NARDI FUNDULEA, ROMANIA ROMANIAN AGRICULTURAL RESEARCH, NO. 32, 2015
www.incda-fundulea.ro Print ISSN 1222-4227; Online ISSN 2067-5720

EFFECT OF PLANT INTERCROPPING AND SOIL TYPE ON SPECIFIC ROOT LENGTH

Agnieszka Klimek-Kopyra[1*], Bogdan Kulig[1], Tomasz Głąb[2], Tadeusz Zając[1], Barbara Skowera[3], Joanna Kopcińska[4]

[1]University of Agriculture, Department of Crop Production, Faculty of Agriculture and Economics, Al. Mickiewicza 21, 31-120 Kraków, Poland; aklimek@ur.krakow.pl (*corresponding author)

[2]University of Agriculture, Institute of Machine Exploitation, Ergonomy and Production Processes, Faculty of Production and Power Engineering, ul. Balicka 116B, 30-149 Krakow, Poland

[3]University of Agriculture, Department of Ecology, Climatology and Air Protection, Faculty of Environmental Engineering and Land Surveying, Al. Mickiewicza 24/28, 30-059 Kraków, Poland

[4]Agricultural University, Department of Applied Mathematics, Department of Environmental Engineering and Land Surveying, Al. Mickiewicza 24/28, 30-059 Kraków, Poland

ABSTRACT

A three year experiment was intended to evaluate the effect of intercropping and soil type on specific root length (SRL). Crop mixtures included: (i) linseed with pea; (ii) linseed with vetch. Experiment was conducted on different soil type: Chernozem (A) and Cambisol (B). Roots length demonstrated high degree of plasticity in development in response to local heterogeneity of the soil profile - determined by water availability, and plant diversity. The studies found significant differences of SRL between species. Significantly greater SRL value was noticed for species in pure sowing, while lower values were observed for plants in mixture. Higher SRL was noticed for plants in Cambisol soil, which was characterized by higher soil humidity, regardless of drought periods occurring.

Better soil conditions, described by higher amount of precipitation, significantly influenced the SRL of the species tested. The value of specific leaf area index significantly increased with increasing amount of precipitation (TP) in Olszanica (Cambisol). Higher value of SRL to TP association was noticed for legumes (pea or vetch) in mixture with linseed. Significant positive relations exist between SRL and TP of legumes cultivated in mixture with linseed; SRL increased with increasing amount of precipitation (TP). The highest correlations of SRL and TP were observed for pea in mixture with linseed (for pea r=0.982: P≤0.05).

Key words: specific roots length (SRL), legumes, linseed.

INTRODUCTION

Competition for below-ground resources between edible plants may provide for a long term sustainability of agriculture systems. Competition depends on above-ground demands for water and nutrients, as well as on root parameters. Intercrop can be more productive than pure crop, provided that morphological difference between species exists (Van Noordwijk and Purnomosidhi, 1995). In pure cropping all biophysical interactions between plants occur via soil conditions. Plants growing on soil with sufficient nutrient reserves in the subsoil and developing root system composed of wide set up basal root and deep tap root are able to bring nutrients to the surface. In intercropping, competition for water and nutrients is of major importance, but, if the root of one species occupy the zone just underneath the other crop roots, they can capture current losses from the first crop root zone (Van Noordwijk et al., 1991). This possibility is immensely important for nutrients depending on precipitation surplus.

The purpose of intercropping is to generate biological interactions between plants in crop. Intercropping can increase plant stability and potential usage of available resources (Jensen et al., 2006), but on the other hand, water intercepting ability of the plants may be limited (Ufoegbune et al., 2010). Root systems demonstrate high degree of plasticity in their development in response to local heterogeneity of the soil profile and

Received 20 February 2014; accepted 16 March 2015. First Online: April, 2015. DII 2067-5720 RAR 2015-42

plant density. Specific root length is determined by the density of the root and its length per unit root volume, which depend on the diameter of the root. High specific root length appears attractive for pure cropping system, as it probably increases nutrient capture by nutrient mobilization for the crop through organic residues. A dense root system probably also enhances biological formation of soil structure (Kooistra and Van Noordwijk, 1995). For intercropping systems, complementarities in root distribution between species is desirable to reduce competition. Reducing competition between lateral roots can affect the effective spatial distribution of roots in the soil profile.

Plant species differ in the way they allocate biomass and this feature impacts on their competitiveness in relation to soil nutrient and light availability. Species differ in root morphology which is important for their competitive abilities in relation to soil resources and water limitation (Olff, 1992). Körner and Renhardt (1987) and Mortimer (1992) used the root parameters to express the magnitude of the changes in the surface of these parameters, obtained by varying the mass of the unit. The ability to predict the outcome of competition by investigating the relationship between traits of plants and their competitiveness has long been an objective for ecologists (Grace, 1990). When considering plant traits the different competitive mechanisms of fine roots must be considered. Roots in the topsoil engage in exploitation and competition through depletion of water resources. Shortage of water is a major limitation to crop growth in many areas of the world. Typically, plants respond to water shortage by larger relative allocation of carbon to roots and if this occurs for a prolonged period, it may lead to enhanced root growth in absolute terms (Hussain and Ahmed, 1990). Root length to leaf area relation provides a better expression of the relative sizes of above – and below – ground exchange surfaces.

Plant developed a wide diversity of morphological and physiological drought tolerance mechanisms (Blum, 1996). Progressive water limitation can affect the plant organs growth in a different way, which may result in the modification of morphological features of the plants (Spollen et al., 1993; Cox and Conran, 1996; Erice et al., 2010). Water limitation, linked with short drought stress, abridges root growth. These adaptive responses in morphology may be species-specific mechanisms to cope with the environmental characteristic of their habitats (Patterson et al., 1997).

Therefore the main task of this study was to assess the effect of intercropping and soil type on specific root length (SRL). We used specific root length as the indicator of root parameter suitable for estimating below-ground relations between linseed with pea and linseed with vetch. The second task referred to the presumed correlation between SRL and water availability in soil during vegetation period. If any relationship exists it would be interesting to assess the form of this relation and to investigate how far analysed species may deviate from the general trend.

MATERIAL AND METHODS

The experiment was conducted under field conditions in the Experimental Station of Agricultural University in Prusy n/Krakow ($50^o07^/01^{//}$N and $20^o05^/19^{//}$E which is 270 m above sea level) and in the field in Olszanica ($50^o06^/01^{//}$N and $19^o58^/19^{//}$E which is 150 m above sea level) from April to March in the period of 2006-2008. The experiment in Prusy was established in Chernozem (A), whereas in Olszanica - in Cambisol (B). Cambisol is a fine-grained soil with sand : silt : clay ratio in the following proportions 10:77:13 and is characterized by moderate amount of nutrients – 23.2 $mg \cdot 100\ g^{-1}$ P, 15.4 $mg \cdot 100\ g^{-1}$ K, 11,8 $mg \cdot 100\ g^{-1}$ Mg, 1,21% organic carbon, 0,14% total nitrogen. Owing to higher amount of the clay in soil structure, with low precipitation during vegetation period, Chernozems are considered the best soils for water demanding crop plants, but they have a slow drainage system and too much water in the soil profile can cause formation of marginal lakes. This type of soil is fine-grained (14:39:47) and is characterized by sensible amount of nutrients – 26.2 $mg \cdot 100\ g^{-1}$ P, 16.9 $mg \cdot 100\ g^{-1}$ K, 13.8 mg·100 g^{-1} Mg, 2.36% organic carbon, 0,18% total nitrogen.

The replacement design was used for the two mixtures and involved the replacement of a proportion of one species with another. A 0.5:0.5 replacement design was used: each species was sown at 50% of its pure sowing population. A basic density for linseed was 480 seeds per square meter, for pea 80 seeds /m^2 and for vetch 200 seeds/m^2 .

The experiment was conducted in RCB design with split-plot arrangement using four replications. The size of each plot was 1.25m x 8 m. Four replications were used to assess below - ground root weight in flowering stages. Plant habitats, characterized by two types of soil, were compared independently. pea (*Pisum sativum* L. cv. Ramrod - breeder 'Hodowla Roślin Szelejewo Sp. z o.o.'), vetch (*Vicia sativa* L. cv. Ina - breeder 'Hodowla Roślin Danko Sp. z o.o.') and linseed (*Linum usitatissimum* L cv. Flanders - breeder 'AgriFood Canada') were grown in the pure sowing or in mixtures and were cultivated till flowering stages, when the root system is fully developed. Soil cultivation was carried out in proper time for both habitats. Crops were fertilized with 56 kg×ha^{-1} P and 139 kg×ha^{-1} K in 2006, 2007 in each soil type. For the linseed growth as mixture or pure sowing, nitrogen was applied two times; before sowing (30 kg×ha^{-1} N) and in the stem extension stage (20 kg×ha^{-1} N). Weeds, pests and diseases were controlled with appropriate pesticides. Plants were sown in 1-2 decade of March while harvesting was conducted in 2-3 decades of July in each year respectively. The roots were sampled using the soil-core method during the flowering stage. The core diameter was 80 mm. The samples were collected from a depth of 30 cm. The roots were washed using a hydropneumatic elutriation system to remove mineral particles. Before scanning, all organic contaminations were manually removed. Digital images were obtained with an Epson Perfection 4870 Photo scanner. The collected images were saved in the .tif format with a resolution of 600 dpi. Then the images were analyzed using APHELION software to calculate the root indices.

Specific root length (SRL) is the ratio of root length to its mass. SRL is considered the belowground analogue of 'harvest index' or absorptive tissue deployed per unit mass invested.

Statistical evaluations

The data were subjected to analysis of variance (ANOVA) using the General Linear Model procedures of the Statistica program (Statistica 10; StatSoft, Inc.). The dependences between SRL (specific root length) and TP (total precipitation) were checked by multiply linear regression with the statistics software (Statistica 10; StatSoft, Inc.). Results of the statistical analyses are presented in the tables and figure legends.

Evaluation of hydrothermal Extreme Conditions

The attempt of quantitative evaluation of pluviothermic extreme conditions during the vegetation period on the area of Prusy and Olszanica in 2006-2008 based on Sielianinow's hydrothermal index (K) was one of the aims of the work. Calculated values of hydrothermal index (K) for 2006-2008 period allowed determining regions and months. K is known as a coefficient of water supply in plant. The index is computed as follows:

$$K=P/0.1\Sigma t$$

where: P is the sum of monthly precipitation in mm. Σt is the sum of daily mean air temperatures >0°C.

Jędrszczyk et al. (2012) cited nine classes of the hydrothermal index K: dry ($K\leq0.4$), very dry ($0.4<K\leq0.7$), dry ($0.7<K\leq1.0$), relatively dry ($1.0<K\leq1.3$), optimal ($1.3<K\leq1.6$), relatively humid ($1.6<K\leq2.0$), humid ($2.0<K\leq2.5$), very humid ($2.5<K\leq3.0$), and extremely humid ($K>3.0$) in the area of Prusy and Olszanica. Water limitation is described by total precipitation (TP) (which was presented as a total precipitation during vegetation period of analysed species).

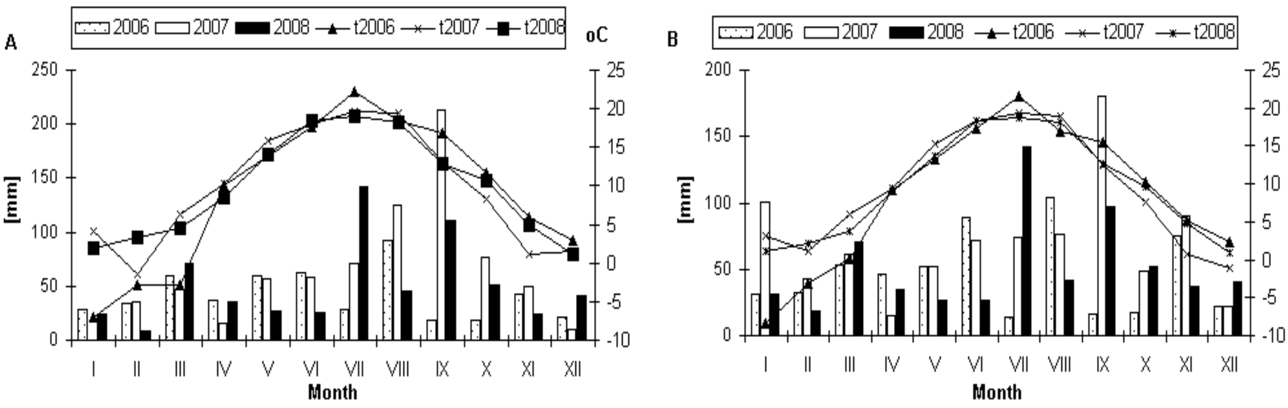

Figure 1. Weather conditions from April to June of 2006-2008 at Prusy (A), Olszanica (B)

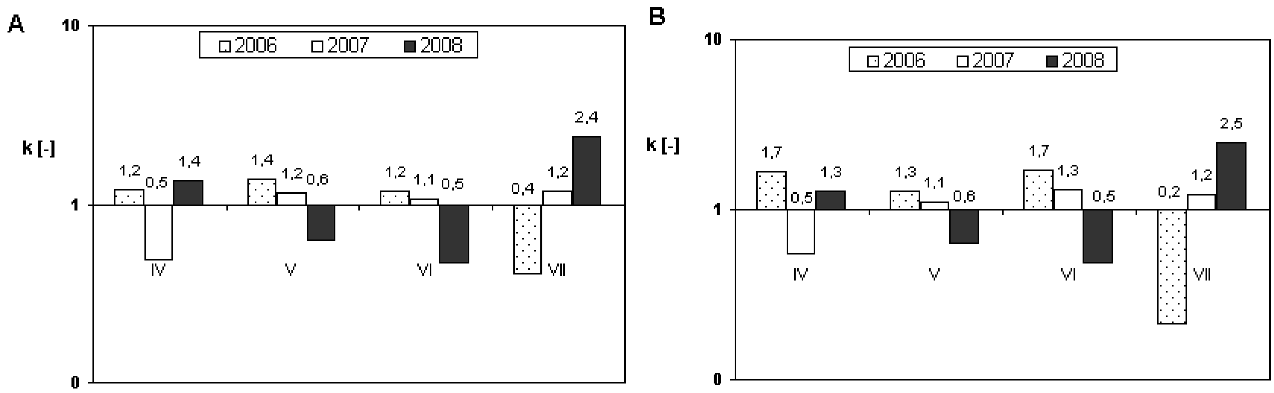

Figure 2. Quantitative evaluation of pluviothermic extreme conditions in the vegetation in the Prusy (A) and Olszanica (B) area in 2006-2008 based on hydrothermal Sielianinow's coefficient

RESULTS

Weather conditions

In the period 2006-2008 the average annual temperature recorded in Prusy was 9.5°C. Only for the vegetation period (April - July) this value was 13.0°C. Similar average temperatures from 2006-2008 were measured in Olszanica (average annual temperature was 9.0°C and 12.9°C from vegetation period). In order to determine the thermal and water conditions during the growing season of plants more accurately, hydrothermal index (K) was used. This index is the quotient of temperature and precipitation sums, and reflects the dynamics of the vegetation from April to July in the studied years. In Prusy an average total precipitation was 284 mm, while in Olszanica was higher (296 mm).

We noticed high precipitation fluctuation in 2006 and 2007. In Olszanica the highest monthly precipitation was measured in 2007 (130 mm in June), while in Prusy in 2006 (128 mm in June). Similar difference of monthly precipitation distributions was noticed in 2008. In order to analyse meteorological conditions on species development, Sielianinow's hydrothermal index (K) was used (Skowera and Puła, 2004). Meteorological conditions during vegetation in investigated years (2006-2008) were very much diversified (Figure 1). Variability of weather conditions was illustrated by climatic indicators, i.e. Sielianinow's hydrothermal index (K). Sielianinow's hydrothermal index higher than 1.6 defines humid conditions; whereas values from 1.0 to 1.6 indicate optimal and relatively dry conditions. Precipitation deficiency takes place when index values are lower than 1.0. The value of climate indicators measured in Prusy included in Figure 2. A showed, that period from May to June in 2007 was relatively dry, while 2007(April), 2008 (May) were very dry and in 2006 (July) even extremely dry conditions appeared. Stronger fluctuations of precipitation took place in Olszanica than in Prusy. Extremely dry conditions were observed in 2006 (July) while 2007 (April) and 2008 (May) were dry. The remaining vegetation period was optimal for species, except for 2007 (July) when very humid conditions were noticed.

Table 1. Analysis of variance of SRL for linseed, pea and vetch in pure crop and mixture Cultivated in different soil type, sowing method

Source of variation - Linseed	df	SS	Mean square	F
Factor A - year	2	19.2477	9.6238	7.51**
Error	8	11.6523	1.4565	
Factor B - habitat	1	46.1533	46.1530	6.61*
Interaction AB	2	2.8032	1.4016	15.26**
Error	12	36.2831	3.0235	
Factor C - sow	2	5.7916	2.8958	0.46
Interaction AC	4	10.9302	2.7325	2.65*
Interaction BC	2	26.1459	13.0720	2.50*
Interaction BC	4	14.9906	3.7476	11.98**
Interaction ABC	48	52.3754	1.0911	3.43*
Error	89	270.1150		
Source of variation - pea	df	SS	Mean square	F
Factor A - year	2	75.6441	37.8220	469.24**
Error	8	0.6448	0.0806	
Factor B - habitat	1	14.8902	14.8900	292.69**
Interaction AB	2	107.2850	53.6420	1054.43**
Error	12	0.6105	0.0508	
Factor C - sow	1	48.5100	48.5100	531.93**
Interaction AC	2	24.0945	12.0470	132.10**
Interaction BC	1	7.6255	7.6255	83.62**
Interaction BC	2	41.6119	20.8050	228.14**
Interaction ABC	24	2.1887	0.0911	
Error	59	323.4120		
Source of variation - vetch	df	SS	Mean square	F
Factor A - year	2	116.9980	58.4990	1204.39**
Error	8	0.3886	0.0485	
Factor B - habitat	1	2.6797	2.6797	39.22**
Interaction AB	2	31.1393	15.5690	
Error	12	0.8110	0.0683	113.29**
Factor C - sow	1	8.0374	8.0373	311.22**
Interaction AC	2	44.1601	22.0800	143.09**
Interaction BC	1	10.1517	10.1510	323.03**
Interaction BC	2	45.8352	22.9170	
Interaction ABC	24	1.7027	0.0709	
Error	59	262.6360		

*significant at the 0.05 probability level; **significant at the 0.01 probability level; ***significant at the 0.001 probability level.

SRL stability depending on intercropping and soil type

Linseed SRL values were significantly influenced by 3 factors under this study: A-year, B - soil type C - way of sowing (pure crop and mixture with legumes) (Table 1). The effect of studied factors on SRL varied from year to year, as indicated by the very significant interactions of 'A x C sowing type', 'A - year x B - soil type x C - sowing type'. Values of SRL, both for pea and vetch were also significantly influenced by 3 factors under this study. The effect of studied factors on SRL for pea and vetch varied from year to year, as indicated by very significant interactions of soil type and sowing type as well. The value of specific leaf area (SRL) index significantly increased with increasing amount of total precipitation (TP) in Olszanica (Cambisol) (Table 2). Higher value of SRL corresponding to higher TP was noticed for linseed in pure crop and linseed in mixture with pea, while for linseed in mixture with vetch the correlation was not significant. The highest correlations of SRL and TP were observed for legume in mixture with linseed (for pea r=0.982: P≤0.05; for vetch r=0.954: P≤0.05).

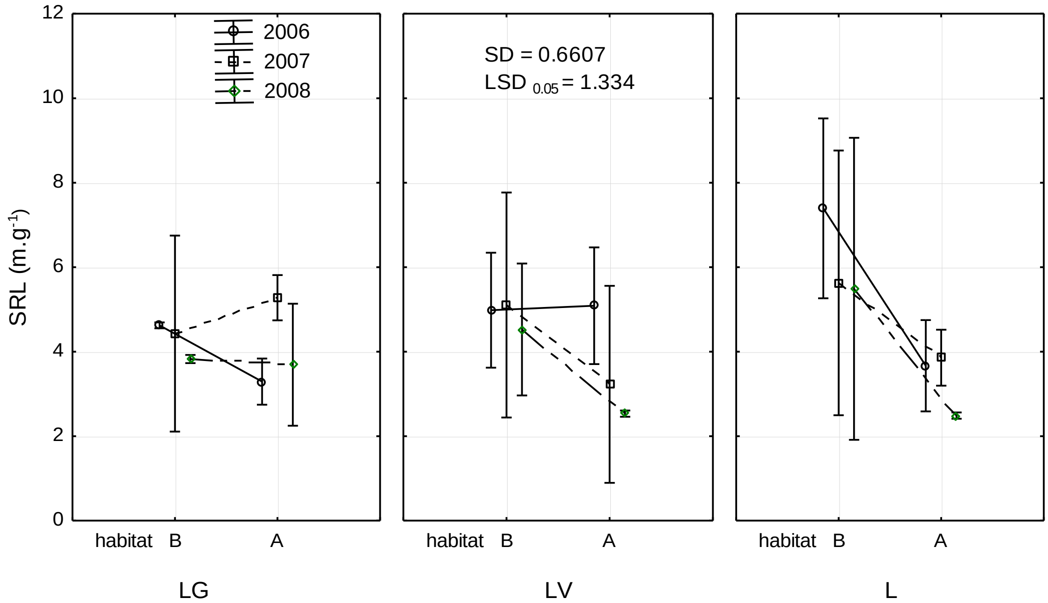

Figure 3. SRL interaction between years: soil type: sowing type - linseed in pure sow (L) and linseed in mixture with pea (LP) and vetch (LV); A - Chernozem, B - Cambisol

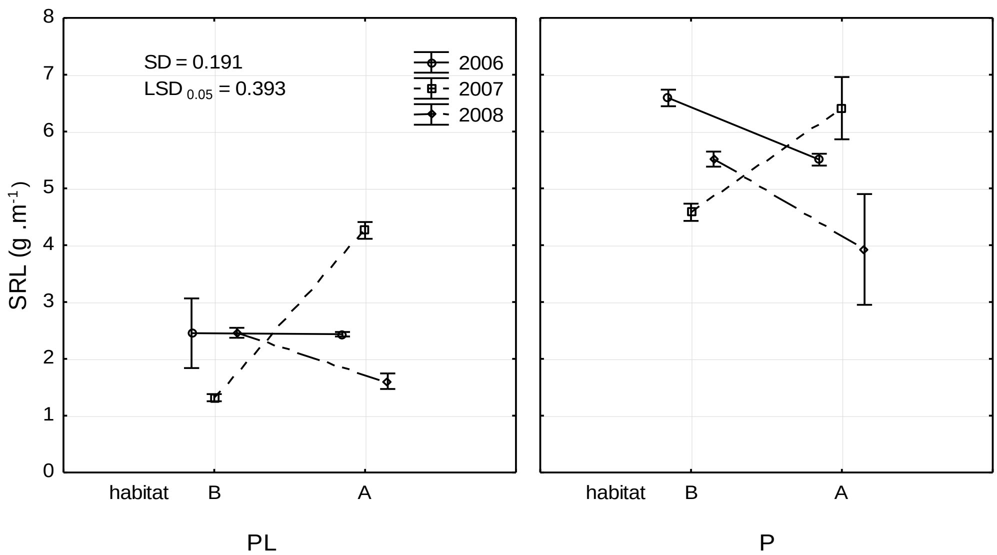

Figure 4. SRL interaction between years: soil type: sowing type - pea in pure sow (P) and pea in mixture with linseed (PL); A - Chernozem, B - Cambisol

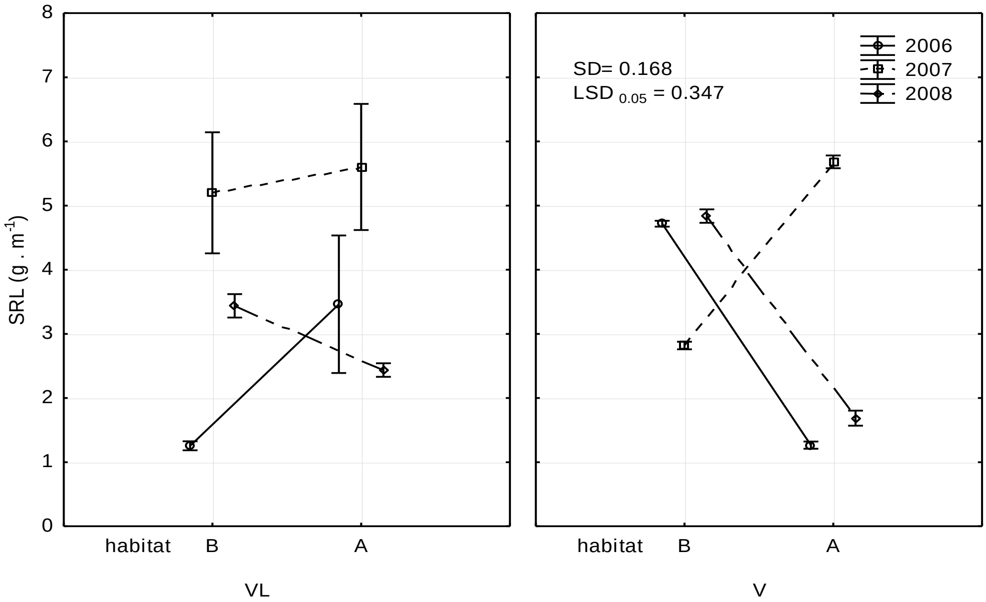

Figure 5. SRL interaction between years: soil type: sowing type - vetch in pure sow (V) and vetch in mixture with linseed (VL); A - Chernozem, B - Cambisol

The specific root length values of the analysed plants were affected by weather conditions, the soil type and by the method of sowing (Figures 3-5). The results show significant interactions between years: soil type: sowing type of SRL parameter for linseed (LSD=1.33). Higher SRL values were observed for linseed in sole crop (L) cultivated in Cambisol (B). Lower SRL parameters were obtained for linseed in mixture with pea (LP) or vetch (LV). Linseed cultivated in sole crop gained higher results of SRL regardless of seasons of vegetations, while in mixture with vetch in 2006 we observed the highest SRL, while the lowest in mixture with pea.

The results show a significant interactions between factors of the SRL for pea (LSD=0.393). The pea cultivated in sole crop obtained higher SRL value, than in mixture with linseed. In sole crop pea gained higher SRL in Cambisol (B). Pea cultivated in mixture with linseed achieved lower results in specific roots length in chernozem (A).

Specific root length (SRL) values for vetch were impacted by weather conditions, soil type and way of sowing as well (Figure 5) (LSD=0.347). In 2006 and 2008 higher value of SRL was observed in sole crop in Cambisol (B), whereas SRL for vetch in 2007 was lower. Vetch cultivated in mixture varied in years and habitat (soil type). In Chernozem (A) vetch in mixture with linseed gained higher SRL in 2006 and 2007, whereas in 2008 gained the lowest SRL.

Table 2. Correlation coefficient values between specific root length (SRL) and total precipitation (TP)

Items		†L	LP	LV	P	PL	V	VL
SRL:TP	Chernozem (A)	0.304	0.324	0.181	0.374	0.483	0,212	0,064
	Brown soil (B)	0.672*	0.632*	0.137	0.883*	0.982*	0.875*	0.954*

† Abbreviations: L – linseed in pure sowing, LP – linseed in mixture with pea, LV – linseed in mixture with vetch, P – pea in pure sowing, PL – pea in mixture with linseed, V – vetch in pure sowing, VL – vetch in mixture with linseed.

Correlation coefficient values indicate the association of the specific root length (SRL), and total precipitation (TP). *Significant at the 0.05 probability level.

The value of specific leaf area (SRL) index increases along with total precipitation (TP) regardless of the way of sowing and soil type. In Cambisol (B), significantly higher value of SRL to TP was noticed for linseed in pure crop, while for legumes in mixture. Significant positive relations between SRL and TP in legumes cultivated in mixture with linseed increased with increasing amount of total precipitation (TP). The highest correlations of SRL and TP were observed for legume in mixture with linseed (for pea $r=0.982$: $P\leq0.05$; for vetch $r= 0.954$: $P\leq0.05$).

DISCUSSION

The experimental results revealed that SRL is the effective index to assess the plant relations in mixture in contrasting soil types. Soil conditions and distribution of precipitation during vegetation period in Olszanica (Cambisol) were more suitable for legumes in mixtures with linseed while linseed preferred the pure sowing.

Specific root length (SRL) varied in different soil types but significant correlations between specific root length (SLR) and total precipitation (TP) were only observed in Cambisol soil. The SRL index reflects the habitat richness (Ryser, 1998) and is determined by physiological characteristics of plant. Our research shows that increase of SRL was caused by higher water availability in soil. We noticed increased values of SRL index of pea in mixtures regardless of soil type. The performed research confirmed Poot's and Lambers's (2003) conceptions.

Deep rooting was positively associated with soil water extraction, provided that soil types did not restrict rooting potential (Sponchiado et al., 1989). In our experiment root potential of pea and linseed were similar in different soil types. Regardless of habitat, greater SRL of linseed was noticed in sole crop, while for pea it was greater in mixture with linseed. Opposite results were obtained for vetch. On Chernozem soil greater SRL value of vetch was measured in pure crop than in mixture with linseed, while on Cambisol the results were contrary.

Songsri et al. (2009) claimed that the genotypes with larger root systems could maintain relatively high water effectiveness under water stress conditions. His studies demonstrated that root parameters are important traits relating to water efficiency under moderate and severe drought, respectively. Under drought stress the species with large root systems could obtain more water than the species with small ones. Our investigation did not support Songsri et al. (2009) claims. In Prusy (Chernozem), short-term droughts have occurred during the growing season, legumes were characterized by high SRL parameters regardless of sowing method. Ours results confirmed studies conducted by Leuschner and Hertel (2002). Researches found a highly significant positive relationship between root biomass and annual precipitation. According to Ostonen et al. (2007) enhanced nutrient availability under fertilization reduces the need for explorative root length growth and thus account for decrease in SRL. Specific root length decreased significantly with increasing concentration of soil nutrients. In our studies, lower values of SRL were measured for linseed mixture with pea or vetch comparing to pure sow. It appears that pea or vetch, which are able to fix nitrogen from the atmosphere, enriched soil with this element and then provided some of the nitrogen to accompanying plant – linseed. Better conditions for linseed growth were observed in the mixture and therefore it had less developed root system.

CONCLUSIONS

Root system demonstrated high degree of plasticity in their development in response to soil type and plant intercropping. Better soil conditions, described by higher amount of water absorption, significantly differentiated the SRL of the species tested. The SRL index significantly increased along with amount of total (TP) in Cambisol. Higher value of SRL in response to higher TP was noticed for legumes in mixture. Significant positive relations between SRL and TP in legumes cultivated in mixture with linseed increased with increasing amount of precipitation (TP). The highest correlations of SRL and TP were observed for pea in mixture with linseed. SRL value of vetch depended on sowing type and weather conditions. In brown soil vetch cultivated in pure sow had the highest value of SRL, whereas vetch in mixture with linseed had the lowest SRL value.

REFERENCES

Blum, A., 1996. *Crop responses to drought and the interpretation of ada*ptation. Plant Growth Regulation, 20: 135-148. DOI: 10.1007/BF00024010

Cox, J.A., Conran, J.G., 1996. *The effect of water stress on the life cycles of Erodium crinitum Carolin and Erodium cicutarium (L.) L'H erit. ExAiton (Geraniaceae*). Australian Journal of Ecology**,** 21: 235-40.

Erice, G., Louahlia, S., Irigoyen, J.J., Sanchez-Diaz, M., Avice, J.C., 2010. *Biomass partitioning, morphology and water status of four alfalfa genotypes submitted to progressive drought and subsequent recovery*. Journal of Plant Physiology, 167: 114-120. DOI:10.1016/ j.jplph.2009.07.016

Grace, J.B., 1990. *On the relationship between plant traits and competitive ability*. In: Grace, J.B. & Tilman, D. (eds.), Perspectives on plant competition, pp. 51-65, Academic Press, San Diego, CA.

Hussain, A.M.N., Ahmed, A.S., 1990. *Protect chillies crop from Phytophthora, a new disease in Pakistan*. Capsicum Newsletter, 8: 9-59.

Jensen, E.S., Ambus, N., Bellostas, N., Boisen, S., Brisson, N., Corre-Holou, G., Crosat, Y., Dahlman, C., Dibet, A., Fragstein, F., Gooding, M., Hauggaard-Nielsen, H., Kasyanova, E., Launay, M., Pristeria, A., 2006. *Intercropping of cereals and grain legumes for increased production, weed control, improved product quality and prevention of N-losses in European organic farming systems*. Proceedings of the European Joint Organic Congress: 180-181.

Jędrszczyk, E., Skowera, B., Kopcińska, J., Ambroszczyk, A.M., 2012. *The influence of weather conditions during vegetation period on yielding of twelve determinate tomato cultivars.* Notulae Botanicae Horti Agrobotanici, Cluj-Napoca, 40: 203-209. http://www.notulaebotanicae.ro/ index.php/ nbha/article/view/8252/7056

Kooistra, M.J., Van Noordwijk, M., 1995. *Soil architecture and distribution of organic carbon*. In: M.R. Carter, B.A. Stewart (Eds.), Structure and organic matter storage in agricultural soils. Boca Raton (USA) etc., Lewis, 1996. Advances in Soil Science: 15-56.

Körner, C., Renhard, U., 1987. *Dry matter partitioning and root length/leaf area ratios in herbaceous perennial plants with diverse altitudinal distribution*. Oecologia, 74: 411-418.

Leuschner, C., Hertel, D., Coners, H., Büttner, V., 2001. *Root competition between beech and oak: a hypothesis.* Oecologia, 126: 276-284. DOI: 10.1007/s004420000507

Mortimer, SR., 1992. *Root length/leaf area ratios of chalk grassland perennials and their importance for competitive interactions*. Journal of Vegetation Science, 3: 665-672. DOI: 10.2307/3235834

Olff, H., 1992. *On the mechanisms of vegetation succession*. Doctoral Thesis, University of Groningen.

Ostonen, I., Püttsepp, Ü., Biel, C., Alberton, O., Bakker, M. R., Lõhmus, K., 2007. *Specific root length as an indicator of environmental change*. Plant Biosystems. 141: 426-442. DOI: 10.1080/11263500701626069

Patterson, T.B,, Guy, R.D., Dang, Q.L., 1997. *Whole-plant nitrogen- and water-relations traits, and their associated trade-off, in adjacent muskeg and upland boreal spruce species*. Oecologia, 110: 160-168. DOI: 10.1007/s004420050145

Poot, P., Lambers, H., 2003. *Are trade-offs in allocation pattern and root morphology related to species abundance*? *A congeneric comparison between rare and common species in the south-western Australian flora*. Journal of Ecology, 91: 58-67. DOI: 10.1046/j.1365-2745.2003.00738.x

Ryser, P., 1998. *Intra- and interspecific variation in root length,root turnover and the underlying parameters.* In: Lambers, H., Poorter, H., van Vuuren, M.M.I. (Eds.), Variation in plant growth. Backhuys Publishers, Leiden: 441-465.

Skowera, B., Puła, J., 2004. *Pluviometric extreme conditions in spring season in Poland in the years 1971-2000*. Acta Agrophysica, 3: 171-177.

Sponchiado, B.N., White, J.W., Castillo, J.A., Jones, P.G., 1998. *Root growth of four common bean cultivars in relation to drought tolerance in environments with contrasting soil types*. Australian Journal of Experimental Agriculture, 25: 249-257. DOI:10.1017/S0014479700016756

Songsri, P., Jogloy, S., Holbroock, C.C., Kesmala, T., Vorasoot, N., Akkasaeng, C., Patanothai, A., 2009. *Association of root, specific leaf area and SPAD chlorophyll meter reading to water use efficiency of peanut under different available soil water*. Agricultural water management, 96: 790-798. DOI: 10.1016/j.agwat.2008.10.009

Spollen, W.G., Sharp, R.E., Saab, I.N., Wu, Y., 1993. *Regulation of cell expansion in roots and shoots at low water potentials*. In: Smith, J.A.C., Griffiths, H. (Eds.), Water deficits: plant responses from cell to community. Oxford: Bios: 37-52.

Ufoegbune, G.C., Ogunyemi, O., Eruola, A.O., Owomeso, J.A., 2010. *Variation of interception* *loss with different plant species at the University of Agriculture*, Abeokuta, Nigeria. African Journal of Environmental Science Technology, 4: 831-844. DOI: 10.5897/AJEST10.130

Van Noordwijk, M., Purnomosighi, P., 1995. *Root architecture in relation to tree-soil-crop interactions and shoot pruning in agroforestry*. Agroforestry Systems, 30: 161-173. DOI: 10.1007/BF00708919

Van Noordwijk, M., Widianto, M., Hairiah, K., 1991. *Old tree root channels in acid soils in the humid tropics: important for crop root penetration, water infiltration and nitrogen management*. Plant and Soil, 134: 37-44. DOI: 10.1007/BF00010715