発根能力からみた夏作イネ科作物の湛水条件における生育反応の比較

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Comparison of Growth Responses to Waterlogging of Summer Cereals with Special Reference to Rooting Ability

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Abstract : The responses of nodal rooting and partitioning of dry matter between shoot and roots were compared among nine species of summer cereals under waterlogging of short-term (seedling stage) and long-term (from seedling to heading) treatments. The crops used showed a general tendency to increase the number of roots from the main stem under both treaments. On the basis of rooting response to the long-term treatment, the crops were classified into three groups as follows ; a crop which decreased the total root number (foxtail millet), crops which slightly decreased the total root number, but increased the root number per main stem (common millet, pearl millet), crops which increased the total root number (rice, finger millet, Job's tears, Japanese barnyard millet, sorghum, maize). The last group was further divided into two subgroups as follows ; crops with tillers (rice, finger millet, Job's tears, Japanese barnyard millet) and crops without tillers (sorghum, maize). The change of the nodal root number was generally associated with the relative changes of dry matter partitioning to roots under waterlogged conditions. The rooting responses to waterlogging of the summer cereals were discussed in relation to their waterlogging tolerances evaluated on the basis of the changes in dry matter production and transpiration coefficient under waterlogged conditions examined in the previous study[8].
Key words : Dry matter partitioning, Nodal root, Root number, Summer cereals, Waterlogging tolerance.

発根能力からみた夏作イネ科作物の湛水条件における生育反応の比較：河野恭広・山内　章・野々山利博*・巽　二郎（名古屋大学農学部）

要　旨：9種の夏作イネ科作物を用い，湛水と対照条件に対する生育反応を，節根数と地上部・根部間の乾物分配に注目して，幼植物期（短期処理）と出穂期（長期処理）の個体で比較した．アワを除く全ての作物の主桿からの節根数は，処理により増加した．アワは短期処理で節根数を増加し，長期処理で減少した．長期処理に対する発根反応に基づき，作物は次の群に分けえた．1) 全根数を減じた作物（アワ），2) 主桿からの発根数を増すが，全根数をわずかに減じた作物（キビ，トウジンビエ），3) 全根数を増加した作物（イネ，シコクビエ，ハトムギ，ヒエ，モロコシ，トウモロコシ）．第3群は分けつの有無によって，a) イネ・シコクビエ・ハトムギ・ヒエと，b) モロコシ・トウモロコシに分けえた．長期処理で地上部/根重比は，第2と第3-a群で減じ，第1と第3-b群で増加した．植物体重は第3-a群では減少程度が小さく，むしろ増加するものもあったが，第2と第3-b 群では減少した．第1群では植物体重の減少は，根への乾物分配の減少のみならず発根数の減少を伴なった．全体として発根数の増減は，根への乾物分配割合の増減を伴なった．長期と短期処理における各作物の共通品種の発根反応を比較すると，概して湛水期間の延長によって個体当たりでも，主桿当たりでも節根数の増加割合が大きくなった．唯一の例外はアワであった．このように，湛水条件に対する発根反応は，作物の発育段階のみならず湛水期間の長さによっても変化した．
キーワード：乾物分配，根数，節根，耐湿性，夏作イネ科作物．

It has been reported that some of woody plants[4] and field crops increased adventitious roots[1,2,7,10~12] together with the proceeding of cortical disintegration causing the formation of aerenchyma when grown under waterlogged soil. This growth response is believed to be a sort of the adaptation to waterlogging.

Although the magnitude of aerenchyma development has been well investigated on various crops [1,5,6,11] grown in waterlogged soil, the rooting ability of adventitious roots under waterlogged conditions has not been studied thoroughly, particularly for crops of graminaceous species.

In a previous study[8], we evaluated the waterlogging tolerance of summer cereals based on the dry matter production and water-use efficiency under waterlogged conditions. Besides, the rooting ability is also believed to

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be one of the key characters of crops[3,7] by which they tolerate waterlogged soil.

Thus, in this paper, we examined the formation of nodal roots, and the partitioning of dry matter between shoot and roots of nine species of summer cereals in waterlogged soil, and discussed the results in relation to their waterlogging tolerances.

Materials and Methods

Two experiments were carried out under outdoor conditions at Nagoya University in 1984. Experiment 1 was conducted by maintaining the waterlogged conditions for 12—29 days after the 4th leaf stage. Experiment 2 was conducted by maintaining the waterlogged conditions from the 4th leaf stage to heading stage.

1. *Sowing and treatment.* Plastic Wagner pots (1/2,000 a) were filled with Kisogawa sandy loam soil mixed with 5 g of a compound fertilizer (N, 12%; P, 16%; K, 14%) as a basal manure. In Exp. 1, pregerminated seeds of the cultivars of nine species shown in Table 1, were sown in the pots on May 18. On June 4, when most of the plants had emerged the 4th leaf, the seedlings were thinned into three plants per pot, then waterlogging was started and continued for 29 days (short-term treatment). Half number of the pots of each cultivar were prepared for the W-plot (waterlogged conditions) and the others for the C-plot (moderate soil moisture conditions). The pots for the W-plot were plugged up and filled with water. The water level in each pot was maintained at 3 to 5 cm above the soil surface until harvest. The pots for the C-plot were left drained with daily watering. Seeds of the cultivars of Job's tears and foxtail millet were sown again on June 4, because the seedlings were injured by insects. Therefore, the waterlogging treatment for these two plants was started on June 21, and continued for 12 days.

In Exp. 2, seeds of cultivars of each species shown in Table 2 were sown on July 5, and thinned into three plants per pot on July 19. Then the waterlogging treatment was started in the same manner as described in Exp. 1 and the treatment continued for 28—72 days until harvest (long-term treatment). On August 22, 3 g of the same fertilizer as mentioned above were top-dressed per pot.

2. *Harvest and measurement.* Plants of Exp. 1 were harvested on July 3 and plants of Exp. 2 were harvested one week after heading of each species (Table 2). The roots were washed to remove soil with a gentle stream of tap water. Then the plants were carefully divided into the main stems and tillers. After counting the number of nodal roots emerging from the main stem and tillers separately, the roots were cut apart from their mother shoots. The plant parts were dried in an oven at 90°C for 3 days, and their dry weights were measured. Root dry weight was determined by the ashing method reported previously[8,9].

Results

1. *Effect of waterlogging on the emergence of nodal roots.* Table 1 shows the response of the plants to the short-term treatment in the number of nodal roots emerging from the main stem and tillers at the seedling stage (Exp. 1).

The number of nodal roots emerging from the mother stem was increased by the waterlogging treatment in all crops except common millet. Especially in lowland rice, finger millet, Job's tears, Japanese barnyard millet and maize, their mean root numbers increased by more than 30%, judging from the mean value of each crop. In contrast, the increment was less than 10% in pearl millet and sorghum. Only in common millet, the mean root number decreased slightly due to a significant decrease in one of the varieties (Gifu).

The number of tiller roots increased in crops which developed tiller shoots in the W-plot. In finger millet and pearl millet the number of tiller roots and that of tiller shoots decreased. On the contrary, in upland rice, Job's tears and Japanese barnyard millet, the number of tiller roots increased in spite of the decrement of tiller shoot number. This indicates that not only the root number per main stem, but also the root number per tiller shoot increased by the treatment in these crops. Besides, the same trend was found in lowland rice. The total number of roots per plant increased as a result of the treatment in all crops except common millet and pearl millet. In pearl millet a reduction in the total root number per plant was due to the depression of tiller development because the root number of main stem of this crop was slightly increased.

Table 2 shows the results of the long-term

Table 1. Effects of waterlogging on the emergence of nodal roots of nine species of summer cereals (Exp. 1).

Crops (cv/source)	plot	Main stem Number of Leaves	Main stem Number of Roots	Tiller Number of Shoots	Tiller Number of Roots	Total number of roots
Lowland rice (japonica) (*Oryza sativa* L.)						
Nipponbare	C	9.5	55.7	5.7	57.0	112.7
	W	10.7	52.7 (95)	14.3*	211.3* (370)	264.0* (234)
Koshihikari	C	9.3	46.3	2.7	12.3	58.7
	W	10.6	77.3* (167)	14.7*	216.0* (176)	293.3* (500)
Kinmaze	C	10.7	50.0	16.0	181.0	231.0
	W	10.8	91.7* (123)	19.3	297.7 (164)	377.3* (163)
Mean	C	9.8	50.1	8.1	83.4	134.1
	W	10.7	73.9 (148)	16.1	241.7 (290)	311.5 (232)
Lowland rice (indica) (*Oryza sativa* L.)						
Karalath	C	8.8	41.7	4.7	26.3	68.0
	W	10.4	53.0* (127)	4.3	48.0* (183)	100.3 (148)
Te-tep	C	10.7	36.0	6.0	36.7	72.7
	W	11.2	58.0* (161)	10.0*	190.0* (518)	248.0* (341)
Ko-sen	C	9.1	34.7	9.0	80.7	136.3
	W	9.5	63.7* (155)	18.3*	141.3 (175)	205.0 (150)
Mean	C	9.5	37.5	6.6	47.9	92.3
	W	10.4	58.2 (155)	10.9	126.4 (292)	184.4 (200)
Upland rice (*Oryza sativa* L.)						
Norin 11	C	10.0	33.7	11.3	94.7	127.3
	W	10.2	59.0* (175)	11.7	127.0 (134)	186.0 (146)
Norin 7	C	10.9	72.7	9.3	142.7	215.3
	W	9.5	59.7 (82)	7.0	67.7* (47)	127.3* (59)
Norin 21	C	10.6	52.5	15.0	86.0	138.5
	W	10.7	71.0 (135)	12.0	170.0 (198)	241.0 (174)
Mean	C	10.5	53.0	11.9	107.8	160.4
	W	10.1	63.2 (119)	10.2	121.6 (113)	184.8 (115)
Finger millet (*Eleusine coracana* (L.))						
Gifu	C	17.E	18.3	3.7	38.3	56.7
	W	18.E	27.3* (149)	2.3*	41.0 (107)	68.3* (120)
Gunma	C	18.E	14.7	3.7	44.7	59.3
	W	17.E	28.3* (193)	2.3	45.0 (101)	73.3 (124)
Okayama	C	18.E	21.0	6.3	65.0	86.0
	W	18.E	43.7* (208)	3.0*	52.3 (80)	96.3 (112)
Mean	C	18.E	18.0	4.6	49.3	67.3
	W	18.E	33.1 (184)	2.5	46.1 (94)	79.3 (118)
Job's tears (*Coix lacrima-jobi* L.)						
Kyoto	C	8.E	12.7	2.3	2.3	14.7
	W	8.E	16.7* (131)	1.0	2.7 (135)	19.3* (131)
Saga	C	8.E	15.3	2.0	1.0	16.3
	W	8.E	14.7 (96)	2.0	3.0* (300)	17.7 (110)
Niigata	C	8.E	11.0	2.3	5.0	16.0
	W	8.E	20.3* (185)	1.0*	2.7* (54)	21.7* (136)
Mean	C	8.E	13.0	2.2	2.7	15.7
	W	8.E	17.2 (132)	1.3	2.8 (104)	19.6 (125)

(Table 1 Continued)

Japanese barnyard millet (*Echinochloa utilis* Ohwi *et* Yabuno)						
Okayama	C	14.E	65.0	5.7	81.7	147.0
	W	14.E	86.3 (133)	4.3	132.3 (162)	218.7 (149)
Hidaakabie	C	14.E	63.0	4.7	80.7	147.0
	W	14.E	86.0 (137)	2.7*	85.3 (106)	171.3 (117)
Chosen	C	13.E	45.0	7.0	123.7	168.7
	W	14.E	85.0* (189)	3.3*	113.0 (91)	197.3 (117)
Mean	C	14.E	57.7	5.8	95.4	154.2
	W	14.E	85.8 (149)	3.4	110.2 (116)	95.8 (127)
Common millet (*Panicum miliaceum* L.)						
Saitama	C	15.E	38.0	2.0	10.7	48.7
	W	14.E	42.0 (111)	0.0*	0.0* (0)	42.0 (86)
Gifu	C	14.E	42.7	2.0	15.3	58.0
	W	12.E	30.0* (70)	0.0*	0.0* (0)	30.0* (52)
Shinano 1	C	12.E	39.7	2.3	24.0	63.7
	W	12.E	43.0 (108)	0.0*	0.0* (0)	43.0* (68)
Mean	C	14.E	40.1	2.1	16.7	56.8
	W	13.E	38.3 (96)	0.0	0.0 (0)	38.3 (67)
Pearl millet (*Pennisetum typhoideum* L.)						
Miyazaki	C	15.E	38.3	3.7	21.7	60.0
	W	13.E	41.0 (107)	0.7*	5.0* (23)	46.0 (77)
Foxtail millet (*Setaria italica* Beauv.)						
Gifu	C	9.E	8.3	0.0	0.0	8.3
	W	8.E	10.7 (129)	0.0	0.0	10.7 (129)
Sorghum (*Sorghum bicolor* Moench)						
Saitama	C	12.E	25.3	0.0	0.0	25.3
	W	12.E	26.0 (103)	0.0	0.0	26.0 (103)
Iwate	C	13.E	23.0	0.0	0.0	23.0
	W	12.E	22.7 (99)	0.0	0.0	22.7 (99)
Aichi	C	11.E	26.7	0.0	0.0	26.7
	W	10.E	30.3 (113)	0.0	0.0	30.3 (113)
Mean	C	12.E	25.0	0.0	0.0	25.0
	W	11.E	26.3 (105)	0.0	0.0	26.3 (105)
Maize (*Zea mays* L.)						
Golden cross bantam	C	14.E	32.3	0.3	1.7	34.0
	W	11.E	41.7 (129)	0.0	0.0 (0)	41.7 (123)
Shimokibi	C	13.E	33.7	0.0	0.0	33.7
	W	11.E	43.0* (128)	0.0	0.0	43.0* (128)
Koshushu	C	14.E	36.7	0.3	1.3	38.0
	W	12.E	58.3* (159)	0.0	0.0 (0)	58.3* (153)
Pop corn	C	14.E	21.7	0.0	0.0	21.7
	W	13.E	27.3 (126)	0.0	0.0	27.3 (126)
Mean	C	14.E	31.1	0.2	0.8	31.9
	W	12.E	42.6 (137)	0.0	0.0 (0)	42.6 (134)

Note. n.E. shown in number of leaves of main stem means that the n-th leaf was emerging. Numerals in parentheses show the percentages to the C-plot. Roots represent nodal roots.
* indicates significant difference between the W- and the C-plots at 5% level within each cultivar (n=3 to 6).

Table 2. Effects of waterlogging on the emergence of nodal roots of nine species of summer cereals (Exp. 2).

Crops (cv/source)	plot	Main stem: Heading Date	Main stem: Number of Roots	Tiller: Number of Shoots	Tiller: Number of Roots	Total number of roots
Lowland rice	C	Sep. 5	64.7	10.7	184.7	249.4
(Nipponbare)	W	Sep. 4	89.0 (138)	16.7*	538.3*	627.3* (252)
Upland rice	C	Sep. 15	63.7	9.0	170.3	234.0
(Norin 11)	W	Sep. 13	91.0* (143)	10.3	227.7*	318.7* (136)
Finger millet	C	Sep. 17	47.7	3.7	95.0	142.7
(Gifu)	W	Sep. 21	96.7* (203)	2.0*	177.0*	273.7* (192)
Job's tears	C	Aug. 23	24.3	3.3	12.7	37.0
(Kyoto)	W	Aug. 26	31.7* (130)	3.0	26.0	57.7 (156)
Japanese	C	Sep. 1	83.3	2.3	97.7	181.0
barnyard millet	W	Sep. 1	162.3* (195)	2.3	156.7	319.0* (176)
(Okayama)						
Common millet	C	Aug. 30	50.3	2.0	33.7	84.0
(Saitama)	W	Aug. 29	79.3* (158)	0.0*	0.0*	79.3 (94)
Pearl milet	C	Aug. 26	43.7	4.0	22.3	66.0
(Miyazaki)	W	Sep. 23	61.7* (141)	0.0*	0.0*	61.7 (93)
Foxtail millet	C	Aug. 10	63.3	0.3	5.7	69.0
(Gifu)	W	Aug. 16	33.0* (52)	0.0	0.0	33.0* (48)
Sorghum	C	Aug. 23	39.3	0.0	0.0	39.3
(Saitama)	W	Sep. 9	55.0* (140)	0.0	0.0	55.0* (140)
Maize (Golden	C	Aug. 16	30.7	0.0	0.0	30.7
cross bantam)	W	Aug. 25	49.7* (162)	0.0	0.0	49.7* (162)

Note. Heading date of maize shows the emergence of tassel.
*See Table 1. Numerals in parentheses show the percentages to the C-plot.

treatment (Exp. 2). All the crops increased the number of nodal roots emerging from the main stem as a result of the treatment, except for foxtail millet. Foxtail millet significantly decreased the root number by the treatment. The crops except for common millet, pearl millet and foxtail millet also increased the total root number per plant under waterlogging.

Although the responses in root number on the main stem, tiller number, tiller root number and total root number in Exp. 2 for the long-term treatment are generally similar to the results obtained in Exp. 1, the following three differences were found: (1) when a comparison is made between the common variety used in Exp. 1 (Table 1) and in Exp. 2 (Table 2), the extent of increase of the root number per main stem, as well as per plant, were greater in Exp. 2 than in Exp. 1; (2) in common millet and pearl millet the extent of decrease in total root number per plant by the treatment was smaller as compared to that in Exp. 1. This was due to the increment of root number on the main stem by the prolonged waterlogging; (3) in foxtail millet both the root number per main stem and the total root number per plant decreased by around 50% by the long-term treatment in Exp. 2,

Table 3. Effects of waterlogging on the partitioning of dry matter between shoot and roots of nine species of summer cereals (Exp. 1).

Crops (cv/source)	Plot	Dry weight: Shoots (g/plant)	Roots (g/plant)	Total (g/plant)	Single root (mg)	Shoot/root ratio
Lowland rice (japonica)						
Nipponbare	C	3.97	0.90	4.87	8.0	4.4
	W	11.66 (295)	1.73 (192)	13.39 (275)	6.6	6.7
Koshihikari	C	1.98	0.62	2.60	10.6	3.2
	W	12.71 (642)	2.44 (394)	15.15 (583)	8.3	5.2
Kinmaze	C	11.05	2.08	13.13	9.0	5.3
	W	12.21 (110)	2.50 (120)	14.71 (112)	6.6	4.9
Mean	C	5.67	1.20	6.87	8.9	4.7
	W	12.19 (349)	2.22 (235)	14.41 (210)	7.1	5.5
Lowland rice (indica)						
Karalath	C	4.55	0.90	5.45	13.2	5.1
	W	5.35 (118)	0.89 (99)	6.24 (144)	8.9	6.0
Te-tep	C	10.11	0.86	10.97	11.8	11.8
	W	12.89 (127)	2.35 (273)	15.24 (139)	9.5	5.5
Ko-sen	C	9.24	2.36	11.60	17.3	3.9
	W	7.47 (81)	1.58 (67)	9.05 (78)	7.7	4.7
Mean	C	7.97	1.37	9.34	14.8	5.8
	W	8.57 (109)	1.61 (146)	10.18 (109)	8.7	5.3
Upland rice						
Norin 11	C	17.09	3.11	30.38	24.4	5.5
	W	14.90 (87)	2.55 (82)	17.45 (86)	13.7	5.8
Norin 7	C	14.62	2.54	17.16	11.8	5.8
	W	12.16 (83)	2.63 (104)	14.79 (86)	20.7	4.6
Norin 21	C	10.21	2.35	12.56	17.0	4.3
	W	14.18 (139)	2.27 (97)	16.45 (131)	9.4	6.3
Mean	C	13.97	2.67	16.64	16.6	5.2
	W	13.75 (103)	2.48 (94)	16.23 (98)	13.4	5.5
Finger millet						
Gifu	C	23.64	3.64	27.28	64.2	6.5
	W	9.64 (41)	1.85 (51)	11.49 (42)	27.1	5.2
Gunma	C	26.34	5.12	42.95	86.3	5.1
	W	13.86 (53)	2.12 (41)	15.98 (51)	28.9	6.5
Okayama	C	30.15	6.53	36.68	75.9	4.6
	W	12.60 (42)	2.68 (41)	15.28 (42)	27.8	4.7
Mean	C	26.71	5.10	47.09	75.8	5.2
	W	12.03 (45)	2.22 (44)	14.25 (45)	28.0	5.4
Job's tears						
Kyoto	C	2.86	1.27	18.38	86.4	2.3
	W	2.51 (88)	0.83 (65)	3.34 (81)	43.0	3.0
Saga	C	1.61	0.82	2.43	50.3	2.0
	W	2.87 (178)	1.42 (173)	4.29 (177)	80.2	2.0
Niigata	C	2.55	1.12	3.67	70.0	2.3
	W	2.33 (91)	1.04 (93)	3.37 (92)	47.9	2.2
Mean	C	2.34	1.07	3.41	68.2	2.2
	W	2.57 (119)	1.10 (110)	3.67 (108)	56.1	2.3

(Table 3 Continued)

Japanese barnyard millet						
Okayama	C	53.96	18.53	76.16	126.1	2.9
	W	52.92 (98)	14.79 (80)	67.71 (93)	67.6	3.6
Hidaakabie	C	56.19	15.26	71.45	103.8	3.7
	W	44.55 (79)	12.36 (81)	56.91 (80)	72.2	3.6
Chosen	C	63.80	14.82	78.62	87.8	4.3
	W	51.18 (80)	16.98 (115)	68.16 (87)	86.1	3.0
Mean	C	57.98	16.20	74.18	105.1	3.6
	W	49.55 (86)	14.71 (92)	64.26 (87)	75.1	3.4
Common millet						
Saitama	C	24.77	4.84	29.61	99.4	5.1
	W	4.79 (19)	0.63 (13)	5.42 (18)	15.0	7.6
Gifu	C	28.56	5.17	33.73	89.1	5.5
	W	4.68 (16)	0.54 (10)	5.22 (15)	18.0	8.7
Shinano 1	C	22.27	4.25	26.52	66.7	5.2
	W	3.82 (17)	0.56 (13)	4.38 (17)	13.0	6.8
Mean	C	25.20	4.75	29.95	83.6	5.3
	W	4.43 (17)	0.58 (12)	5.01 (17)	15.1	7.6
Pearl millet						
Miyazaki	C	43.46	8.64	52.10	1440.0	5.0
	W	4.30 (10)	1.15 (13)	5.45 (10)	25.0	3.7
Foxtail millet						
Gifu	C	0.79	0.10	0.89	12.0	7.9
	W	0.40 (51)	0.05 (50)	0.45 (51)	4.7	8.0
Sorghum						
Saitama	C	17.10	4.44	21.54	175.5	3.9
	W	5.42 (32)	1.21 (27)	6.63 (31)	46.5	4.5
Iwate	C	17.84	3.55	21.39	154.3	5.0
	W	6.74 (38)	1.17 (33)	7.91 (37)	51.5	5.8
Aichi	C	19.50	7.20	26.70	269.7	2.7
	W	5.37 (28)	1.68 (23)	7.05 (26)	55.4	3.2
Mean	C	18.15	5.06	23.21	202.4	3.6
	W	5.84 (33)	1.35 (28)	7.19 (31)	51.3	4.3
Maize						
Golden cross bantam	C	45.88	11.12	57.00	327.1	4.1
	W	14.66 (32)	2.69 (24)	17.35 (30)	64.5	5.5
Shimokibi	C	28.07	5.79	33.86	171.8	4.8
	W	13.24 (47)	3.43 (59)	16.67 (49)	79.8	3.9
Koshushu	C	88.46	30.72	119.18	808.4	2.9
	W	8.00 (9)	1.24 (4)	9.24 (8)	21.3	6.5
Pop corn	C	50.34	13.65	63.99	629.0	3.7
	W	11.19 (22)	2.05 (15)	13.24 (21)	75.1	5.5
Mean	C	53.19	15.32	68.51	480.3	3.5
	W	11.77 (28)	2.35 (26)	14.12 (21)	55.2	5.0

Note. Roots and single root represent nodal root(s).
Shoots and roots include tillers, if tillers are presented.
Numerals in parentheses show the percentages to the C-plot.

Table 4. Effects of waterlogging on the partitioning of dry matter between shoot and roots of nine species of summer cereals (Exp. 2).

Crops (cv/source)	Plot	Dry weight: Shoots (g/plant)	Roots (g/plant)	Total (g/plant)	Single root (mg)	Shoot/root ratio
Lowland rice	C	66.82	11.47	78.29	46.0	5.8
(Nipponbare)	W	92.89 (139)	18.27 (159)	111.16 (143)	29.1	5.1
Upland rice	C	139.54	23.07	162.61	98.6	6.1
(Norin 11)	W	141.74 (102)	25.85 (112)	167.59 (103)	81.1	5.5
Finger millet	C	173.14	32.34	205.48	226.6	5.4
(Gifu)	W	150.27 (87)	29.51 (91)	179.78 (87)	107.8	5.1
Job's tears	C	80.52	21.02	101.54	568.1	3.8
(Kyoto)	W	53.38 (66)	16.83 (80)	70.21 (69)	291.7	3.2
Japanese	C	107.35	35.09	142.44	193.9	3.1
barnyard millet (Okayama)	W	90.60 (84)	37.16 (106)	127.76 (90)	116.5	2.4
Common millet	C	74.60	11.82	86.42	140.7	6.3
(Saitama)	W	10.26 (14)	2.11 (18)	12.37 (14)	26.6	4.9
Pearl millet	C	133.00	18.83	151.83	285.3	7.1
(Miyazaki)	W	12.27 (9)	1.99 (11)	14.26 (9)	32.3	6.2
Foxtail millet	C	32.81	4.73	37.54	68.6	6.9
(Gifu)	W	1.28 (4)	0.12 (3)	1.40 (4)	3.6	10.7
Sorghum	C	72.40	10.26	82.66	261.1	7.1
(Saitama)	W	27.00 (37)	3.66 (36)	30.66 (37)	66.5	7.4
Maize	C	74.40	24.83	99.23	808.8	3.0
(Golden cross bantam)	W	17.03 (23)	1.84 (3)	18.87 (19)	37.0	9.3

Note. Roots and single root represent nodal root(s).
Shoots and roots include tillers, if tillers are presented.
Numerals in parentheses show the percentages to the C-plot.

although these values were increased by 29% in Exp. 1 for the short-term treatment. The differences in the response found in common millet and pearl millet indicate that common millet and pearl millet could adaptively increase the root number under prolonged waterlogging. In contrast in foxtail millet the rooting ability was temporally enhanced by the short-term treatment, thereafter the rooting ability declined by the prolonged waterlogging.

2. *Effects of waterlogging on the production of dry matter and its partitioning between shoot and roots.* It was shown in Table 3 (Exp. 1) that the mean plant weight decreased considerably by the treatment in common millet, pearl millet, sorghum and maize, while the plant weight was scarcely affected in rice, Job's tears and Japanese barnyard millet. This trend in plant weight was clearer in data obtained in Exp. 2 for the long-term treatment (Table 4).

The S/R ratios (shoot/root ratio) in the mean value of the following crops were clearly increased by the short-term treatment (Table 1) ; common millet, sorghum and maize. In other crops the effects of the treatment on the ratio were very small. As shown in Table 4 (Exp. 2), the S/R ratios in all the crops except for foxtail millet and maize, were decreased by the long-term treatment. This indicates that the prolonged waterlogging tends to increase relatively the partitioning of dry matter to roots, as compared with that to shoot. However, on the contrary, S/R ratio in foxtail millet and maize was increased more than 150% by the treatment. Especially in maize, root growth was severely depressed to 7.4% of control plants (C-plot). This severe depression in maize root might be partly due to the damage by reducing substances such as hydrogen sulfide evolving in waterlogged soil because many of the roots were observed to be dark colored.

Discussion

All the crops used in this study headed their ears and completed maturation under the waterlogged conditions. This growth of the summer cereals is different from some other species[4,7] which eventually perished under prolonged waterlogging, although they showed the adaptive response of temporal rise of adventitious rooting and increase of porosity in stem and root.

As shown in Table 2 the total number of roots per plant increased in rice, finger millet, Job's tears, Japanese barnyard millet, sorghum and maize under waterlogged conditions. This indicates that the rooting ability of these crops is greater than that of the other crops under the long-term waterlogging. In common millet and pearl millet, though the root number per main stem increased considerably, the total number of roots per plant did not increase since tiller was absent or tiller development was strongly depressed under waterlogging. In foxtail millet total root number per plant as well as root number per main stem decreased significantly. This suggests that the rooting ability of foxtail millet under waterlogging is smaller than the other crops examined.

Thus, the crops examined in the present study can be classified into three groups on the basis of response of rooting to the long-term waterlogging as follows : 1) a crop in which the total root number decreased, *i.e.*, foxtail millet ; 2) crops whose total root number slightly decreased, *i.e.*, common millet and pearl millet ; 3) crops whose total root number increased, *i.e.*, rice, finger millet, Job's tears, Japanese barnyard millet, sorghum and maize. The last group is further divided into two subgroups as follows ; a) crops with tillers (rice, finger millet, Job's tears and Japanese barnyard millet) and b) crops without tillers (sorghum and maize).

It was shown in Table 4 that dry matter production (plant weight) of crops in group 3-a was not greatly depressed or even accelerated, while in the other groups it was greatly depressed under waterlogging. This indicates that in crops of group 3-a the enhancement of rooting played an important role in dry matter production, while in crops of group 3-b and 2, dry matter production was depressed in spite of the enhancement of rooting. The single root weight was obtained by dividing the dry weight of roots of a plant by the total root number (Table 4). The single root weight represents root development in terms of length or the extent of branchings. In the crops of group 3-b and 2, single root weight was strongly depressed as compared with that of crops of group 3-a under waterlogging. This seems to indicate that the single root weight is closely related to dry matter production of crops under waterlogged conditions.

As shown in Table 4 the increment of root number was associated with the slight increment of dry matter partitioning to the roots in the crops of group 3-a and 2. In foxtail millet (group 1) the decrement of root number was associated with the decrease of dry matter partitioning to the roots. This indicates that the change in dry matter partitioning is closely related to the development of the roots. In contrast, in crops of group 3-b (sorghum and maize) the root number increased, in spite of the decrease of the dry matter partitioning to roots under waterlogged conditions. As for maize it may be possible that the dry matter partitioning to roots relatively increased under waterlogged conditions, but the root dry weight determined was underestimated due to the root rot observed at harvest, as stated in the results. Yet, this interesting phenomenon observed in sorghum needs further investigation since root rot was not observed in sorghum under waterlogged conditions.

In the previous study[8], we evaluated the waterlogging and drought tolerances of summer cereals on the basis of the changes of dry matter production and transpiration coefficient under different soil moisture conditions. We classified the summer cereals examined into four groups as follows : (1) the species very susceptible to drought conditions (D) and tolerable to waterlogged conditions (W) ; lowland and upland rice, and Job's tears, (2) the species relatively tolerable to both W and D ; finger millet and Japanese barnyard millet, (3) the species relatively susceptible to W and tolerate to D ; common millet, pearl millet, sorghum and maize, (4) the species very susceptible to W and tolerable to D ; foxtail millet.

In comparisons between the classification of the present data based on the rooting ability and the classification of the previous study[8], it is clear that crops of group 3-a in the present experiment correspond to crops of No. 1 and 2 groups in the previous study, and that crops of groups 2 and 3-b correspond to crops of No. 3 group, and crops of group 1 in the present study to No. 4 group of the previous study.

The correspondence found in foxtail millet indicates that a poor rooting ability of this crop under waterlogging is closely related to its poor waterlogging tolerance. In contrant, the correspondences found in rice, finger millet, Job's tears and Japanese barnyard millet indicate that high rooting ability of these crops is closely related with their high waterlogging tolerance. These results seem to offer an evidence of a view that adventitious rooting is an important character for the crops to grow under waterlogging. It is interesting that crops of group 3-a in the present study can be further divided by the criteria of waterlogging and drought tolerance of the previous study, suggesting that some other factors other than the rooting ability may be involved in the waterlogging tolerance of these crops. It is also suggestive that crops of both groups 2 and 3-b in the present study fell in one group (No. 3) which was classified based on the waterlogging previously studied[8]. This suggests that the tolerance of the crops seems to be scarcely related with whether they can produce tiller roots or not under waterlogged conditions.

In comparisons between the rooting responses to the long-term waterlogging with those to the short-term waterlogging, the prolonged waterlogging treatment promoted generally the rooting of nodal roots of the cereals examined, on both nodal roots per main stem and per plant. An exceptional case was found in foxtail millet that the root number was increased under the short-term waterlogging, but it was remarkably decreased under prolonged waterlogging. These facts strongly indicate that the rooting abilities of the crops change with duration of the waterlogging treatment as well as the plant growth stages.

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