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Influence of Planting Density on Root Growth and Yield in Potato*

Kazuto IWAMA, Toshie HUKUSHIMA**, Tohru YOSHIMURA***
and Kimio NAKASEKO
(Faculty of Agriculture, Hokkaido University, Sapporo 060, Japan)

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Abstract : The influence of planting density on root growth and its relationship to leaf and tuber growth were investigated with two maincrop varieties in the potato. Three levels of planting density were examined ; 23810, 47620 and 95240 hills ha^{-1}. The root length (RL) was investigated to a depth of 1 m at 90 days after emergence (DAE). The root length density (RLD) to a depth of 30 cm was also investigated at 30 DAE. The leaf area and tuber dry weight were measured at several stages. Total RL to a depth of 1 m at 90 DAE in the sparse, intermediate and dense plots was 12.5, 15.9 and 24.1 km m^{-2} in Norin 1 and 6.4, 7.0 and 10.4 km m^{-2} in Konafubuki, respectively. These differences were mainly due to those in RL at a depth of 0—30 cm. RL below a depth of 30 cm did not increase in Norin 1, or decreased in Konafubuki in the dense plot. The similar differences were also seen in RLD at 30 DAE. Total RL at 90 DAE showed significant positive correlations with leaf area index (LAI, $r=0.929^{**}$) and tuber growth rate (GR, $r=0.913^{**}$) at the late stage. These results confirmed the importance of longer RL to maintain larger LAI and tuber GR at the late stage. They also suggested that poorer deep roots at the dense plot might cause severe drought in dry soil conditions.

Key words : Canopy structure, LAI, Root distribution, Root length, Root length density, *Solanum tuberosum* L., Tuber dry weight.

バレイショの根の生長と収量に及ぼす栽植密度の影響：岩間和人・福島淑恵**・吉村　徹***・中世古公男（北海道大学農学部・**神奈川県農業総合研究所・***北海道立農業試験場）

要　旨：栽植密度はバレイショの生育と収量を左右する重要な要因の一つであるが，異なる栽植密度条件下での根の生長の差異については，極めて知見が少ない．そこで本研究では，栽培条件に対する適応性の異なると思われる晩生2品種（農林1号とコナフブキ）について，疎植（23810株/ha），中植（47620株/ha），密植（95240株/ha）における根の生長の差異を明らかにし，これと葉および塊茎生長との相互関係を検討した．根の調査は，萌芽後30日目に深さ30cmまでをモノリス法で，また90日目に深さ1mまでをコアサンプリング法で行なった．また，生育期間中数回，葉面積と塊茎乾物重を測定した．90日目の全根長は，両品種とも栽植密度の増加にともないほぼ直線的に増加し，またいずれの栽植密度でもコナフブキに比べ農林1号の方が著しく大きな値を示した．処理間，品種間の差異は，深さ30cmまでの耕土層で大きく，これ以下の心土層では密植区での増加が認められなかった．また，根の生長の差異は30日目の調査でもほぼ同様に認められ，比較的早い時期から現れることがわかった．さらに，90日目の全根長は，同時期の葉面積指数および60日目以降の塊茎乾物重の増加速度とそれぞれ高い正の相関関係（$r=0.929^{**}$ および $r=0.913^{**}$）を示したことから，生育後期における根長の差異は葉面積の維持および塊茎生長の差異と密接に関係しているものと考えた．また，密植区では深い土層での根の生長が抑制されるため，旱魃の影響を受けやすいと推論した．

キーワード：塊茎乾物重，根系分布，根長，根長密度，*Solanum tuberosum* L.，葉群構造，葉面積指数．

Planting density is a main factor influencing tuber yield in potato. Many studies concerning this relationship have been reported1,2,3,4,11,12,13,14,16,18,19). In these studies, however, information on root growth was very scarce. Since increasing planting density may cause competition between plants not only for light but also for water and nutrients, information on roots will be very important to fully understand the influence of planting density on plant growth and tuber yield1).

An aim of this study is to clarify the influence of planting density on root growth and its relationship to leaf and tuber growth in potato. Two maincrop varieties, which were considered to be different in adaptability for environmental conditions, were used.

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** Present address : Agricultural Research Institute of Kanagawa Prefecture, Hiratsuka, Kanagawa 259-12, Japan.

*** Present address : Hokkaido Prefectural Agricultural Experiment Stations, Iwamizawa, Hokkaido 069-03, Japan.

Materials and Methods

The experiment was sited at the Experiment Farms, Faculty of Agriculture, Hokkaido University (Sapporo, 42° N latitude) in 1991. The soil was a Brown Lowland Soil (Typic Udifluvent), of which some characteristics are listed in Table 1. Two maincrop varieties of potato (*Solanum tuberosum* L.), Norin 1 and Konafubuki, were used. Although Norin 1 is an old variety, it is still widely cultured at various environmental conditions in Japan. Konafubuki is a new variety with high starch content and dry tuber yield. It is, however, sometimes said that it is weak against drought in the farmer's fields of the Hokkaido area.

The certified seed tubers (about 100 g per piece) were bisected and pre-sprouting was induced in a glass house for three weeks. They were planted on May 8 with a row width of 70 cm. The hill distance in rows was changed depending on planting densities ; 15 cm in the dense plot (95240 hills ha^{-1}), 30 cm in the intermediate plot (47620 hills ha^{-1}) and 60 cm in the sparse plot (23810 hills ha^{-1}). The main plot for the density treatment consisted of 14 rows and 18 hills in a row, being divided to sub-plots for two varieties. Although the treatments were arranged in two randomized blocks, samplings were usually done at one replication. Samplings at the harvesting stage were done at two replications. A combination of fertilizers at a rate of 1000 kg ha^{-1} of 7-11-9 (N, P_2O_5, K_2O) was banded about 5 cm beneath the seed tubers in a row just before planting. The emergence occurred on May 25 and 26 in Norin 1 and from May 29 to June 1 in Konafubuki. On June 3 the number of main stems per hill was adjusted to approximately two by thinning other main stems. The number of main stems per ha in the sparse, intermediate and dense plots on June 26 was 48000, 95000 and 190000 in Norin 1, and 48000, 119000 and 219000 in Konafubuki, respectively.

The root samplings were done twice. On June 26, (approximately the first flowering stage in all plots ; about 30 days after emergence, DAE), soil monoliths (5 cm in width, 30 cm in length and 30 cm in depth per monolith) were dug from the center of the row and parallel to the row. The number of sampled monoliths in each variety was two in the dense and intermediate plots, and three in the sparse plot. From August 24 to 30 (approximately the maximum stage of root growth ; about 90 DAE), soil cores (5 cm in depth and 100 cm^3 in volume per core) were dug in the soil layers to depths of 0—15 cm, 15—30 cm, 30—50 cm, 50—70 cm and 70—100 cm. The number of sampled cores was 72 in the dense plot and 144 in the intermediate and sparse plots. They were soaked for one night in water and the roots were washed by running water. A nylon cloth (about 0.2 mm of mesh size) was used to collect the roots. The washing process was divided into two parts. The samples consisting of only roots (Sample A) were collected at first. Then, the samples consisting of thin roots and inseparable plant residues (Sample B) were collected. To measure the root length, an image processing device developed by Yamaguchi and Tanaka[20]) was used for Sample A. Since this device was unable to

Table 1. Some properties of soils in each soil layer of experimental plot just after the harvesting stage.

Depth in soil (cm)	pH (H_2O)	Total C (%)	Cation-exchange capacity (mmol(+)kg^{-1})	Exchangeable cations (mmol(+)kg^{-1})			Saturation degree (%)	Available phosphorus* (P mg kg^{-1})	Bulk density (g cm^{-3})
				K	Mg	Ca			
0—15	5.7	3.0	300	12.3	39	175	75.4	360	1.01
15—30	5.7	3.1	300	15.9	43	191	83.1	370	1.10
30—50	6.0	2.9	300	12.9	34	160	67.8	280	1.33
50—70	6.1	0.7	220	7.8	37	136	82.7	20	1.08
70—100	6.6	0.5	220	2.5	37	122	72.3	20	1.04

* Truog method.

differentiate roots and plant residues, the modified intersecting method by Tennant[17] was used for Sample B. Two values of root length were added at the data analysis stage.

The shoots and tubers of 2—3 hills in the sparse and intermediate plots, and of 4 hills in the dense plot in each variety were sampled at approximately 30, 45, 60 and 97 DAE. The leaf area was measured with an automatic leaf area meter (AAM-7, Hayashi Denkoh Ltd.) and the dry weight (DW) of tubers was recorded after oven drying for 72 hours at 70°C. At 60 DAE, the leaf area was measured separately at a 10 cm interval in the height within the canopy. On October 13 the dry tuber yield was recorded with 20 hills in each plot. Before that stage, the date of leaf senescence (the leaf yellowing stage) was recorded. The meteorological data during the growing season was listed in Table 2.

Table 2. Monthly mean of the daily temperature (°C), solar radiation (S.R., MJ m^{-2}) and humidity (Hu, %), and the accumulated precipitation per month (Pr, mm) during the growing season.

Month	Temperature Max.	Min.	Mean	S.R.	Hu	Pr
May	18.0	8.1	13.2	19.8	65	20
June	23.3	13.9	18.2	18.3	79	28
July	23.3	16.7	19.7	15.8	81	86
August	24.6	17.1	20.8	16.5	79	103
September	21.6	12.3	17.4	12.0	77	63
October	16.0	7.4	12.0	7.7	73	83

Results

1. The root growth

Fig. 1 shows the root length density (RLD) at the vertical plane intersecting the row at 90 DAE. Each value was the mean of several RLD values measured parallel to the row. Among the soil layers to the depth of 1 m in each plot, RLD was the largest at the depth of 0—15 cm and usually the second largest at the depth of 15—30 cm. RLD at the depth of 30—50 cm tended to be smaller than that of 50—70 cm depth. It may be due to soil compaction by the tractor cultivations since soil bulk density was the largest at this depth (Table 1). Within each soil layer, RLD tended to be larger at the position near to the row center. These differences were, however, much smaller than those between the soil layers.

The differences in RLD between the densities and between the varieties were also the largest at the depth of 0—15 cm. RLD at the same position in the soil layer was larger in the denser plot in each variety. It was also larger in Norin 1 than in Konafubuki at each density. The similar tendency was also shown at the depth of 15—30 cm. Although the differences in RLD between the plots became unclear at the depth below 30 cm, RLD at the depth of 70—100 cm tended to be smaller in the dense plot than in the intermediate plot in two varieties, especially in Konafubuki.

Using these RLD values we calculated the root length per unit soil area (RL) at the depth of 0—30 cm (Upper RL), 30—100 cm (Lower RL) and 0—100 cm (Total RL). As shown in Fig. 2, Upper RL in both varieties increased almost linearly according to the density increase. The varietal difference was also apparent at each density. The differences in Lower RL between the plots were, however, small. Although Lower RL increased in both varieties when the density increased from the sparse to the intermediate, it showed no increase in Norin 1 and some decrease in Konafubuki when the density increased further. The two varieties showed almost the same value in the sparse and intermediate plots. The differences in Total RL between the densities and between the varieties were, therefore, mainly due to those in Upper RL.

The differences in the root growth between the plots were already seen at 30 DAE. As shown in Fig. 3, RLD at the depth of 0—15 cm in the center of the row showed a larger value at the greater density, except for the value of Konafubuki in the dense plot. It was also larger in Norin 1 than in Konafubuki at all densities. There was a highly significant positive correlation between Total RL at 90 DAE and RL per monolith at 30 DAE among all plots ($r=0.942^{**}$).

2. The relationship of root growth to leaf growth

Fig. 4 shows the leaf area index (LAI) during the growing season. In general, the differences in LAI between the plots showed a similar tendency to those in RLD at the depth of 0—15 cm at 30 DAE and Total RL at 90

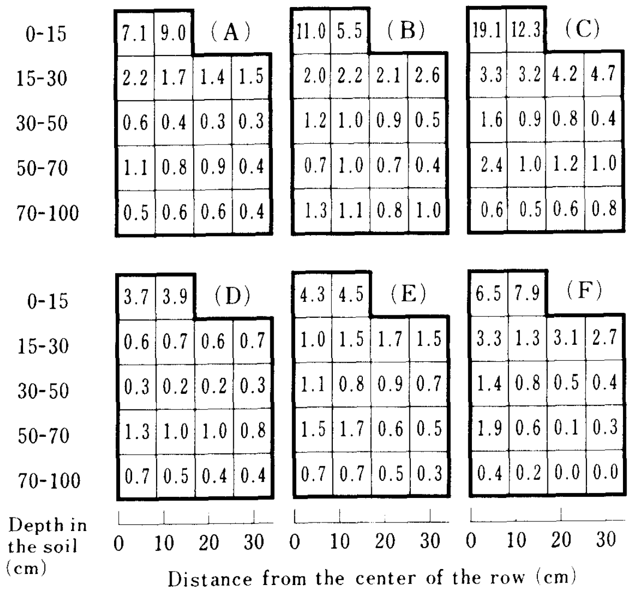

Fig. 1. The root length density (cm cm^{-3}) at the vertical plane intersecting the row at 90 DAE. (A) Sparse plot, (B) Intermediate plot, (C) Dense plot in Norin 1, and (D) Sparse plot, (E) Intermediate plot, (F) Dense plot in Konafubuki.

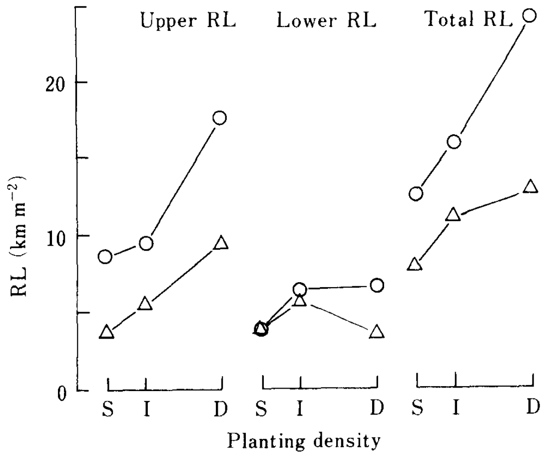

Fig. 2. The root length (RL) per unit soil area at the depth of 0—30 cm (Upper RL), 30—100 cm (Lower RL) and 0—100 cm (Total RL) at 90 DAE. ○ : Norin 1, △ : Konafubuki. The planting density of S, I and D shows 23810, 47620 and 95240 hills/ha, respectively.

DAE. Especially, as shown in Fig. 5, there was a highly significant positive correlation between Total RL at 90 DAE and LAI at 97 DAE among the plots. The regression lines were, however, somewhat different between the varieties. Norin 1 showed higher ratios of Total RL relative to LAI in the intermediate and dense plots. It was due to the larger varietal difference in Total RL than in LAI.

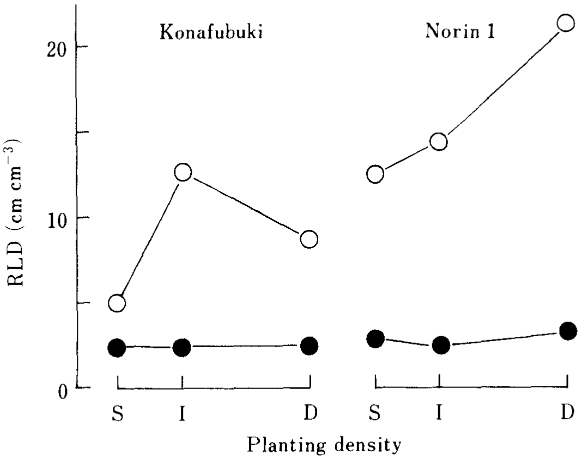

Fig. 3. The root length density (RLD) at the center of the row and parallel to the row at the depth of 0—15 cm (open symblos) and 15—30 cm (closed symbols) at 30 DAE. The symbols of planting density are the same as those shown in Fig. 2.

The vertical distribution of leaf area within the canopy at 60 DAE was also different between the plots. Fig. 6 shows that the height where the leaf area attained the largest value within the canopy was lower in Konafubuki than in Norin 1 at all densities. Its difference was the largest in the sparse plot because that height in Konafubuki tended to become lower according to the density decrease. These differences between the plots were not due to those in stem length. The stem length differed only 5—10 cm between the plots.

3. The relationship of root growth to tuber growth

Fig. 7 shows tuber DW during the growing season. At 30 DAE, it was small at all densities in Norin 1, while it increased according to the density increase in Konafubuki. It was much larger in Konafubuki than in Norin 1 at all densities. At 60 DAE, it was the largest in the intermediate plot in both varieties. Konafubuki continued to show much larger values in the intermediate and dense plots than Norin 1. On the other hand, tuber DW at the harvesting stage (Tuber Yield) was the highest in the dense plot in two varieties. It showed a very high value, 1.43 kg m^{-2} in Norin 1 and 1.40 kg m^{-2} in Konafubuki. In addition, although the differences were small, Tuber Yield in Norin 1 was consistently higher at all densities than in

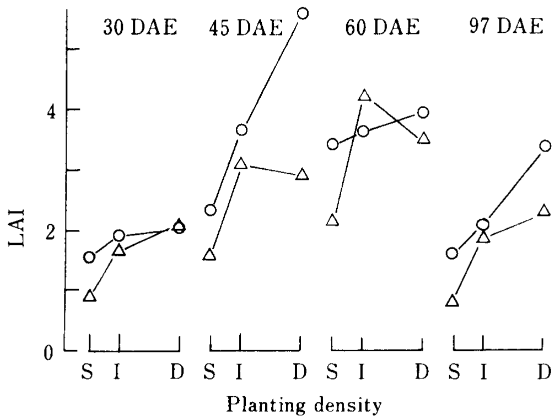

Fig. 4. Influence of the planting density on the leaf area index (LAI) in two varieties at 30, 45, 60 and 97 DAE. The symbols are the same as those shown in Fig. 2.

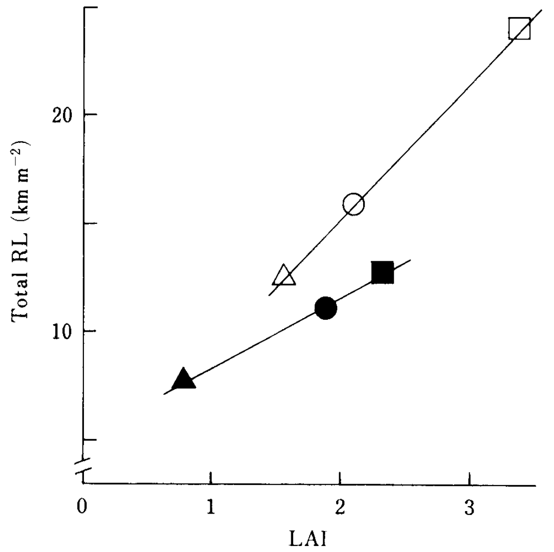

Fig. 5. The relationship between Total RL at 90 DAE and LAI at 97 DAE. The triangle, circle and square symbols show the sparse, intermediate and dense plot, respectively. Open sybols : Norin 1, $y=6.40x+2.44$, $r=1.00^{**}$. Closed symbols : Konafubuki, $y=3.21x+5.23$, $r=0.998^{*}$. Two varieties : $y=6.05x+1.90$, $r=0.929^{**}$.

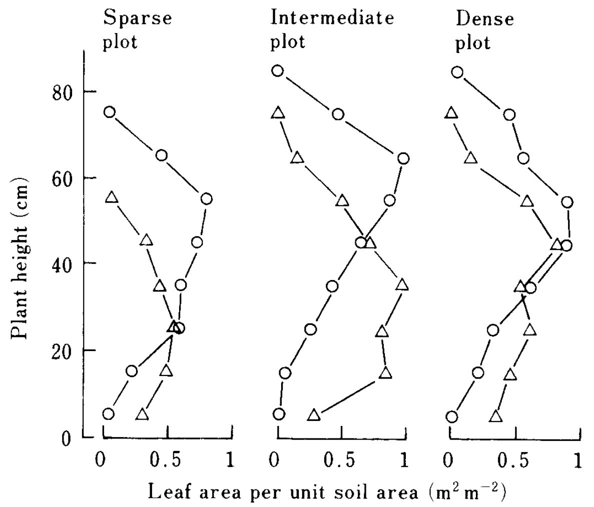

Fig. 6. The vertical distribution of leaf area within the canopy at 60 DAE. The variety symbols are the same as those shown in Fig. 2.

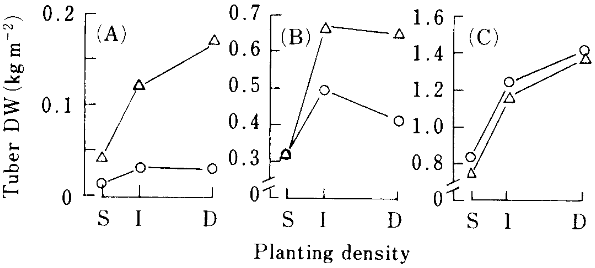

Fig. 7. The tuber dry weight (DW) at 30 DAE (A), 60 DAE (B) and the harvesting stage (C). The symbols are the same as shown in Fig. 2.

Konafubuki.

These results showed that the differences in Tuber Yield between the plots were mainly due to the differences in the increase of tuber DW at the late stage. The increase of tuber DW from 60 DAE to the harvesting stage in the sparse, intermediate and dense plots was 0.51, 0.75 and 1.02 kg m^{-2} in Norin 1, and 0.44, 0.50 and 0.75 kg m^{-2} in Konafubuki. There was a significant positive correlation between these tuber DW increase and Tuber Yield among all plots ($r=0.838^{*}$). Although the date of leaf senescence was later in the denser plot and in Norin 1 than in Konafubuki, the differences were small. It was from October 7 to 10 in Norin 1 and from October 3 to 6 in Konafubuki. Whereas tuber growth rate (GR) from 60 DAE to the date of leaf senescence in the sparse, intermediate and dense plots was 7.0, 10.3 and 13.4 g m^{-2} day^{-1} in Norin 1, and 6.4, 7.0 and 10.4 g m^{-2} day^{-1} in Konafubuki. The differences in the increase of tuber DW at the late stage between the plots were mainly due to the differences in tuber GR. A simple correlation coefficient between two characters among all plots was highly significant ($r=0.998^{**}$).

Tuber GR from 60 DAE to the date of leaf

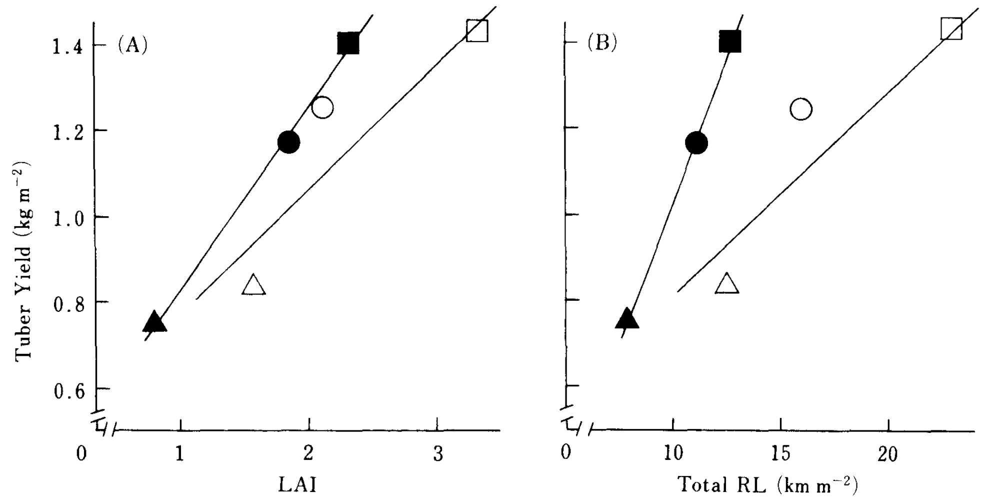

Fig. 8. The relationship of the tuber DW at the harvesting stage (Tuber Yield) with LAI at 97 DAE (A) and Total RL at 90 DAE (B). The symbols are the same as those shown in Fig. 5. (A) Norin 1 : $y=0.297x+0.470$, $r=0.897$. Konafubuki : $y=0.420x+0.409$, $r=0.997^*$. Two varieties : $y=0.297x+0.541$, $r=0.887^*$. (B) Norin 1 : $y=0.046x+0.355$, $r=0.899$. Konafubuki : $y=0.131x-0.275$, $r=1.00^{**}$. Two varieties : $y=0.036x+0.633$, $r=0.698$.

senescence showed significant positive correlations with Total RL at 90 DAE ($r=0.913^*$) and LAI at 97 DAE ($r=0.928^{**}$). As a result, the increase of tuber DW during that period also showed significant positive correlations with Total RL ($r=0.935^{**}$) and LAI ($r=0.937^{**}$). Fig. 8 shows the relationships of Tuber Yield with Total RL and LAI. The correlation coefficient was high in each variety, especially in Konafubuki. The varietal difference in the regression line of Tuber Yield with Total RL was mainly due to the varietal difference in the tuber increase at the early stage before 60 DAE.

Discussion

It is generally known that LAI increases with the increase of planting density in potato[1,3,4,15,16]. The present results clearly show that RL also increased with the increase of planting density. Especially at 90 DAE when the root growth was the maximum[8]), each variety showed an almost linear relationship between Total RL and LAI. The differences in the ratio of Total RL to LAI (RL/LA ratio) between the densities were small. The present finding almost agrees with the results reported by Vander Zaag et al.[18]. Calculating from their data, root DW at the depth of 0—30 cm increased with the increase of planting density in New York and in Philippines. They noted that changes in shoot/root ratio between the densities were small. These results indicate that a relative valance between the roots and the leaves is constantly maintained even if their growths change largely according to planting spacing.

There were, however, some changes in the distribution of the roots in the soil. When the density increased from the intermediate to the dense, only Upper RL increased. Lower RL did not change in Norin 1, and decreased in Konafubuki. The ratio of Lower RL to Total RL, therefore, became much smaller in the dense plot than in the others. It may bring some agricultural problems. Although the RL/LA ratio was almost constant between the densities, the ratio of Lower RL to LAI largely decreased in the dense plot. In general, the deep roots are more necessary than the shallow roots to absorb water in dry soil conditions. The present results, therefore, suggest that in dry soil conditions, a water shortage in the leaves may become more severe in the dense plot. Although in the present study the leaves showed no symptoms of water shortage at the late stage, we supposed that it might be due to plentiful rainfall at that stage of the present year. At the early stage we observed some symptoms of water shortage ; e.g. rolling and withering of leaves in the dense plot, especially in Konafubuki. Allen[1] noted that any decline in yield at high stem densities seemed to occur when growing conditions were poor, especially where water was lacking. The present results support his description.

There were also some changes in the distribution of the leaves in the canopy. The position of highest leaf area density in the canopy became higher in Konafubuki when planting density increased. Nakaseko et al.[13] and Isoda et al.[3] reported the same phenomenon. They explained that larger shading between the leaves increased the leaf death at the low position in the canopy in the denser plot. In the case of root distribution, however, it would be unreasonable to explain that some competition between the roots increased the root death in the deep soil layer in the dense plot. Because, the deep roots generally grow at a later stage than the shallow roots[8]. We supposed that the shallow roots got priority to grow when the root growth per plant was depressed in the dense plot.

Each variety showed a very high Tuber Yield in the dense plot. It mainly resulted from higher tuber GR at the late stage. Although the amount of fertilizers applied in the present experiment were equal in all plots, the present soils were rich for nutrients, especially nitrogen. We considered that longer Upper RL at the dense plot made it possible to absorb more soil nutrients and to maintain larger LAI and higher tuber GR at the late stage. These results agree well with our previous finding on the relationship of root DW to tuber GR in comparison between years and cropping seasons[10]. Our results in the root pruning experiment[9] also support the above interpretation. The decrease of root DW caused by root pruning under the field condition induced the significant decrease of nitrogen content and growth of leaves during 2—3 weeks after the treatment and resulted in the decrease of Tuber Yield.

Another interesting finding was the large varietal difference in Total RL at 90 DAE. This was consistent at all densities. RLD at 30 DAE also showed the varietal difference with a similar tendency. We considered that the two varieties differed in root growth from the early stage until the late stage. As to its cause, we are now paying attention to the negative relationship of the root growth with the tuber growth at the early stage. Tuber DW at 30 DAE was apparently larger in Konafubuki than in Norin 1 at all densities. We suppose that there is competition for the growth materials, i.e. photosynthetic products and/or nutrients, between two organs.

In the comparison of varieties and breeding lines with different maturity classes[5,6,7], the amount of roots usually corresponded well with the growing period and Tuber Yield. In the present study, however, Konafubuki showed similar growing period and Tuber Yield with Norin 1 in spite of their large difference in Total RL. The larger increase of tuber DW at the early stage in Konafubuki than in Norin 1 compensated its smaller increase of tuber DW at the late stage. It is a subject for future study to clarify the differences in root contribution to maintain leaf area and tuber growth between the varieties in the same maturity class. In addition, we suppose that larger root growth in Norin 1 than in Konafubuki may contribute stability in Tuber Yield under a wide range of environmental conditions. The relationship of root growth with the stability of Tuber Yield under conditions deficient for nutrients or water is also of subsequent interest.

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* In Japanese with English summary.

** In Japanese without English summary.