Andosol.

As the conclusion of the present study, emphasis must be placed on the following points in establishing rational cultural techniques of soybean for crop diversification on paddy fields:

1) Application of basal nitrogen to promote active metabolism of whole root systems of soybean plants.

2) Improvement of soil physical properties to maintain good oxygen permeability and/or O.D.R.

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