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Research Paper

Growth, zinc concentration and absorption rates of transplanted oilseed rape (*Brassica napus* L.) to Zn-HEDTA and root pruning

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ABSTRACT

Transplanted oilseed rape (*Brassica napus* L.) plants were reported to be sensitive to zinc (Zn) deficiency and had a higher external Zn requirement. However, it was not clear whether the increased external Zn requirement was due to transplanting. The aims of this study were to clarify the dynamics of root and shoot recovery growth after transplanting and to assess the effect of Zn supply and root pruning on growth and Zn absorption by transplanted oilseed rape. Transplanted oilseed rape was grown in chelate-buffered nutrient solution and harvested successively at 5-day intervals from 0 to 25 days after transplanting. Treatments consisted of two levels of Zn-HEDTA (0.02 and 5.0 µM) and two root treatments (unpruned and 50% root pruning). The experiment was arranged in a Randomized Complete Block Design (RCBD). Plants were harvested at 5, 10, 15, 20 and 25 days after transplanting. Significant treatment effects were separated with LSD at $P \leq 0.05$. Results showed that low Zn solution and 50% root pruning depressed the growth rates including shoot and root dry weights. The root dry weight of plants with pruned roots recovered only 70% of that with unpruned roots. In addition, plants with unpruned roots had higher Zn absorption rate in their shoot and root dry weights. High solution Zn alleviated but did not fully overcome the effects of pruning on growth of transplanted oilseed rape. Hence, it would be worthwhile to examine the rhizosphere modification including organic acids released by growing roots after transplanting and their response to Zn supply and root pruning.

Keywords: Transplated oilseed rape, Zn-HEDTA, root pruning.

INTRODUCTION

Transplanted oilseed rape plants were more sensitive to Zn deficiency as compared to direct-sown plants before the full recovery of root system (Mulyati et al., 2005; Mulyati, 2008). Zinc deficiency appeared to limit post-transplanting growth during the recovery phase particularly by limiting the new root growth, and this in turn inhibited the Zn absorption rates. In addition, transplanted oilseed rape plants were strongly responsive to the external Zn supply in their early post-transplanting root growth but the response weakened with time.

Oilseed rape seedlings raised in nursery beds and then transplanted into the main field may experience nutritional problems that are not found by direct-sown plants (Hu et al., 1996). Seedlings raised in nursery beds are generally uprooted with minimal care, which would cause loss of fine roots and root tips, the portion of the root system most important for nutrient uptake. Uprooting from the nursery beds recovers less than 50% of the root system and markedly increases the shoot: root ratio (Hu et al., 1996). Thus, seedlings would suffer from transplanting stress and this leads to interruption of plant growth (Sand, 1984; Vavrina et al., 1998). As a result, the rapid recovery of the plants from transplanting stress is recognized as critical for successful survival and establishment growth after transplanting. However, the dynamics and dry matter partitioning associated with root and shoot recovery after

transplanting and the effect of Zn application on nutritional status and growth of transplanted plants have not been investigated.

Root pruning at transplanting was found to reduce vegetative growth and dry matter production in a number of plant species (Alexander and Maggs, 1971; Geisler and Ferree, 1984). The removal of various proportions of roots of grapevines led to the decline of shoot dry weight in proportion to the degree of root pruning. Abod et al. (1979) reported that root pruning in pine reduced net photosynthesis but it returned to normal rates after an initial decrease. Most researchers found that the effect of root pruning on subsequent growth may be described by a combination of a lower leaf water potential, reduced mineral nutrient uptake, reduced hormone synthesis and an increased proportion of photosynthate translocated to the roots (Humphries, 1958; Alexander and Maggs, 1971; Richards and Rowe, 1977). However, once new roots grew and developed, shoot growth could attain normal or even higher growth rates (Geisler and Ferree, 1984).

Increasing solution Zn-HEDTA concentration in solution culture from 0 to 0.05 and 5.0 µM increased shoot and root dry matter of both direct-sown and transplanted plants. It was suggested that increasing solution Zn concentration stimulated the root recovery by increasing Zn absorption. The present study was conducted to clarify the mechanisms of root recovery after transplanting and to assess the effect of Zn supply and root pruning on the rate of Zn uptake from chelate-buffered nutrient solution by transplanted oilseed rape.

MATERIALS AND METHODS

Transplanted oilseed rape was grown in chelate-buffered nutrient solution and harvested successively at 5-day intervals from 0 to 25 days after transplanting. Treatments consisted of two levels of Zn-HEDTA (N-(2-hydroxyethyl) ethylenedinitrilotriacetic acid) (0.02 and 5.0 µM) and two root treatments (unpruned and 50% root pruning). The experiment was set up as a three-way analysis of variance arranged in a Randomized Complete Block (RCB). Pots were arranged in a complete factorial combination and each treatment consisted of 15 replicates. Three replicates were selected for each harvest. Significant treatment effects were separated with Fisher's Protected LSD at $P \leq 0.05$.

Before sowing, the soil was leached with double deionized water (DDI) water and thereafter, complete nutrients were added and mixed evenly into seedbed soil to provide adequate nutrients for seedling growth. Basal fertilizer rates for all nursery bed pots were applied at the following rates (mg kg^{-1} air dried soil): K_2SO_4, 174; $CaCl_2.2H_2O$, 98; NH_4NO_3, 93; KH_2PO_4, 90.7; $MgSO_4.7H_2O$, 24.6; $MnSO_4.7H_2O$, 8.5; $CuSO_4.5H_2O$, 1.3; H_3BO_3, 0.85; $Na_2MoO_4.2H_2O$, 0.4, and $ZnSO_4.7H_2O$ (Huang et al., 1995). Only analytical grade chemicals were used. The basal culture solution used in this experiment contained (µM): KNO_3, 2800; NH_4NO_3, 2000; $Ca(NO_3)_2$, 1600; $MgSO_4$, 1000; KH_2PO_4, 100; FeEDTA, 40; NaCl, 8; H_3BO_3, 2; $MnSO_4$, 2; $CuSO_4$, 0.5 and Na_2MoO_4, 0.08 (Hewitt, 1996).

When seedlings had 4 leaves, 8 uniform seedlings were transferred to each pot containing chelate-buffered nutrient solution. Seedling roots were lifted gently and then rinsed thrice with DDI water and for half of the plants, 50% of the root mass was removed by cutting roots from the tips to simulate transplanting root damage. Seedlings were kept in the shade with their roots kept moist with DDI water in a plastic bag before transplanting. Selected seedlings were transferred to 5 L plastic pots lined with polythene bags containing Zn-HEDTA and basal culture solution.

All pots were continuously aerated with filtered air and randomly repositioned every day to minimize effects of position on growth. Root zone temperature was maintained at 20 to 22°C throughout the experimental period using a temperature-controlled water bath. At 5 days, seedlings were thinned to six plants per pot. The nutrient solutions were renewed and initial pH adjusted to 6.0 in every 10 days.

Seedlings were harvested on day 0 for determination of root and shoot dry weight and Zn content. Plants were harvested at 5, 10, 15, 20 and 25 days after transplanting (DAT) and each plant was separated into shoots and roots for determination of dry weight. Root length was measured by using a Comair root length scanner (Newman, 1966). All samples were oven-dried at 65 to 70°C to constant weight for dry weight and plant analysis for Zn and P determination by ICP-OES (Zarcinas et al., 1987).

Zinc content of shoots and roots were calculated by multiplying shoot or root Zn concentrations with their respective shoot and root dry weights. Zinc uptake per unit root dry weight was determined by dividing plant Zn content with root dry weight. Zinc absorption rates (ZAR) were calculated by the formula of Williams (1948), but were expressed on a root fresh weight basis (Loneragan and Snowball, 1969).

RESULTS AND DISCUSSION

Growth of transplanted oilseed rape

At day 5, no symptoms of Zn deficiency were observed in any treatment. However, plants with 50% roots pruned exhibited loss of leaf turgour during the day and the oldest two leaves senesced: this did not occur in plants with unpruned roots. By day 10, plants grown at 5.0 µM Zn-HEDTA (high Zn) were larger and had darker green foliage than those grown at 0.02 µM Zn-HEDTA (low Zn). The cotyledon leaves of plants with 50% root pruning were

Table 1: Effect of solution Zn-HEDTA concentration and root pruning on shoot dry weights (g plant^{-1}) of transplanted oilseed rape at 5, 10, 15, 20 and 25 days after transplanting (DAT) in chelate-buffered nutrients solution.

Treatment		Time (days after transplanting)				
Zn supply (µM)	Pruning (%)	5	10	15	20	25
		Shoot (g plant^{-1})				
0.02	0	0.11	0.20	0.54	1.06	1.32
5.0	0	0.12	0.28	0.87	1.79	2.27
0.02	50	0.11	0.17	0.45	0.78	0.95
5.0	50	0.12	0.23	0.68	1.33	1.67
LSD (P ≤ 0.05)						
Zn supply		ns	0.06**	0.11**	0.23**	0.24**
Pruning		ns	0.06*	0.11**	0.23**	0.24**
Zn × pruning		ns	ns	ns	ns	ns

* P ≤ 0.05, ** P ≤ 0.01, ns = not significant (P > 0.05) for F test. Values are means of three replicates.

abscised.

By day 15, low Zn and 50% root pruning induced younger leaves were yellowish in colour. The older leaves became thicker and dull in appearance. By day 20, these symptoms progressively worsened on plants grown at 0.02 µM and 50% root pruning. The younger leaves tended to be yellowish in colour and then developed a marginal necrosis and by the end of the experiment, plant grown at low solution Zn exhibited symptoms resembling phosphorus toxicity (Loneragan et al., 1979), that is, reddish-brown spots developed on old leaves. Leaves with reddish-brown spotting eventually yellowed and dropped off. As a consequence, the newly formed leaves were smaller and plants experienced severe reduction in shoot growth.

Shoot and root dry weights

At day 5 after transplanting, root dry weight was significantly reduced by low Zn and 50% root pruning (Table 1). There were only additive effects of Zn supply and root prunning on root dry weight responses until day 10 and by the end of the experiment root growth increased from 0.26 g plant^{-1} when low Zn was supplied to 0.49 g plant^{-1} when high Zn was applied with no root pruning (Table 1). However, at low solution Zn concentration and root pruning decreased root dry weight from 0.26 to 0.17 g plant^{-1} and the decline due to pruning was not as severe as the effect of solution Zn supply.

At 5 days after transplanting, there was no difference in shoot dry weight (Table 1). Significant responses in shoot dry weight to increasing solution Zn concentration and to root pruning were just apparent at day 10. The number of leaves increased with an increase in the solution Zn. With time the response in shoot dry weight to increasing solution Zn-HEDTA became more obvious. By day 25 after transplanting, Zn supply had a marked effect on shoot dry weight and the average shoot dry weight at 0.02 µM was 42% of that produced in 5.0 µM Zn. Root pruning depressed shoot dry matter at 10 days after transplanting and at each harvest thereafter. The effect of Zn supply was additive to that of root pruning on shoots dry weight at all harvests from day 10.

Shoot: root ratio

Figure 1 shows the effect of solution Zn-HEDTA concentration and root pruning on shoot: root ratio of transplanted oilseed rape at 5, 10, 15, 20 and 25 days after transplanting (DAT) in Chelate-buffered nutrient solution. This figure indicated that increasing solution Zn decreased shoot: root ratio significantly at day 5 and 10; from day 15 until the end of experiment, there was no significant effect. The shoot: root ratio strongly decreased with time. By day 5, shoot: root ratio declined from 13.1 at 5 DAT to 5.2 at 25 days after transplanting for plants grown in low solution Zn. Contrary to the effects of Zn, root pruning had no effect on shoot: root ratio at day 5 and by day 10 onward 50% root pruning significantly ($p \leq 0.05$) increased shoot: root ratio.

Root length and root hair density

By day 5, raising solution Zn concentration from 0.02 to 5.0 µM increased root length and 50% of root pruning depressed the root length (Table 3). The combined effect of low solution Zn-HEDTA and root pruning strongly inhibited root length. From 15 days onward, root length recovered strongly from root pruning when plants were grown at 5.0 µM Zn.

In all harvests, the lowest root hair density was obtained

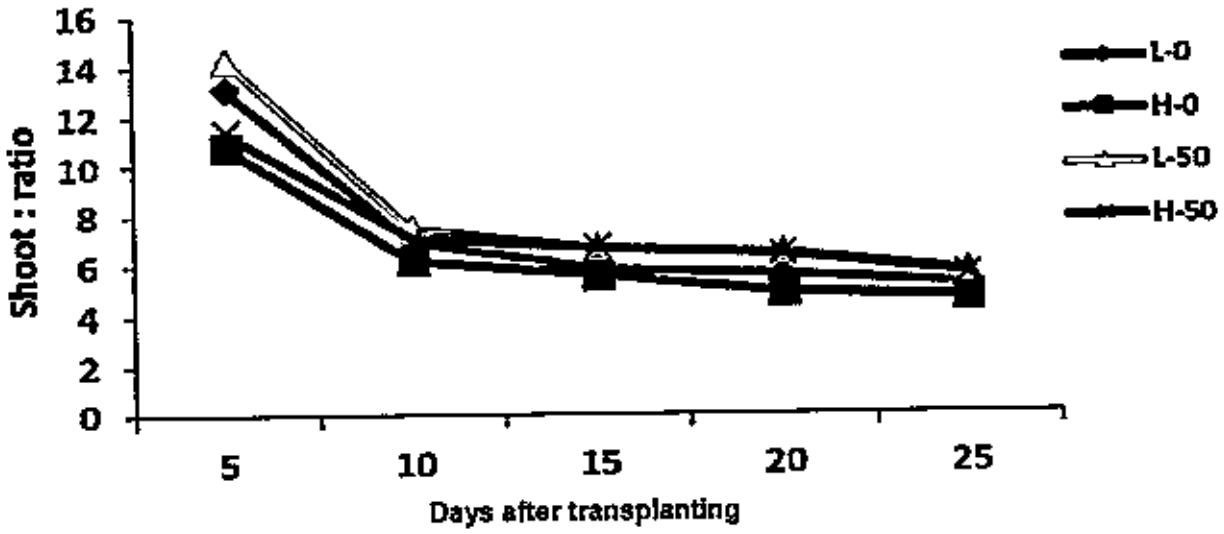

Figure 1: Effect of solution Zn-HEDTA concentration and root pruning on shoot: root ratio of transplanted oilseed rape at 5, 10, 15, 20 and 25 days after transplanting.

Table 2: Effect of solution Zn-HEDTA concentration and root pruning on root dry weights (g plant^{-1}) of transplanted oilseed rape at 5, 10, 15, 20 and 25 days after transplanting (DAT) in chelate-buffered nutrients solution.

Treatment		Time (days after transplanting)				
Zn supply (µM)	Pruning (%)	5	10	15	20	25
		Root (g plant^{-1})				
0.02	0	0.008	0.029	0.094	0.187	0.255
5.0	0	0.011	0.044	0.157	0.354	0.487
0.02	50	0.008	0.023	0.067	0.124	0.167
5.0	50	0.010	0.033	0.100	0.200	0.269
LSD ($P \leq 0.05$)						
Zn supply		0.002*	0.006**	0.013**	0.037**	0.031**
Pruning		0.002*	0.006**	0.013**	0.037**	0.031**
Zn × pruning		ns	ns	0.019**	0.052**	0.044**

Values are means of three replicates. * $P \leq 0.05$, ** $P \leq 0.01$, ns = not significant ($P > 0.05$) for F test

from the combination treatment of low solution Zn concentration and root pruning (Table 5). At 5, 10 and 15 DAT, the number of root hairs produced by plants grown at 0.2 µM Zn was higher than that produced by plants grown at 5.0 µM Zn. However, by day 20 and 25, plant grown from 5.0 µM Zn had a greater root hair density than plants grown from 0.2 µM Zn. Therefore, at 25 days after transplanting low solution Zn concentration and root pruning depressed the root hair density.

Zinc concentrations in plant parts

Effect of solution Zn-HEDTA concentration and root pruning on Zn concentration (mg kg^{-1}) in shoots and roots of transplanted oilseed rape at 5, 10, 15, 20 and 25 days after transplanting (DAT) in chelate-buffered nutrient solution (Figure 2a and b). Root pruning decreased root Zn concentration at all harvests except at 5 days for low Zn supply. Increasing solution Zn concentration increased root Zn concentration of transplanted oilseed rape at all harvests. At most harvests, Zn concentration in roots was lowest with root pruning and low solution Zn. Raising solution Zn-HEDTA concentration from 0.02 to 5.0 µM consistently increased Zn concentration in shoots. The combination of low Zn (0.02 µM) supply and 50% root pruning resulted in lower shoot Zn concentration, especially from day 15. Increasing solution Zn-HEDTA

Table 3: Effect of solution Zn-HEDTA concentration and root pruning on root length (m plant^{-1}) of transplanted oilseed rape at 5, 10, 15, 20 and 25 days after transplanting (DAT) in chelate-buffered nutrient solution.

Treatment		Time (days after transplanting)				
Zn supply (µM)	Pruning (%)	5	10	15	20	25
		Root length				
0.02	0	0.68	1.46	2.71	6.18	7.06
5.0	0	0.86	2.65	3.68	6.38	9.10
0.02	50	0.27	1.16	2.17	4.75	5.63
5.0	50	0.36	2.18	3.12	6.29	8.63
LSD (P ≤ 0.05						
Zn supply		0.20*	0.41**	0.32**	0.43*	0.34**
Pruning		0.20*	0.41**	0.32**	0.43*	0.34**
Zn × root treatment		ns	ns	ns	0.61**	0.48**

(Values are means of three replicates). * P ≤ 0.05, ** P ≤ 0.01, ns = not significant (P > 0.05) for F test.

Table 4: Effect of solution Zn-HEDTA concentration and root pruning on Zn absorption rate (mg kg^{-1} root fresh weight day^{-1}) by transplanted oilseed rape at 5, 10, 15, 20 and 25 days after transplanting (DAT) in chelate-buffered nutrient solution.

Treatment		Time (days after transplanting)				
Zn Supply (µM)	Pruning (%)	5	10	15	20	25
0.02	0	5.1	3.7	3.4	1.7	1.0
5.0	0	25.2	12.3	8.4	2.5	1.5
0.02	50	3.8	3.2	2.0	1.2	0.8
5.0	50	21.8	12.0	7.9	1.8	1.4
LSD (P ≤ 0.05)						
Zn supply		0.6**	0.5**	0.4**	0.2**	0.2**
Pruning		0.6**	ns	ns	0.2*	ns
Zn × root treatment		ns	ns	ns	ns	ns

Values are means of three replicates. P ≤ 0.05, ** P ≤ 0.01, ns = not significant (P > 0.05) for F test.

concentration tends to increase zinc absorption rate (ZAR).

Removal of 50% of the roots depressed ZAR over the periods 0 to 5 and 15 to 20 days but this effect was not significant during other periods of growth. There was a sharp increase in shoot Zn content with an increase of Zn-HEDTA in solution at all harvests. Highest shoot Zn content was recorded in the combination treatment of high Zn (5.0 µM) and root pruning, while low solution Zn and root pruning had the lowest shoot Zn absorption rate. However, there was no interaction between Zn rates and root pruning across all harvests. Furthermore, the effect of solution Zn-HEDTA concentration and root pruning on Zn absorption rate (mg kg^{-1} root fresh weight day^{-1}) by transplanted oilseed rape at 5, 10, 15, 20 and 25 days after transplanting (DAT) in chelate-buffered nutrient solution can be seen in Table 4.

Previous experiments in soil and solution culture have shown that transplanted oilseed rape required higher external Zn as compared to direct-sown plants. It was hypothesized that transplanted plants required higher external Zn supply due to the damage of the root system at transplanting, an increase in shoot: root ratio and because pruning of root tips and root length at transplanting inhibited Zn absorption rates. Solution Zn-HEDTA application previously was reported to increase shoot dry weight of barley (Norvell and Welch, 1993), chickpea (Khan et al., 1998) and rice (Mulyati, 2017). In the present study at 5 days after transplanting, Zn supply did not affect shoot growth, but at 10 days after transplanting and onward, there was a substantial increase in shoot growth with higher Zn supply. By contrast, from 5 days onwards, high Zn supply increased root dry weights. The increase in root relative growth rate from day 0 to 5 probably had a

Table 5: Effect of solution Zn-HEDTA concentration and root pruning on root hair density (number g^{-1} root fresh weight) of transplanted oilseed rape at 5, 10, 15, 20 and 25 days after transplanting (DAT) in chelate-buffered nutrient solution.

Treatment		Time (days after transplanting)				
Zn Supply (μM)	Pruning (%)	5	10	15	20	25
		Root hair density				
0.02	0	1018	1197	2677	3376	3518
5.0	0	686	807	2145	4442	4612
0.02	50	278	361	1243	3043	3394
5.0	50	392	587	1327	3308	3531
LSD ($P \leq 0.05$)						
Zn supply		19**	13**	22**	96*	85**
Pruning		19**	13**	22**	96*	85**
Zn × pruning		27**	18**	32**	137**	120**

Values are means of three replicates. * $P \leq 0.05$, ** $P \leq 0.01$, ns = not significant ($P > 0.05$) for F test.

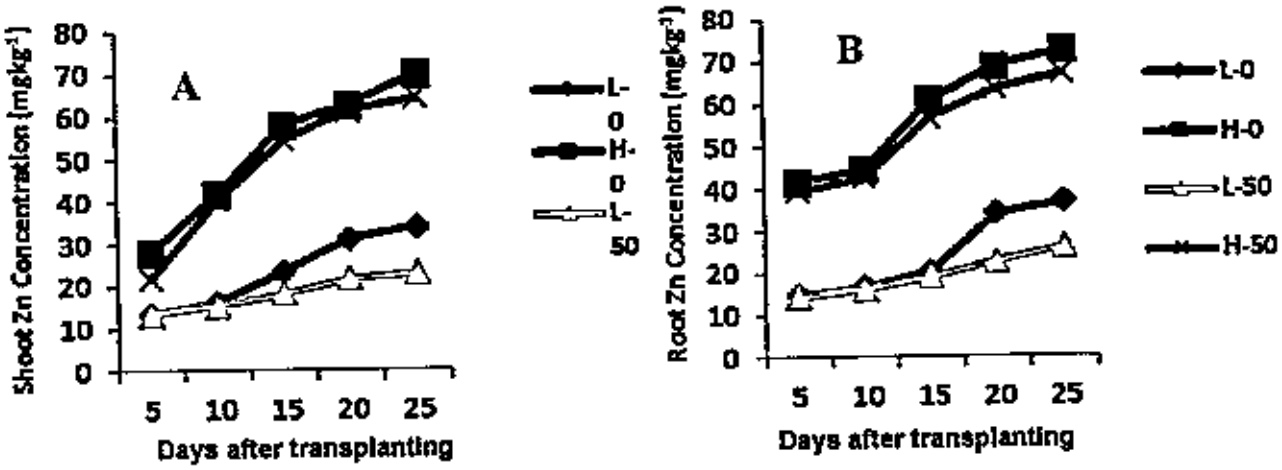

Figure 2: Effect of solution Zn-HEDTA concentration and root pruning on Zn concentration (mg kg^{-1}) in shoots and roots of transplanted oilseed rape at 5, 10, 15, 20 and 25 days after transplanting (DAT).

large bearing on the subsequent effects on root dry weights, even though high solution Zn consistently increased relative growth rate of roots until day 20 (Table 2). Hence, roots responded more rapidly than shoots to low external Zn supporting the previous conclusions that the higher Zn requirement of transplanted oilseed rape was due to the root requirement.

Root recoveries began immediately after transplanting as reflected in higher relative growth rate from day 0 to 5 and increasing Zn in solution increased root dry matter at day 5. Shoot relative growth rates from 0 to 10 days in the present study were low regardless of their Zn status, but by 10 to 15 DAT, they had recovered and reached maximum values. The retranslocation of stored and fixed carbohydrates to roots from shoots may be the main reason for low relative growth rate of shoots from day 0 to 10. During the regeneration of the root system in previous studies, the proportion of photosynthates translocated to the root increased (Richards and Rowe, 1977). Old leaves senescence observed in the plants after transplanting suggested loss of stored carbohydrates from the shoot. High solution Zn appeared to hasten the recovery of shoot growth rates after transplanting. Thus, partial recovery of shoot relative growth rate was evident during the period 5 to 10 days with adequate solution Zn but not with low Zn. It appears that the early growth response of shoots to increasing external Zn was secondary response, whereas the primary effect was on root growth.

Welch and Norvell (1993) pointed out that Zn plays an important role in regulating ion uptake by plant roots. Adequate Zn in the external solution is necessary to maintain membrane integrity and may be especially beneficial to alleviate the effects of transplanting ion uptake by roots. In soil, nearness of the Zn supply to the

roots of the transplanted seedlings would be required as a prior condition for rapid root growth after transplanting. On the other hand, as a consequence of root pruning, the relative growth rate of roots declined after transplanting and so too did shoot relative growth rates. Whereas root dry weight was depressed at 5 days by root pruning, relative growth rate of roots during the period day 0 to 5 was not. Previously, root pruning has been shown to reduce vegetative growth in a number of plant species (Geisler and Ferree, 1984; Ferree et al., 1999) such as barley and rye plants (Humphries, 1958); sweet orange seedlings (Alexander and Maggs, 1971); peach seedlings (Richards and Rowe, 1977) and apple trees (Geisler and Ferree, 1984).

During the early growth stage, the effect of root pruning could be explained by the retardation of the nutrient uptake by roots. The present experiment indicated that root pruning increased root hair density but decreased root length. However, neither of these two changes in root characteristics explains the decline in Zn absorption rate which accounts for differences in root size and should respond positively rather than negatively to increased root hair density.

Richards and Rowe (1977) found that even if root length was comparable for pruned and unpruned roots, root number was depressed. Thus, root pruning may decrease root surface areas to mass ratio and lead to decreased Zn uptake by plant roots. However, it seems more likely that the impairment of Zn uptake was related to the kinetics of uptake rather than root morphology. The lower shoot relative growth rate and leaf senescence between day 0 to 5 in plants with pruned roots may be significant for Zn uptake since it suggests that root growth was a major sink for carbon. Inadequate carbohydrates for metabolism may slow Zn uptake in plants with root pruned. Decreased leaf area would exacerbate the shortage by decreasing current photosynthesis. The synthesis of growth substances such as cytokinins occurs in root tips (Richards and Rowe, 1977; Geisler and Ferree, 1984). Thus, the damage of root system at transplanting or root pruning that removed the root tips, removed the part of the roots with the highest concentration of cytokinins. The implications of a decrease in cytokinin levels for shoot and root growth after transplanting are not clear.

Root pruning disturbed the shoot: root ratio of transplanted oilseed rape (Figure 1). Shoot: root ratio decreased substantially with time, such that at 25 days plants with 50% root pruning had a slightly lower, but generally comparable shoot: root ratio to those with intact root. When the roots had recovered from transplanting, the favourable shoot: root ratio was constant (Table 1) at about 5. The recovery of shoot: root ratio in solution culture was obtained at approximately 7-leaf stage: it was slower in plants grown in soil culture taking until 10 leaf stage (Mulyati et al., 2009). This result is consistent with previous report by Richards and Rowe (1977) who stated that plants with pruned roots had a high shoot: root ratio, yet, soon after transplanting plants re-established their root growth by redistributing carbon and growth substances (Geisler and Ferree, 1984). In other root systems, stored starch and carbohydrates were translocated rapidly to roots once new roots developed (NeSmith, 1999). The apparent root recovery involved a redistribution of growth substances and increased assimilate translocation to the root.

It was concluded that at 25 days after transplanting, roots had fully recovered so no difference was found between unpruned and pruned roots in the growth rate. However, because root pruning decreased the root dry weight at 5 days after transplanting, at the end of the experiment root dry weight of pruned roots was still only 70% of that in unpruned roots. Root pruning depressed both Zn concentration in shoots and roots. When 50% of roots were removed, Zn absorption rate (ZAR) by the roots declined. The Zn absorption rate declined with time, and there was no significant difference in ZAR at the end of experiment between plants which had their roots pruned and those with intact roots. The relationship between ZAR and plant growth depends on the ability of plant to transport absorbed Zn to meet functional Zn requirements of the developing tissue and root system. High solution Zn partly compensated for the effect of root pruning on ZAR and root pruning reduced photosynthesis, transpiration and growth (Ferree et al., 1999). Hence, it is plausible to conclude that root pruning impaired the ability of roots to absorb Zn and increased sensitivity of plant growth to Zn deficiency after transplanting.

Conclusion

Low solution Zn and 50% root pruning depressed shoot and root dry weights. Plants without pruning had a higher Zn concentration and Zn content in their shoots and root after transplanting. Lack of pruning and high solution Zn hastened the recovery of root and shoot growth. During the growth period, the root dry weight of plants with pruned roots recovered only 70% of that with unpruned roots. High solution Zn alleviated but did not fully overcome the effects of pruning on growth of transplanted oilseed rape.

Factors such as increased external Zn supply or lack of root pruning hasten root recovery. However, it is possible that application of Zn in the nursery bed could stimulate the root recovery after transplanting. In the prior experiments, reported in this thesis, external Zn levels supplied in the nursery to oilseed rape seedlings were deficient or marginal. In addition, it appears that solution acidification was impaired by root pruning and low solution Zn. This may have implications for Zn uptake after transplanting in soil where rhizosphere modification could have significant effects on Zn availability. Hence, it would

be worthwhile to examine the rhizosphere modification including organic acids released by growing roots after transplanting and their response to Zn supply and root pruning.

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