Subsoil Compaction as a Climate Damage Indicator

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Summary

Some forms of soil compaction occur on arable lands both in Hungary (1.82 million ha) and in Croatia (0.97 million ha) having negative impacts on agricultural production. Tillage-induced subsoil compaction has often occurred in the Pannonian region in relation to traffic-induced compaction. Soil compaction has become a soil management problem during the last decade as a result of the occurrence of periods of water-logging as well as droughts. This study contains an evaluation of factors relating to subsoil compaction, as indicator of climate effects on arable fields. This paper is based on soil condition monitoring and measuring that was started 32 years ago and on short and long-term experiments modelling and checking the extension of compaction in the soil. The survey comprised 1526 monitoring places and 38 experimental plots. The following five points were chosen for monitoring: 1) root zone state (to a depth of 0-60 cm); 2) occurrence of compacted layer (indicating likelihood of risk); 3) extension of the compacted layer (indicating the degree of damage); 4) long term effects of tillage (soil state deterioration or improvement), and 5) tillage-induced water-logging and drought damage impacts on yield loss. The main objectives of the experiments were: 1) occurrence and the extent of tillage-pan damage in soils of different susceptibility to compaction; 2) consequences on water management in each of the years covered by the experiments; 3) soil quality consequences, and 4) alleviation of pan-compaction by mechanical and biological methods. Long-term field monitoring and experimental work have both convincingly proven a correlation between subsoil compaction and the degree of climatic damage. In view of the findings, trends in soil tillage can be grouped into the following two categories: climate damage mitigating and climate-stress increasing ones. The formation and location of compacted layers provided information concerning the depth, the method and the type of tillage applied, along with the expected risk for crop production under extreme climate conditions.

Key words

compaction, climate, indicator, alleviation

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Introduction

Soil compaction is a consequence of natural processes and human activity. Compaction of the latter type has been caused by man ever since the first forms of agricultural production appeared (Van Ouwerkerk and Soane, 1994) and is now present in countries of advanced agricultural sectors just as well as in countries of poorly developed agriculture. In the Pannonian region tillage-induced compaction affected increasingly large areas during the nineties as a result of deteriorating general economical conditions and a decline observed in *tillage culture* itself (Birkás et al., 2004). Authors discussing aspects of soil compaction in the Pannonian region consider that under less favourable economic conditions tillage-induced soil compaction occurs more frequently than does traffic-induced soil compaction (e.g. in West Europe the latter type of damage outweighs the former type; Hakansson, 1994; Lipiec and Simota, 1994; Birkás, 2000; Tursić et al., 2008). Soils susceptibility to compaction is influenced by physical features, structure, bearing capacity and soil moisture content. Organic matter content is of outstanding importance, because the lower its organic matter content, the more susceptible a soil is to compaction (Soane, 1990; Várallyay, 2007).

Types of tillage-induced soil compaction may be grouped according to the depth of occurrence (compaction in top layer, and subsoil compaction; Canarache, 1991) – or by cause (disk pan - plough pan compaction). In both of the latter two ones compaction is caused by operating the tillage implement in the same depth over and over again, in humid or wet soil. Plough pan forms in the ploughed layer, depending on the most frequent ploughing depth; anywhere between 22 and 35 cm (Birkás, 2000). Disk pan forms underneath the most frequent disking depth; between 12 and 20 cm (Birkás, 1987; Chen and Tessier, 1997).

The detrimental consequences of tillage-induced soil compaction have been identified by a number of researchers (Chen and Tessier, 1997; Gyuricza, 2000; Horn et al., 2000; Birkás et al., 2008). Some of the most noteworthy consequences include structure deformation, intensification of anaerobic processes, breakdown of useful biological processes and the decomposition of field residues. Tillage of compacted soil – regardless of its moisture content – takes an increased energy input and the increment is to be booked as a loss (Birkás 1987, 2000). From the aspect of crop production restricted water intake, drainage and storage as well as the blockage of the movement of water from deeper soil layers towards the root zone, are some of the most unpleasant consequences of soil compaction. As an overall consequence of the above changes compaction in the root zone causes an indirect water shortage which will substantially reduce plant growth and production in a dry period. Compaction has a complex impact on plants, including restricting the depth of root growth, water and nutrient uptake and, as a consequence of these effects it restricts the growth and development of the parts and organs of the plant above the ground. A plant of impeded growth is less resistant to pests, pathogens and weeds. Physiologically immature ripening during a period of drought is, in many cases, a consequence of actual and relative shortage of water, in addition to the effects of a long period of extreme heat. Soil compaction has been discussed by many authors in a large number of publications and some publications contain data concerning estimated and actual losses of energy and yields as well. Despite the rapid increase in the number of works focusing on global climate change as well, few references were found (e.g. Lipiec and Simota, 1994; Kvaternjak et al., 2008), concerning potential relationships between soil compaction and susceptibility to climate extremes or between the location (depth) and heaviness of the compact layer and the likely climate damage.

Material and methods

This paper is based on soil condition monitoring and measuring that was started 32 years ago in Hungary by the Department of Soil Management at Szent István University Gödöllő (Birkás et al., 2004), and in Croatia by the Department of General Agronomy, Faculty of Agriculture, University of Zagreb (Kisić, 2008; Mesić et al., 2008) and by the Department of Crop Production at Strossmayer University in Osijek (Jug et al., 2007; Sabo et al., 2007). Soil condition monitoring is aimed to assess: 1) whether there is harmful compaction in the top 60 cm layer of the soil, and if there is, 2) at what depth it is to be found, and 3) how extensive the damage is. Additional tasks include assessing and evaluating impacts on soil, environment and plants, particularly in periods of drought and in those of excessive precipitation. Periods of extremely dry weather occurred in the eighties and in the nineties as well, but the authors paid particular attention to signs of and trends in global climate change (2000, 2003 and 2007) and to their consequences. Preliminary soil condition-related measurements were carried out with the aid of soil probes, followed by actual measurements with the aid of penetrometers and in some cases in sample pits. Measurements were taken and studies were conducted in soils under the following crops between 1976 and 2001: winter wheat (2800 ha), maize (4090 ha), sugar beet (550 ha), sunflower (1340 ha); peas (370 ha), and others (alfalfa, tomato, winter and spring barley, 570 ha), total 9720 ha, and under the following crops between 2002 and 2007: winter wheat (1197 ha), maize (1195 ha), sugar beet (507 ha), sunflower (717 ha), winter oil-seed rape (715 ha), others (alfalfa, tomato, winter barley, pea, 359 ha); that is, on a total area of 4690 hectares. The involvement of winter oilseed rape fields was necessitated by the utilisation of this crop for the purposes of the energy sector and the growth in the area on which it is produced.

Conventional (CT), reduced (RT) or shallow (ST), direct drilling (DD) and soil condition improving tillage variants at each of the three production sites were involved in the long term tillage experiments. Crops that are best suited to the given production site are grown in the experiments, e.g. the Croatian scientists were focused on winter wheat, maize and soybeans, while the Hungarian scientists were concentrated on winter wheat, maize and sunflower. In recent years the studies were extended to relationships between soil quality and climate effects. The experiments are set up, the tillage variants are arranged and the measurements of the soil condition parameters and the crops responses were taken at each of the three locations in accordance with the relevant standards and regulations (Tóth et al., 2005; Tóth and Koós, 2006; Jug et al, 2007; Kisić, 2008; Birkás, 2008; Birkás et al., 2008).

This paper discusses the following aspects: 1) studying relationships between the occurrence, position (depth) and the thickness of tillage-induced soil compaction and losses caused by climate extremes, and 2) assessment of potential impacts of climate changes (milder winters of more precipitation and warm/hot dry summers) expected according to various climate scenarios on compacted soils and offering possible solutions. The authors present measurements and findings that may be also applied as indicators in the relevant models.

Results and discussion

Studying relationships between the occurrence, position (depth) and thickness of tillage-induced soil compaction and losses caused by climate extremes

The most frequently encountered positions (depths) of soil compaction resulting from wrong tillage practices have been regularly scrutinised in fields of soils of different physical types – sandy loam, loam, clayey loam, clay and heavy clay, in terms of clay content: 26-30, 40-60, 60-70, and 80-85 %, respectively – since 1976. This 32-year period has been divided into five phases by tillage mode and soil condition: 1976-1987: a phase of *development*, 1988-1990: a phase in which development *ground to a halt*, 1991-1997: a phase of *decline*, 1997-2001: a phase of *transition*, 2002-2007: a phase of *a new beginning*.

Initially a total of 13 *typical versions* of *compaction* caused by wrong tillage practices were identified, later on this number was reduced to 10, then to 9 and finally to the following 7 versions: 1) favourable to a depth of 60 cm; 2) favourable to a depth of 40 cm; 3) compaction below 28-32 cm; 4) compaction below 22-26 cm; 5) compaction at 18-22 cm; two compact layers below 16 cm, and 7) three compact layers below 16 cm (Table 1). The categorisation is necessitated by the different effects of the different versions (assisted by information supplied by scientists working in Croatia). No similar categorisation has been encountered in other publications so far. The condition described by numerous authors (e.g. Hakansson, 1994; Van Ouwerkerk and Soane, 1994) was categorised as 'compact'. In a compact layer the soil's bulk density was up to 1.59-1.61 t m^{-3} while its penetration resistance - when wet - exceeded 3.0 MPa. The so-called 'favourable looseness' (bulk density not exceeding 1.38-1.48 t m^{-3} and 2.5-2.8 MPa penetration resistance) was characteristic to soils loosened to a depth of 60, 40, 28, 22, 18 or 16 cm and only to such depths.

It is also important that we should use precise definitions of climatic effects. *Climate stress* is temporary damage to soils (and plants) caused by an extended period of extreme heat or by heavy and excessive rains. *Climate damage* is a permanent damage to soil caused by an extended period of extreme heat or by heavy and excessive rains. In cropping this is applied to losses caused by climate extremes. *Climate risk* is the expected or likely consequences of soil state defects or of interventions affecting the soil, in a growing season of extreme weather patterns.

The *loosened state of the root zone* (the state of the top 60 cm soil layer) shows whether there is any compact layer in the root zone blocking water transports. The following has been concluded from crop and yield assessments and evaluations between 2000 and 2007 at a total of 1,526 sites:

In the soil profile concerned:	Soil susceptibility	Climate damage
no layer blocking water transport	moderate	modest
no layer blocking water transport, settled soil, limited water transport	medium	medium
one or more layers blocking water transport	high	heavy

It was not possible to definitely establish that loosened state of the top 60 or 40 cm is a pre-requisite for mitigating susceptibility to climate damage for we found different results in three drought periods. Looseness to a depth of 40 cm, however, was always more favourable than looseness only in the top 28 cm layer, i.e. looseness to a depth of 40 cm may be taken as an indicator. It should be noted that direct drilling involves no deepening of the cultivated layer at all, at the same time DD that is competitive in comparison to any other type of tillage is characteristic of soils not damaged by tillage pan formation. In our experiments the clay contents of the soils concerned also had an impact on the findings, for deeper loosening had a more effective climate damage mitigating impact in soils of higher clay contents.

The location of the *compact layer impeding water transport* is indicative of the cause of compaction (tillage- or traffic-induced) and of the likely risks. The following were found in the above period at 1,342 sites:

In the soil profile concerned	Soil susceptibility	Climate damage
below 40/60 cm	modest	none or small
in the 28-34 cm layer	low-medium	modest-medium
in the 22-26 cm layer	medium-high	medium-heavy
in the 16-20 cm layer	high	heavy
right from the surface (e.g. 0-35 cm)	high	heavy

The negative effects entailed by the *location (*depth*) of the compact layer* were not affected by the soil properties or clay content: the closer the compact layer was to the surface, the more susceptible the soil and the crop was. Accordingly, this feature is indicative not only of the soil quality but also as a climate indicator. The shallower the layer in which roots could grow and expand the less favourable the conditions were. Compaction between 16 and 20 cm was found primarily in fields of farmers preferring disking as a means of primary tillage and in fields of those choosing disking as secondary tillage after ploughing (Figure 1). Under such soil conditions

Table 1. Subsoil compaction observed on 14,410 ha of land during five examination periods in Hungary (1976-2007; Birkás, 2008)

Location of subsoil compaction	Examination periods				
	1st (1976-1987)	2nd (1988-1990)	3rd (1991-1997)	4th (1998-2001)	5th (2002-2007)
	Percentage of observed land area				
Below 60 cm	14	4	1	0	11
Below 40 cm	22	12	6	2	21
At the depth of 28-32 cm	44	47	42	36	30
Below 22-26 cm	14	22	23	14	21
At the depth of 18-22 cm	6	10	16	22	12
Two compacted layers below 16 cm	0	3	7	14	5
Three compacted layers below 16 cm	0	2	5	12	0
Examined area (ha)	2420	2860	2580	1860	4690

Table 2. Percentage of total agricultural land affected by human-induced soil degradation in selected countries*

Selected countries	Agricultural land area (1000ha)	Soil compaction	Temporary drought/water-logging effects	Wind erosion	Water erosion
		As a percentage of the total agricultural land			
Bulgaria	5 725	47	40/35	15	43
Croatia	3 220	25-35	35/25	10	35
Czech Republic	3 674	40-50	31/27	10	52
Hungary	5 585	30-35	27/23	24	39
Poland	16 136	20-25	16/24	27.6	28.5
Romania	14 714	54	48/26	2.6	43
Slovakia	2 437	26.5	Under monitoring	6.2	43.3

*Data from: Basic (2003), Bielek (2003), Dumitru et al (2002), Janeček (2003), Kozák (2003), Kisic (2008), Lipiec (2007), Szewranski, et al. (2003), Source Ministry of Agriculture and Forestry, Agrostatistics Directorate, Sofia (from "Agro-climatic resources in Bulgaria for field crop cultivation under irrigated and rain-fed conditions"), VUPOP, 2007: Výročná správa Výskumného ústavu pôdoznalectva a ochrany pôdy Bratislava za rok 2006, Bratislava, VUPOP, State of the environment report, SR 2001, and Kobza et al. (2005).

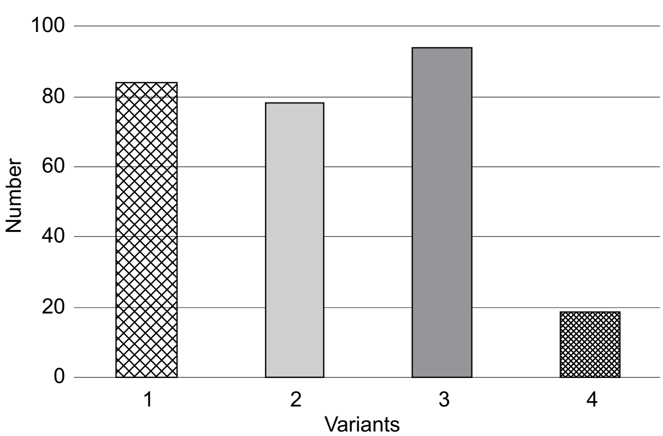

Figure 1. Ploughed soil condition after seedbed preparation (n=275, 2006, April); 1: soil free from compaction, 2: compacted state conserved, 3: recompacted by surface disking, 4: recompacted by seedbed preparation

the assumption that some crops need only shallow tillage (e.g. winter wheat) should be re-considered, since wheat suffered heat stress sooner in soils compacted at 16, 18 or 22 cm during dry years than in soils where compaction occurred in layers deeper down. In fields where there was a compact layer close to the surface some 26, 33 or 51 % of the potential yields could be harvested, respectively (given the required nutrient supplies and crop protection interventions). By contrast, in fields where compact layer was at or below 28, 40 or 60 cm, some 81, 99 and 100 % of the potential yield was achieved where negative impacts of other factors (e.g. nutrient deficit, poor crop protection practices) could be ruled out.

Right in the first years of the monitoring programme the authors found that the *thickness of the compact layer* may be – in relation to the soil water transports – an important indicator. The thickness of the compact layer enables conclusions concerning the gravity and likelihood of loss. The following were concluded from evaluating the results of measurements taken at 1,342 sites:

Thickness of the compact layer in the soil profile concerned	Soil susceptibility	Soil water transport	Climate damage
0-10 mm	low-moderate	excellent - good	modest
10-20 mm	medium	impeded at some points	medium
30-60 mm	high	impeded	heavy
> 100 mm	very high	heavily impeded	very heavy

Authors (Lipiec and Simota, 1994; Chen and Tessier, 1997; Várallyay, 2007) have found that initial tillage-induced soil compaction is substantially affected by the soil moisture and clay content, the machines weight and the smearing, puddling and pressing effects of the tillage implements. The repeated pressure and puddling effects of so-called tillage pan forming elements – plough share, conventional disk plate – in the same dept over and over again result in increasing the thickness of the compact layer. It was found during the monitoring programme that a medium degree of damage (10-20 mm compact layer) may develop in a single growing season of ample precipitation. By contrast, heavier damage (60-100 mm compact layer) was always found to have been caused by the lack of variations in the tillage depth (over a 2-4 year period).

The authors have data from a total of 914 measurements so far concerning *tillage induced stagnant water coverage of the soil surface and drought damage*. Cases where lack of other technological interventions (fertilisation, crop protection) would have affected the findings were not included in the evaluation of the measurements. The following details should be viewed only as working conclusions drawn from information available so far:

Degree of compaction	Surface stagnant water coverage	Loss of yield caused by drought damage %
none	on < 2.5 % of the arable field	< 5
low	on 2.5-5 % of the arable field	5-10
medium	on 6-10 % of the arable field	10-20
heavy	on 11-20 % of the arable field	20-30
very heavy	on 21-30 % of the arable field	> 40

In addition to the condition of the root zone, studies of *tillage and climate effect* deal with the state of the soil surface as well. The state of the root zone affects drainage and the storage of water, while the surface affects infiltration and loss of water through evaporation (Várallyay, 2007). The relationship between soil structure disturbance and the likely climate effect was studied at 1,155 sites. No climate damage or only mild climate damage was observed where the drought period was preceded by a year of tillage interventions aimed at preventing or alleviating compaction and at water and carbon conservation (climate damage mitigating tillage). By contrast, where tillage had been shallower than necessary and where more than the optimum number of tillage passes took place as well as where the surface was left in a shape leading to loss of water and carbon (in other words, climate damage aggravating tillage), the next – droughty – growing season saw substantial losses. Maintaining the soil's favourable water transport conditions can, therefore, be regarded as a drought damage mitigating technique, while tolerating soil conditions hindering water transports will aggravate drought damage. Carbon conservation or loss have indirect effects (compared to Soane, 1990) affecting the sustainability of the soil loosened state and its susceptibility to compaction.

The effects of climate change expected according to the climate scenarios, on compacted soils: possible solution

According to the projections comprised in climate scenarios (e.g. Bartholy et. al., 2008) from the second half of the 21st century the Pannonian region is likely to be characterised by mild and wet winters and warm and dry summers. Moreover, summers will see uneven distribution of precipitation, including intensive rainy periods. The number of windy days will grow and so will the frequency of storm force winds. The appearance of an increasingly well defined rainy season points to the need for improving the soils quality in this region and

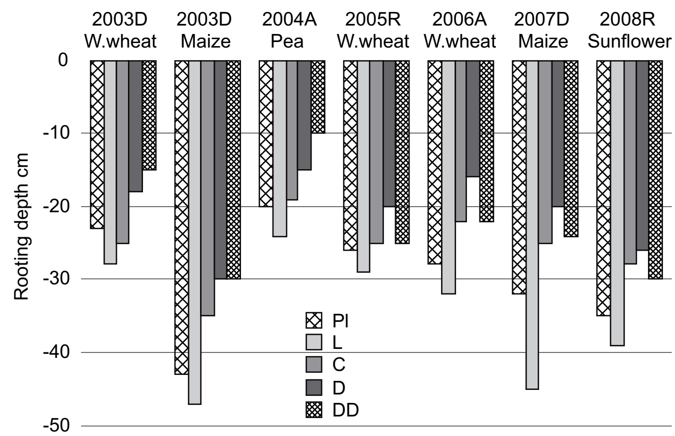

Figure 2. Rooting depths (cm) of crops in experimental conditions (2003-2008) D: dry season, A: average season, R: rainy season, P: ploughed (30 cm), L: loosened (42 cm), C: cultivator used (20 cm), D: disked (18 cm), DD: direct drilled. LSD5%: 2.46, P>1%

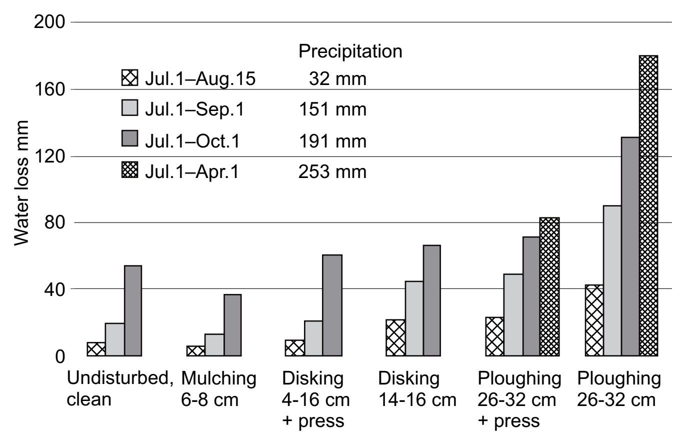

Figure 3. Water loss (mm) from soil prepared differently during periods (July 2006 – April 2007). E = (W_0+P) – W (from Szász and Tőkei, 1997); E = evaporated water during a period, W_0 = soil water content at the beginning of a period, P = precipitation during a period, W = soil water content at the end of a period

for exploiting the soil water storage capacity (the soil being the largest water reservoir). Table 2 presents noteworthy data from this aspect as well.

A *mild and rainy winter* is less disadvantageous from the aspect of tillage than it is from that of crop protection. Spring-sown crops can definitely be more reliably grown where moisture still available in the soil after the preceding crop is not wasted, where primary tillage results in soil conditions not only helping water infiltration in the soil but also reducing the loss of water outside the growing season.

Accordingly, the new climate conditions underscore the need for eliminating compact layers in arable lands. The active root zone depth – that is at least 40 cm – will be required for

Table 3. Differences between climate damage mitigation and intensifying tillage variants

Factors	Climate damage mitigating	Climate damage intensifying
Soil looseness to a depth of 0-40 cm	favourable	compaction in root zone
Extension of compacted layer	0- mm	> 40 mm
Moisture intake and storage	adequate	limited
Moisture utilization	optimal (minimal loss)	poor (great loss)
Soil surface	minimal (water conservation)	large (water loss)
Surface cover (mulch)	in critical period: 35-55%	in critical period: 0-10%
Aggregation	permanent in growing and tillage seasons (slight fluctuation)	poor (deterioration)
Aggregate %	>75-80% , dust: < 10 %	~25-50%, dust: > 25%:
Earthworms pc m^{-2}	5-10	0-1
OM (C)	harmony between sequestration and decomposition	decomposition and loss
CO_2 emission following disturbance	450-600 ppm	>1000 ppm
C-flux t ha^{-1} in a season	<0.5	2.2-2.9

weathering summer drought at the cost of minimised losses in yields (Figure 2).

The lack of frost effects will have no negative consequences on degraded soils (deflation is likely to be less severe in the spring). On the other hand, freezing will not crumble clods left behind by ploughing in the autumn and clods of a certain size will not soak through either. These points to the need for using primary tillage implements in combination with secondary tillage elements and for effective clod breaking without dust forming. With a view to the expected milder but windy winters there will be an increasing need for secondary tillage in the autumn in the wake of the autumn primary tillage interventions (Figure 3), without restricting the soil water infiltration capacity. There is a close relationship between water conserving and carbon conserving tillage techniques anyway (Birkás et al., 2008; Kvaternjak et al., 2008). In contrast to earlier solutions, harmful recompacting of the soil by secondary tillage in separate passes should be avoided. Our monitoring programme has shown that such wrong practices will result in increased damage by drought as well as by waterlogging.

We have seen *hot and dry summers* in the recent decade as well. The period between harvest and sowing should be devoted to soil moisture and carbon conservation. Increased attention should be paid to covering the surface (by chopped residues), to shallow tillage leaving mulch cover and to primary tillage adapted to the soil existing moisture content (Table 3).

Moisture conserving stubble tillage makes it possible to improve the soil condition through loosening. Soil conditions suitable for sowing are likely to be easier to produce by shallow primary tillage, however, the need for mitigating climate damage necessitates requires root zones without compact layers. Accordingly, the advantages of loosening/deepening/crumbling techniques may need to be focused on. The extremes in the distribution of rainfalls in the summer also call for increased focus on maintaining or improving the soil water infiltration capacity – that is, creating or maintaining soil structures without compact layers – with a view to the periods of heavy rainfalls.

The frequency of *rainy periods and storm-force winds* call for conserving the soil structure, for rationalising the number of interventions and for extending the period of surface coverage (even after sowing). The preservation of the soil structure is linked to compaction for heavy clodding (entailing a need for crumbling large clods) is likely to occur not only in dry soils but also in compact and dry soils as well (Birkás et al., 2004).

Conclusions

The findings of soil condition monitoring and the long term experiments indicate a close link between tillage-induced soil compaction and the level of climate damage. Some compaction-related factors, such as the state of the root zone, the depth and the thickness of the compact layer and the occurrence of heavy damage caused by droughts and- by waterlogging may be used as indicators of climate damage. Based on the findings of the experiments and monitoring condition and tillage techniques fall into two main groups: those having climate damage mitigating and those having climate damage aggravating effects. Both features are indicative of the level of likely climate risks in cropping. Climate change scenarios are projecting extreme rainfall distributions, longer dry periods and shorter rainy periods, where the application of tillage techniques keeping arable lands free of tillage or traffic-induced soil compaction (*pan* compaction), maintaining soils water infiltration capacity and conserving their moisture contents will increase in importance.

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