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Effect of soil compaction on root growth and crop yield in Central and Eastern Europe

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A b s t r a c t. Variations in root growth and functions in response to soil compaction associated with soil and crop type, and soil wetness at the time of load application and weather in Central and Eastern Europe are reviewed. The effects of soil compaction on the morphological and anatomical modifications of the roots were shown. The influence of soil compaction on plasticity in root growth and functioning in relation to structural discontinuity is discussed. Possible mechanisms of root-shoot relations as affected by soil compaction are presented. Crop yields on compacted soil largely depend on weather conditions and initial soil compactness.

K e y w o r d s: soil compaction, root growth and functions, root-shoot relations

INTRODUCTION

Soil compaction has been recognised as a major physical threat to soil fertility throughout the world [57]. The increasing use of heavy machinery is the major cause of soil and subsoil compaction. Strong compaction occurs when heavy combine harvesters and transport vehicles are used in high soil wetness. Such conditions are common during the harvest of root crops in the autumn in many countries [23,71].

Alterations in aggregate and pore structure by soil compaction influence several aspects of the soil such as soil strength, air and heat. Soil compaction effects are long lasting or even permanent, particularly in soils with a low clay content [19]. These alterations strongly affect root growth and functions and thereby contribute to crop production and to the leaching of agrochemicals. In this paper we review the effects of soil compaction on root growth and functions and crop yield. This work was done within the framework of INCO-Copernicus project on soil compaction in Central and Eastern Europe.

ROOT DISTRIBUTION

A common response of the root system to increasing bulk density is to decrease its length, concentrating roots in the top layer and decreasing rooting depth [24,33,46,61]. Figure 1 presents the effects of compaction in the plough layer on the root distribution of spring barley grown on variously textured [4] soils of several countries. It is worth noting that irrespective of soil type and country, root distribution was similar. In all experiments, soil compaction led to the higher concentration of roots in the top layers and reduced roots in the deeper layers. A similar response increased the potential for the exchange and mutual use of the results – so far obtained – of expensive experiments performed in different countries. Better rooting in loose soil can also be partly due to the warmer top layer compared to that in compacted soil early in the growing season [33]. The effect of soil compaction on root growth was well predicted by the SIBIL model [54].

This concentration of roots in the upper layer of compacted soil can be due to more horizontal growth. In strongly

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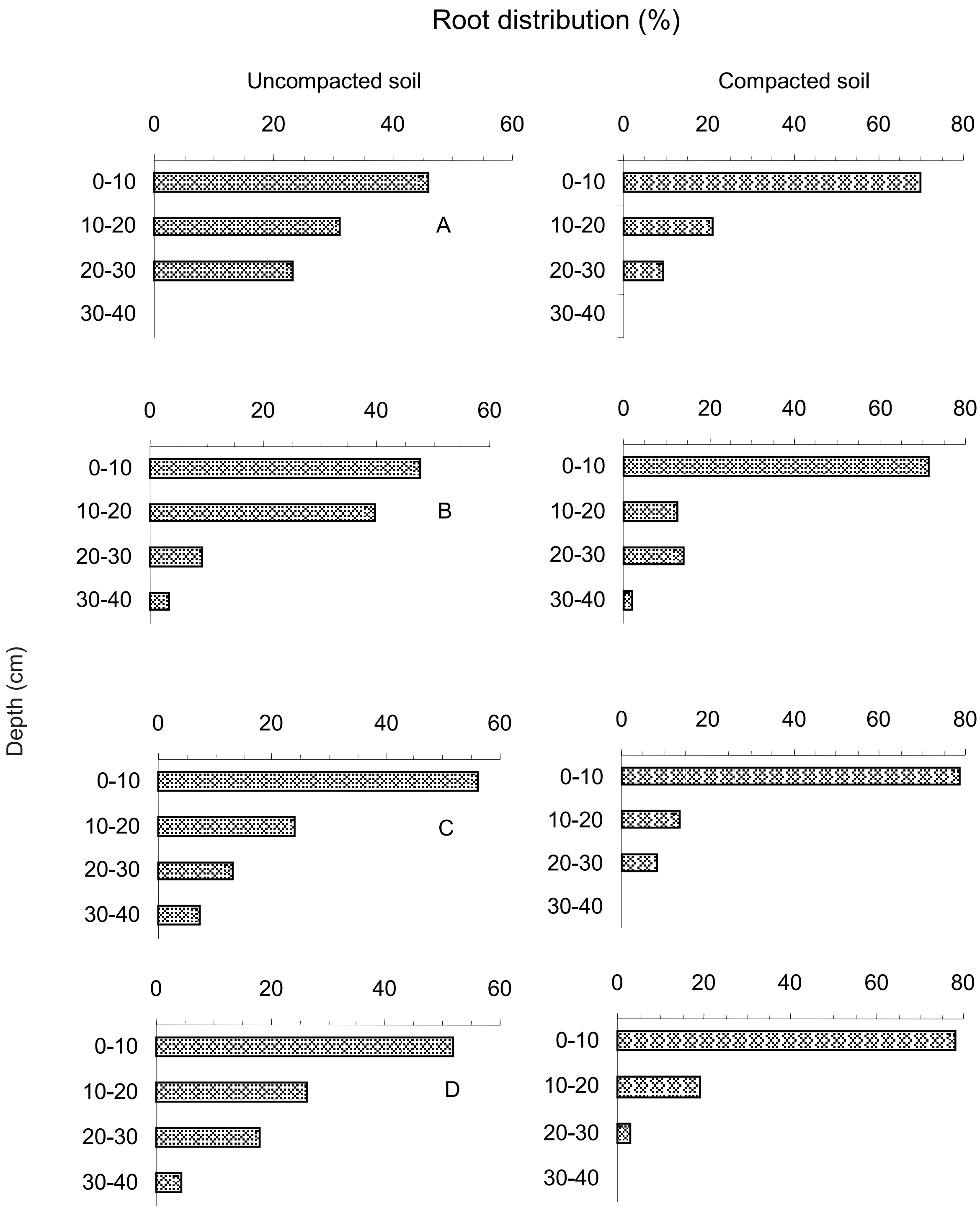

Fig. 1. Relationship between root distribution of spring barley and soil bulk density in the plough layer. A – typical chernozem (heavy loam), Kharkiv Region, Ukraine (after Medvedev *et al*. [46]); B – Gleyic Cambisol (loam), Slovakia (after Jurcova and Zrubec [24]); C – Orthic Luvisol (silty loam), Lublin Region, Poland (after Lipiec *et al*. [33]); D – Leptic Podzol (loamy sand), Lublin Region, Poland (after Lipiec *et al*. [33]).

compacted soil, such root distribution can be partly attributed to the horizontal orientation of pores [56]. Deeper but reduced root growth was attributed to excessive mechanical impedance (3 MPa), especially in dry seasons and insufficient aeration (air-filled porosity <10%) in wet seasons [32,46].

The effect of soil compaction on root growth largely depends on the type of tractor used and soil wetness during tractor use [33,61,62]. Figure 2 shows that the reduction in root size of oats in the ploughed layer increased with the weight of the tractor wheels and the soil water content. In deeper soil the relation was less pronounced indicating that root growth is affected by other factors.

Root growth is also largely limited by plough pan or dense layers induced by pedogenetic compaction in the soil profile [5,46,49,69]. Usually, such layers can be localized at sites with the maximu bulk density and the cone resistance in the soil profile [39] or aeration parameters in wet soil [16]. An increase in subsoil compaction resulted in the higher concentration of roots in the upper part of the subsoil layer and in reduced rooting in the deeper layers. In general, this effect increased with the decreasing depth and thickness of the dense layer [5]. In acid soils the physical constraints on root growth are accompanied by low pH [15,29]. In soils with the water table within the root zone, root development may be affected not only by anoxic conditions, but also by the lower soil temperature in cold climates and by the presence of salt in hot climates [70].

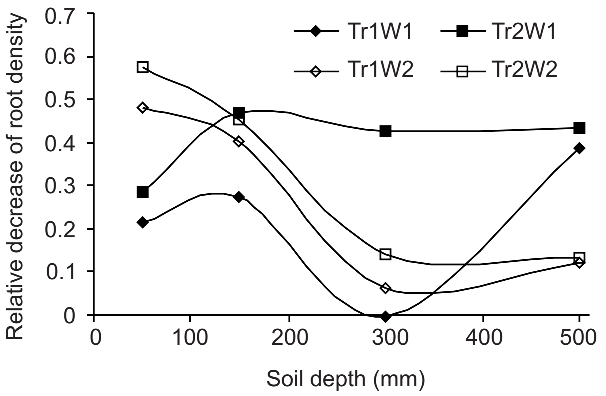

Fig. 2. Relative decreases of root density in oat harvests, depending on the type of tractor (Tr1 and Tr2 with respective weights of 5400 and 3030 kg and contact area pressures of 35 and 47 kPa), the antecedent soil moisture content (W1 = 0.28 g g^{-1} and W2 = 0.37 g g^{-1}) and the soil depth (after Stoinev and Ivanov [62]).

To improve root penetrability in compacted soils, Calcium microelements, growth stimulators, optimization of the depth of the mineral fertilizers, soil surface mulching were applied [45,46]. These practices improved growth and the physiological activity of the cereal's roots grown in compacted layers of Phaeozem in the Ukraine [45]. At the same time the enhanced root growth caused loosening of the layers.

Root response to soil compaction depends on the presence and distribution patterns of pores – having a diameter greater than the roots – and on pore continuity. A soil matrix with a larger pore size, structural cracks, macropores and worm holes will offer greater potential for undisturbed root growth because the roots can by pass the zones of high mechanical impedance [15,35]. They can also benefit in poorly aerated soils since they drain at higher water potential and remain air-filled for longer compared to smaller pores. An important property of the vertical biopores in deeper soil is that they are able to resist vertical compression and they remain stable as the soil swells [68].

MORPHOLOGICAL AND ANATOMICAL MODIFICATIONS

Experiments in growth-chambers under controlled conditions showed that the proportion of main axes decreased whereas that of secondary roots increased with increasing soil compaction (Table 1).

The roots of spring barley grown in severely compacted soil were characterised by a greater diameter, a higher degree of flattening, radially enlarged cortex cells, twisted growth and an irregular surface with distorted epidermal cells which had been penetrated by soil particles [15,33]. The wider cortex cells with their greater absorptive surface area will aid in overcoming nutrient stress. The thickening of roots grown in compacted soil indicates the absence of pores with a diameter equal to – or larger than – the roots. It is suggested that thicker roots aid penetration of roots in stronger

Table 1. Selected root characteristics as related to soil compaction. L – loose, MC – medium compacted, HC – heavily compacted (after Lipiec and Szustak [43])

Treatment	Total dry weight of roots (mg)	Contribution of roots (%)			Specific root weight (m g^{-1} dry roots)		
		seminal	nodal		seminal	nodal	
			axes	secondary		axes	secondary
L	602	41.6	42.4	16.0	79.6	155.3	47.1
MC	446	38.5	48.1	13.4	52.1	132.3	36.6
HC	367	29.8	55.9	14.3	43.3	119.9	32.1

soil by increasing growth pressure and resistance to buckling [47]. The tortuous root growth can be partly due to root conforming to structural ped surfaces. Growth of roots in compacted soil requires much greater energy to form and sustain a unit of root length [15]. The alterations in root growth affect root functioning and shoot growth.

WATER AND NUTRIENT UPTAKE

Experiments performed in growth chambers allowed the physical conditions of the soil to be controlled, the precise measurements of the water uptake to be taken and the effects of the different weather conditions to be eliminated. Under conditions of sufficient water supply, total water use decreased with an increasing soil compaction level while the root water uptake rate was highest in moderately compacted soil (Fig. 3). The results indicate that moderate soil compaction can provide a better opportunity for a restricted system, to absorb more water and to increase water use efficiency, owing to the higher unsaturated hydraulic conductivity and greater water movement towards the roots and the better root-soil contact area.

An important factor affecting root growth and water use in the field is vertical strength discontinuity. A sharp discontinuity occurs between the aggregated seedbed and the soil below, between the plough layer and the subsoil. Soil column experiments showed that root length of maize in subsoil horizons (below 30 cm) relative to the total root length varied from 1 to 38% while water use varied from 54 to 74% depending on soil type [36]. In other experiments [40] with continuous water supply, total water use and the efficiency of water use by wheat roots were greater from silty loam than loamy sand subsoil. In both soils the water use from the upper subsoil layer (25–35 cm) was greater than from the deeper subsoil layer (35–45 cm).

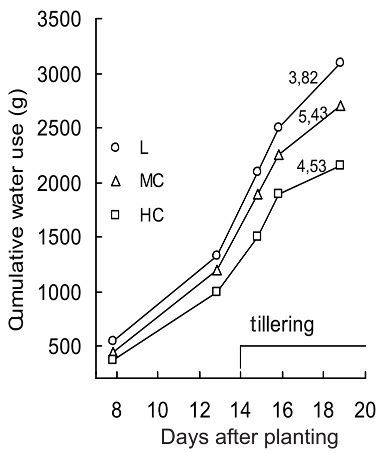

Fig. 3. Cumulative water use by spring barley (nine plants) grown on silty loam soil in growth-chamber experiment. L – loose soil, MC – medium compacted, HC – heavy compacted. Root uptake rate (mm^3 H_2O mm^{-1} root day^{-1}) is indicated after Lipiec and Szustak [43].

Another discontinuity is uneven horizontal soil compaction related to the distribution of wheel tracks [2,67]. In split root experiments, the reduced root growth of wheat and associated total water use from compacted soil were partly compensated for by loose soil of the same pot [48]. This compensatory effect was more pronounced at soil water potential – 8 kPa than – 35 kPa (lower soil wetness).

The data indicates the wide plasticity in root water absorption in response to localised soil compaction. This is significantly important in model predictions of plant water use [40,53,66].

Soil compaction affects nutrient transformations and uptake through changes in the soil's hydraulic, aeration, and diffusive properties and root growth and configuration [42]. Reduced nutrient uptake resulted in the lower effectiveness of fertilisers [30,60]. The lower uptake of Nitrogen by plants and greater denitrification enhance N losses to the groundwater and to the atmosphere [58]. Under moderate compaction, an increase in nutrient inflow rate per unit root length or root surface alleviates the reduction in total nutrient uptake [42].

Higher rates of fertilisers in use on compacted soil to overcome crop yield losses increase the potential for nutrient loss [42]. Greater distances between neighbouring roots in compacted soil enhance these losses. It was shown [34] that half the distance between the nearest maize roots on horizontal planes within a depth of 20 cm is below 0.81 cm for loose soil and increased with an increasing degree of compactness. In most compacted soil the corresponding value was up to below 5.64 cm. However, the absorption of water and nutrients takes place usually in soil adjacent to the root surface from 0.2 to 0.8 cm depending on soil and nutrient types [72].

ROOT-SHOOT RELATIONS

Reduced root growth and uneven root distribution in compacted soil influences the stomatal resistance of leaves which is an important determinant of crop yield. As Fig. 4 shows, the differences in stomatal resistance of spring wheat between the compaction treatments were much greater during droughts, mostly due to its increase in the most compacted soil. As a consequence, the grain yield in the most compacted treatment was reduced by 22%. A substantial increase in the stomatal resistance of plants grown in most compacted soil also occurred in high soil wetness and the associated low air-filled porosity of the laboratory experiment [37].

Several mechanisms are suggested for stomata closure. One mechanism under poor aeration is the reduced water flow through the roots [16]. Accumulation of abscissic acid (ABA) in the leaves seems to induce stomata closure through its effect on the potassium ion regulation of guard cell turgor [59,63]. The stomata resistance of maize grown

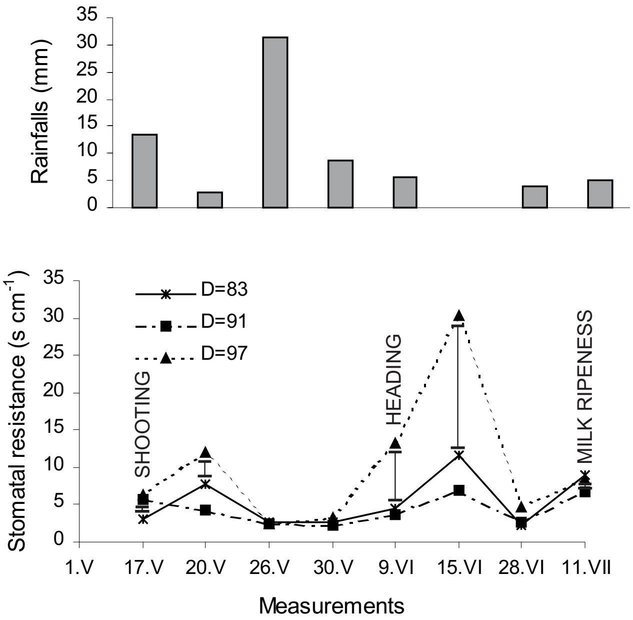

Fig. 4. Stomatal resistance of spring wheat on various occasions during the growing season in relation to three compaction levels and rainfalls (after Lipiec and Gliñski [31]).

in poorly aerated soil was considerably higher in the lower than in the upper leaves [37] and may imply the upward movement of plant hormones or other substances to the shoots [9,63]. This can be supported by recent study [3] indicating that superoxide dismutase (SOD, metalloenzyme, protects aerobic organisms against oxygen activated toxicity) activity in the roots which had been increased earlier (after two days of oxygen stress) while that in the leaves started to increase later (after 8 days). Increased abscissic acid content in the leaves [1] and a greater stomata diffusive resistance in the lower as opposed to the upper leaves [31] have also been observed under dry soil conditions. Some authors [21,63] point out that ABA increase in plants grown in compacted soil is a result of root dehydration due to the limited water supply to the roots. Wartinger *et al.* (1990) (quoted after Horn [22]) and Horn [22] indicate that ABA concentration in plants generally increased proportionally to the previous maximum reduction of water available to the plant rather than water which is not available to the plant. Ali *et al.* [1] reported that the increased leaf stomata resistance occurred even before a measurable change in leaf water potential.

The increased stomatal resistance together with the decreased leaf area index may largely account for crop yield in compacted soil. In experiments performed in the Ukraine the highest yield of barley and millet was obtained on moderately compacted soil (Table 2). A similar parabolic response of cereal yields to compaction was observed in Sweden [18], Germany [52], Poland [51], Bulgaria [60,65] and Lithuania [64] in those experiments where a wide range of bulk densities was compared. In other experiments crop yield decreased with increasing soil compaction [7,8,10, 12,13]. The response under Romanian conditions has been attributed to high initial soil compactness due to the farming system, as well as to the droughtprone climatic conditions.

The values of the ratio of grain yield to roots (Table 2) indicate that soil compaction reduced more the latter than the former. The lower rooting depth and surface concentration of roots in severely compacted Luvisols and the resulting smaller water uptake from the deeper layers was one of the main factors contributing to the yield reduction of spring barley in Poland [26]. These results are in agreement with findings reported by Medvedev *et al*. [46] showing that despite the same root size of winter wheat in the arable layer of uncompacted and compacted soil, the crop yield was lower by 20% in the latter. The yield reduction in Poland was more pronounced in years with unfavourable sowing-shooting weather conditions (low rainfall, high sunshine duration and high air temperature) and on coarse-textured soils of low water holding capacity [26]. However, no negative effect of the dry season was observed on maize grown on compacted Calcaro-Haplic Phaeozem in Slovakia owing to the greater storage of water in the subsoil and thus improved plant water supply [14].

T a b l e 2. Yield and root size of barley and millet as affected by soil compaction (after Gritsaj [17])

Bulk density ($Mg\ m^{-3}$)	Grain ($Mg\ ha^{-1}$)	Roots ($Mg\ ha^{-1}$)	Grain:Roots
	Barley – Chernozem typical heavy loamy		
0.95	1.94	2.31	0.84
1.15	2.05	1.79	1.14
1.35	1.16	1.17	0.99
	Millet – Grey Forest podzolized light loam		
1.06	3.54	2.31	1.53
1.24	4.06	1.98	2.05
1.34	3.88	1.73	2.24
1.51	3.20	1.29	2.42

Root crops are traditionally regarded as particularly sensitive to compaction [41]. Sugar beet was shown to be a crop which is very sensitive to overcompaction in Romania [55], the Czech Republic [28], Slovakia [14], Russia [27], Poland (Pabin *et al*. [50]) and Hungary [4,11]. In the case of carrots and potatoes, soil compaction resulted in a reduced yield and increased the proportion of small and deformed roots and tubers, unsuitable for processing [13,25, Starczewski *et al*., 1984, quoted by Lipiec and Simota [41]. A characteristic morphological response of sugar beets and carrots to mechanical impedance in compacted soil is their forking and fanging [15]. Field studies in Hungury [4] on chernozem soil revealed that the percentage of deformed roots increased significantly with the decreasing depth of the compacted layer in the soil profile (Table 3). At the same time root yield reduced.

The reduction in root yield of the crop was accompanied by a decrease in sugar content [5,11,55]. Figure 5 illustrates the effect of soil compaction on the reduction of sugar beet yield and sugar content. It is worth noting that sugar beet root yield is less affected by soil compaction in the dry season – as compared to the wet season. This implies that the effect of soil compaction in the dry season was masked by a moisture deficit. The reduction of sugar content was greatest in most compacted soil in the dry season. Sugar beets grown in mechanically impeded soil contained more harmful non-sugars [15].

Medvedev *et al*. [46] reported that crop yield on the typical chernozems was still reduced 5–6 years soil compaction penetrated also to the subsoil. The length of time is longer or even permanent in non-swelling and shrinking sandy soils or warm climates with only minimum freezing or with no annual freezing [20].

CONCLUSIONS

Investigations carried out in Central and Eastern Europe within the framework of the INCO-Copernicus project allowed the following conclusions to be drawn:

1. An increase in soil compactness results in decreased root size, the higher concentration of roots in the upper soil, lower rooting depth and a greater distance between the nearest roots. Roots of barley grown in severely compacted soil are thicker and flattened with radially enlarged cortex cells.

2. Insufficient water supply decreased in compacted soil whereas the efficiency of the use of water by the roots increased. Both nutrient uptake and effectiveness of fertilization is reduced by soil compaction.

3. Greater stomatal resistance with lower of plants in most compacted soil is attributed to lower root size and rooting depth. Crop yield increased in moderately compacted soil and decreased with further compaction or decreased

T a b l e 3. Yield response and proportion of deformed roots of sugarbeet in chernozem soil (clay content 41%) in Hungary (average values from 1995–1997) (after Birkás and Gyuaricza [4])

Location of compacted layer (cm)	Decrease of yield (%)	Deformed roots (%)
Non-compacted	100% = 32.54 Mg ha^{-1}	2.1
< 28	10–13	5.6
< 22	21–25	13.4
6–10 and below 28	29–32	18.8
0–30 (compacted after sowing)	55–59	53.2
$LSD_{0.05}$	16.3	2.0

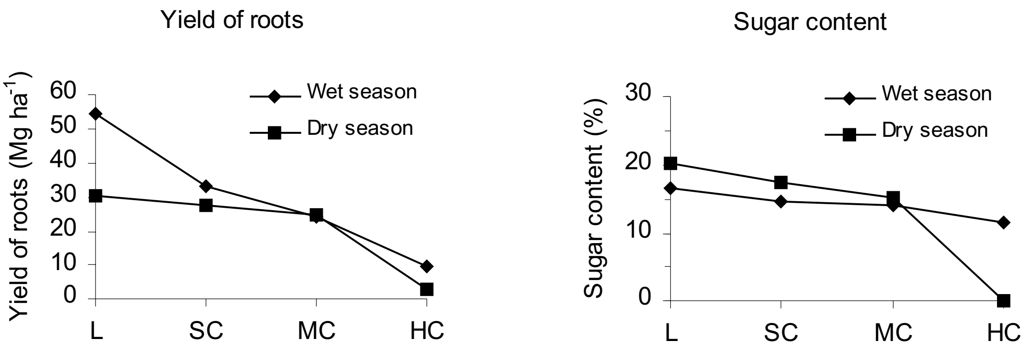

Fig. 5. Yield of storage roots and sugar content of sugar beets. L – loose soil, SC – slightly compacted, MC – medium compacted, HC – heavy compacted (after Csorba [11]).

with soil compaction depending on initial soil compactness, weather and soil type. Yield reduction in compacted soil accounts for greater stomatal resistance and smaller leaf area. The lower root yield of sugar beets was accompanied by a decrease in sugar content.

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