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Crop residue management in arable cropping systems under temperate climate. Part 2: Soil physical properties and crop production. A review

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Introduction. Residues of previous crops provide a valuable amount of organic matter that can be used either to restore soil fertility or for external use. A better understanding of the impact of crop residue management on the soil-water-plant system is needed in order to manage agricultural land sustainably. This review focuses on soil physical aspects related to crop residue management, and specifically on the link between soil structure and hydraulic properties and its impact on crop production.
Literature. Conservation practices, including crop residue retention and non-conventional tillage, can enhance soil health by improving aggregate stability. In this case, water infiltration is facilitated, resulting in an increase in plant water availability. Conservation practices, however, do not systematically lead to higher water availability for the plant. The influence of crop residue management on crop production is still unclear; in some cases, crop production is enhanced by residue retention, but in others crop residues can reduce crop yield.
Conclusions. In this review we discuss the diverse and contrasting effects of crop residue management on soil physical properties and crop production under a temperate climate. The review highlights the importance of environmental factors such as soil type and local climatic conditions, highlighting the need to perform field studies on crop residue management and relate them to specific pedo-climatic contexts.
Keywords. Crop residues, tillage, plant production, soil hydraulic properties, soil structure, temperate climate.

Gestion des résidus de cultures dans les systèmes de grandes cultures sous climat tempéré. Partie 2 : Propriétés physiques du sol et production agricole (synthèse bibliographique)
Introduction. Les résidus de récolte représentent une quantité non négligeable de matière organique qui peut être valorisée soit pour restaurer la fertilité du sol ou pour des usages externes. Une meilleure compréhension de l'impact de la gestion des résidus sur le système eau-sol-plante est nécessaire afin de gérer les terres agricoles de manière durable. Dans cet article, nous nous concentrons sur la physique du sol liée à la gestion des résidus de culture et plus particulièrement sur le lien entre la structure du sol et les propriétés hydrauliques du sol ainsi que son impact sur la production agricole.
Littérature. Les pratiques d'agriculture de conservation, incluant la rétention des résidus de culture et un travail du sol réduit, peuvent améliorer divers aspects qui caractérisent un sol de qualité tels que l'amélioration de la stabilité des agrégats et de la structure du sol. Concernant les propriétés hydrologiques du sol, l'infiltration de l'eau dans le sol peut être améliorée, résultant en une diminution du ruissellement de surface et une plus grande disponibilité de l'eau pour la plante. L'influence de la gestion des résidus sur la production agricole n'est pas clairement définie : dans certains cas, la production agricole est améliorée par la rétention tandis que dans d'autres études, la rétention des résidus peut être la cause de rendements moindres.
Conclusions. Dans cette revue bibliographique, nous montrons les effets divers et variés de la gestion des résidus de culture sur les propriétés physiques du sol ainsi que sur la production agricole sous climat tempéré. Cette revue met en évidence l'importance des facteurs environnementaux tels que le type de sol et les conditions climatiques locales, démontrant l'intérêt de réaliser ce type d'étude sur la gestion des résidus dans un contexte pédo-climatique spécifique.
Mots-clés. Résidu de récolte, travail du sol, production végétale, propriété hydraulique du sol, structure du sol, climat tempéré.

1. INTRODUCTION

In temperate regions with silty loamy soils (such as the Loam Belt in Belgium), it is common for part of the crop residues produced from the annual cropland to be exported for external use, such as fodder or bioenergy production. In the case of fodder, residues tend not to be entirely exported because, in mixed farming, cropland is fertilized with manure from the cattle fed with crop residues. In the case of bioenergy production or other possible uses for crop residues, there is no such circular process and the residues are exported right out of the agro-ecosystem. This raises concerns about the sustainability of such agro-ecosystems. Should farmers retain residues or can they be used elsewhere? If they are retained, how should they be managed in a sustainable way?

In this review, we define crop residue management as "a strategy for applying the above-ground residues produced from previous crops to the soil". It can be considered as an intersection of two factors: the use of crop residues (retention or export) and the type of soil tillage applied. This differentiation is of primary importance because the depth of soil tillage and the mode of action of the tillage tool allocate the residues differently within the soil profile. The chosen residue management strategy affects soil structure, organic matter content (total quantity and repartition within the soil profile [Bassem Dimassi, 2013]), nutrient availability and microbial life and will therefore have concurrent effects on soil strength and porosity, hydraulic properties, air diffusion capacity and crop productivity (Bronick et al., 2005).

We define "conventional tillage" as the tillage method commonly used in the temperate regions and based on a moldboard plough. "Reduced tillage" refers to tillage with reduced intensity and/or depth. "Strip tillage" is where only the sowing line is tilled. "Zero tillage" or "no-tillage" refers to direct drilling. "Conservation tillage" relates to both reduced tillage and no-tillage.

Many authors have investigated the effect of crop residue management on agroecosystem performance at different spatial and time scales and at various resolutions. Many of these studies, however, have been conducted in Asia, Latin America and Africa and show a generally positive effect of crop residue retention on soil health (Turmel et al., 2015). These studies involve residues from crops (including their carbon [C] and nitrogen [N] composition), soil types and organic matter decomposition conditions (mostly soil moisture and temperature) that differ from those in north-western Europe. The objective of this paper is to review the effect of crop residue management on the various compartments (pedo-, hydro- and biosphere) of the arable cropping system under a temperate climate. We focus on a maritime temperate climate (Cfb in Köppen-Geiger climate classification; Peel et al., 2007), although this excludes some relevant studies in similar climates. Where relevant, we include studies conducted in other temperate and continental climate conditions (C and D groups in Köppen-Geiger) in order to strengthen the analysis. This is common practice in review papers (*e.g.*, Morris et al., 2010; Soane et al., 2012). Soil types are cited according to the system used in by the IUSS Working Group WRB (FAO, 2006), USDA (1999) and the Canadian Soil Classification Working Group (1998). **Table 1** provides an overview of the information retrieved from studies cited in this article, including soil types and climate.

The first part of the review (Lemtiri et al., 2016, same issue) focuses on biological and chemical processes. In this review, we look at the various compartments of the soil-water-plant system and their interactions, accounting for both short and long-term effects. We describe the impact of crop residue management on soil structure, and then focus on its effects on the hydrodynamic behavior of the soil, ending with a discussion on its influence on crop production.

2. WHAT ARE CROP RESIDUES?

Crop residues are the above-ground parts of the plant that are not harvested for food production. The stubble (of cereals), however, is always left on the field, even when residues are exported. The quantity of crop residues produced depends on two main factors: crop yield and crop type. For example, where the crop yield is lower, such as in south-eastern Europe, the quantity of residues produced is also lower. Crop type also matters. For cereals, the quantity of straw produced corresponds, on average, to grain yield (in Belgium, about 10 $t \cdot ha^{-1}$), but for other crops (*e.g.*, sugar beet), only the leaves are left (about 4 $t \cdot ha^{-1}$ of dry matter).

Crop residues are composed of lignin, cellulose, hemicellulose, micro and macro-nutrients. The degradation of these residues varies depending on their lignin and cellulose content and their C/N ratio, which is crop dependent, but also on the environment and soil conditions. Residues with a high C/N level (*e.g.*, wheat straw) decompose slowly, sometimes resulting in the immobilization of soil N. This can be positive in no-tillage systems, creating a mulch that protects the soil from erosion and evaporation, but it also means there are fewer nutrients available for the next crop. Residues with a low C/N level mineralize quickly, releasing more N and nutrients for the next crop. Lignin can be degraded only by specialized fungi and some microorganisms. Residues with high lignin content will take longer to decompose than those with low lignin content (Austin et al., 2010).

Table 1. Details of the context of the studies cited in the present review. Soils are classified based on the information in the original articles. The climate code corresponds to the Köppen-Geiger classification. Tillage type is given with the depth of tillage investigation. Tillage types are: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) — *Détails des études citées dans le présent article. Les classifications des sols correspondent à celles citées dans les articles initiaux. Le climat fait référence à la classification de Köppen-Geiger. Le travail du sol est mentionné avec la profondeur de travail atteint par les outils. Les différents types de travail du sol sont : travail conventionnel (CT), travail du sol réduit (RT) et semis direct (NT).*

Reference	Location	Soil type	Climate code	Tillage type	Type of residue	Field experiment settlement	Rotation
Alletto et al., 2009	France	Gleyic Luvisol (FAO)	Cfb	CT(28-30 cm), RT (9-12 cm)	na	5 years	na
Alletto et al., 2015	France	Stagnic Luvisol (FAO)	Cfb	CT (spring)	na	na	na
Bescansa et al., 2006	Spain	Calayery Calcic Haploxerept	Cfb	NT+,-; RT +,- (15cm); CT +,- (25 cm)	barley stubble	5 years	barley monoculture
Blanco-Canqui et al., 2007a	Ohio, USA	Typic Hapludults, Aquic Hapludalfs, Mollic Epiaqualfs (USDA)	Dfb	NT	corn stover	> 8 years	corn -soybean
Blanco-Canqui et al., 2007b	Central Ohio, USA	Aeric Epiaqualf (USDA)	Dfa	NT+, ++, +++	wheat straw	10 years	na
Børresen et al., 1990	Norway	na	na	CT, RT, NT	wheat straw	na	na
Brennan et al., 2014	Ireland	Haplic Luvisol	Cfb	CT +,-, RT +,-	wheat straw	10 years	na
Buysse et al., 2013	Belgium	Eutric Cambisol (WRB)	Cfb	CT (25 cm)	crop residues	50 years	sugar beet - cereal - legume - cereal (for 15 years) sugar beet - winter wheat - winter barley (for 35 years)
da Silva et al., 2001	Canada	Hapludalfs	Dfb	CT , NT	na	14 years	corn - soybean - wheat
Dam et al., 2005	Canada	Dystric Gleysol (FAO)	Dfb	CT+,-; RT+,-; NT+,-	stover	11 years	corn monoculture
De Gryze et al., 2005	Laboratory experiment	Silty clay loam/silt loam/sandy loam	labora-tory	na	wheat straw	na	na
Feiza et al., 2014	Lithuania	Cambisol and Planosol (WRB)	Dfb	NT-, NT+	straw	14 years	winter wheat - spring oilseed rape - spring wheat - spring barley - pea and winter wheat - spring barley - spring oilseed rape

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Table 1 (continued 1). Details of the context of the studies cited in the present review. Soils are classified based on the information in the original articles. The climate code corresponds to the Köppen-Geiger classification. Tillage type is given with the depth of tillage investigation. Tillage types are: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) — *Détails des études citées dans le présent article. Les classifications des sols correspondent à celles citées dans les articles initiaux. Le climat fait référence à la classification de Köppen-Geiger. Le travail du sol est mentionné avec la profondeur de travail atteint par les outils. Les différents types de travail du sol sont : travail conventionnel (CT), travail du sol réduit (RT) et semis direct (NT).*

Reference	Location	Soil type	Climate code	Tillage type	Type of residue	Field experiment settlement	Rotation
Franzluebbers, 2002	Georgia, USA	Typic Kanhapludults	Cfa	RT (10-15 cm), NT	na	25 years	CT field: winter cereals (wheat, barley and rye); NT field: summer/winter double cropping (sorghum, cotton, soybean, wheat, rye, barley and crimson clover)
Karlen et al., 1994	Winsconsin, USA	Typic hapludalf (USDA)	Dfb	NT-,+, NT++	corn stover	10 years	corn monoculture
Lewis et al., 2011	Pennsylvania, USA	Typic Hapludult/ Hapludalf (USDA)	Dfb	CT (23 cm), RT (15 cm)	na	3 years	cover crops - soybean - maize
Linden et al., 2000	Minnesota, USA	Typic Hapludoll (USDA)	Dfa	CT (17-20 cm), RT (17-20 cm), NT	corn stover	13 years	na
MacLeod et al., 1997	Canada	Haverhill asssocia-tion soil	chamber experi-ment (2)	RT-NT	pea (1) - wheat (2)	na	wheat (1) - canola (2)
Malhi et al., 2011	Canada	Gray Luvisol and Black Chernozem (CSS)	Dfb	CT +,-	straw	11 years	wheat/barley - canola - triticale - pea
Mulumba et al., 2008	central Ohio, USA	Stagnic Luvisol	Dfa	NT + >> +++	wheat straw	11 years	no crop
Noack et al., 2014	Australia	Calcarosol	glass-house	RT, NT	pea residues	na	na
Pagliai et al., 2004	Italy	Cambisol (FAO)	Cfb	CT (40 cm), RT (50 cm), RT(10 cm)	na	na	na
Ramos, 2003	Spain	Various types	Various climates	na	na	na	na
Riley, 2014	Norway	Eutro-Gleyic Cambisol (WRB)	Dfb	CT (25 cm) , RT + (8-10 cm)	straw residues	34 years	wheat and oat monoculture
Singh et al., 1994	Central Alberta, Canada	Typic Cryoboroll, Black Chermozemic	Dfb	NT+, RT+,- (10 cm)	barley straw	9 years	spring barley monoculture

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Table 1 (continued 2). Details of the context of the studies cited in the present review. Soils are classified based on the information in the original articles. The climate code corresponds to the Köppen-Geiger classification. Tillage type is given with the depth of tillage investigation. Tillage types are: conventional tillage (CT), reduced tillage (RT) and no-tillage (NT) — *Détails des études citées dans le présent article. Les classifications des sols correspondent à celles citées dans les articles initiaux. Le climat fair référence à la classification de Köppen-Geiger. Le travail du sol est mentionné avec la profondeur de travail atteint par les outils. Les différents types de travail du sol sont : travail conventionnel (CT), travail du sol réduit (RT) et semis direct (NT).*

Reference	Location	Soil type	Climate code	Tillage type	Type of residue	Field experiment settlement	Rotation
Six et al., 1998	na	Haplustoll, Fragiudalf, Hapludalf, and Paleudalf	na	CT, NT	na	44 years (CT), 73 years (NT)	na
Soon et al., 2012	Canada	Dark GreyLuvisol (CSS)	Dfc	RT+, NT+,-	straw	3 years	barley - field pea - wheat - canola
Swan et al., 1994	Wisconsin, USA	Silt loams	Dfb	NT-,+,++	stover	6 years	corn
Tebrügge et al., 1999	Germany	Cambisol, Fluvisol (WRB)	Cfb	CT, RT, NT	na	up to 18 years	na
Vogeler et al., 2009	Germany	Cambisol, Luvisol (WRB)	Cfb	CT (25-30 cm), RT (15-18 cm)	na	8 years	na
Wahl et al., 2004	Germany	Luvisol (WRB)	Cfb	CT (25-30 cm), RT (12-15 cm)	na	10 years	sugar beet - wheat - barley or wheat
Wuest et al., 2000	Oregon, USA	Typic Haploxeroll	glasshouse	NT, RT	na	na	na

The size of the residues is also important. The soil-residue contact area influences the mineralization rate. The smaller the residues, the larger the area of contact with soil and microorganisms. In a no-tillage system, cereal straw should therefore be chopped and spread evenly on the ground (reviewed in Soane et al., 2012). The height at which the plant is cut at harvest is a significant factor. In no-tillage systems, the stubble is left standing, forming large residues that are not in contact with the soil. In reduced tillage, shallow stubble cultivation helps to counter this issue.

It is important to note that crop residues are not only the above-ground part not harvested for crop production, but also the below-ground parts. Root systems are crop residues consistently incorporated into the soil (Soane et al., 2012). The roots correspond to a certain quantity of organic matter and are also affected by type of tillage. Different crop types produce different quantities and sizes of residues at different depths.

3. IMPACT OF CROP RESIDUE MANAGEMENT ON SOIL STRUCTURE AND WATER DYNAMICS

In order to understand the effect of any type of land management on soil hydraulic properties, it is necessary to characterize soil structure. Soil structure refers to the arrangement of soil particles (sand, silt and clay) into units called aggregates or peds. Soil structural patterns influence soil functions such as water storage and movement, air-exchange between soil and atmosphere, and heat transfer in the soil. Soil structure also determines the depth that roots can penetrate into the soil. Overall, soil structure is a property closely related to soil health, and good soil health offers an extensive range of possibilities for various types of agricultural production (Dexter, 2002[1] in Pagliai et al., 2004). In the following section we explore the link between residue management and soil structure using two quality indicators. We then look at the implications for soil hydraulic properties.

3.1. Soil composition and structure

Soil organic matter and aggregate stability. The quality of soil structure greatly depends on the soil organic carbon (SOC) content (Tisdall

[1] Dexter A.R., 2002. Soil structure: the key to soil function. *Adv. Geoecol.*, **35**, 57-69.

et al., 1982), especially on the fraction of labile SOC (also called the "particulate organic matter" because this fraction cycles relatively quickly in the soil). Labile organic matter also plays an important role in maintaining soil structure and providing soil nutrients (Six et al., 1998). Cultivating crops that leave substantial amounts of residues can increase SOC in the soil profile, depending on the tillage practices used.

Buysse et al. (2013) investigated the influence of long-term crop residue management (export *vs* retention) on the fraction of labile SOC in Belgium using a dataset covering 50 years. They observed significantly lower labile SOC in the residue export treatment than in the residue retention treatment. Taking account of the type of tillage practices, Lewis et al. (2011) found lower labile SOC under conventional tillage than under reduced tillage (chisel ploughing) in an experiment in Pennsylvania.

Soils with high organic matter content tend to have larger, stronger and more stable aggregates that resist compaction, whereas the opposite is true for soils with less organic matter. In the temperate regions of Europe, it is generally considered that a soil with less than 3.4% organic matter (*i.e.*, 2% SOC) has unstable aggregates and is therefore prone to soil degradation. Note that this value is just an indication and should not be taken as an absolute threshold (Van-Camp et al., 2004). An improvement in soil aggregate stability has several consequences for an agro-ecosystem, including reduced risk of soil compaction and erosion (Holland, 2004).

Aggregate stability at the soil surface is affected mainly by exposure to rainfall. A bare soil (*i.e.*, a soil from which crop residues have been exported or incorporated into the soil by ploughing) is in direct contact with raindrops, which facilitates a breakdown of soil aggregates, increasing soil erodibility. Aggregate degradation can lead to surface sealing and crust formation, which reduces the water infiltration rate and increases the risk of soil erosion and the loss of valuable topsoil (Franzluebbers, 2002). High silt content, together with low organic matter content, results in soils that are more prone to aggregate breakdown and surface crusting (Ramos et al., 2003). In a review of conservation agriculture in Europe, Lahmar (2010) noted that conservation tillage increased topsoil aggregate stability, especially in no-tillage systems. He explained this by an increase in SOC at the soil surface. For instance, in a 9-year experiment in central Alberta, Singh et al. (1994) compared the effect of three crop residue management practices on several indicators of soil structure quality. Their study highlighted better water-stability of large aggregates and higher SOC for a 0-5 cm soil depth under conditions of no-tillage and straw retention.

Conversely, macro-aggregates play an important role in protecting organic matter by reducing its decomposition rate under conservation tillage (Beare et al., 1994). In a laboratory experiment focusing on the short-term dynamics of macro-aggregates, De Gryze et al. (2005) showed that macro-aggregate formation had a linear relationship with wheat straw incorporation, but no relationship with soil texture (silty clay loam, silt loam and sandy loam). It is important to note that the formation of macro-aggregates takes longer under conventional tillage than conservation tillage (Six et al., 1998).

Indicators of soil compaction: soil bulk density, penetration resistance. Generally, soil compaction is quantified by one of four indicators: total porosity, pore size distribution, bulk density and penetration resistance. Given that root growth is impeded by soil compaction, these indicators are probably negatively correlated with root growth and rooting depth.

Crop residue retention in agricultural systems generally increases soil porosity, regardless of tillage practice. Large pores are particularly favored because organic matter is much less dense than mineral particles. When they are mechanically incorporated, crop residues can reduce the bulk density at depth. In zero tillage, the incorporation of organic particles below the soil surface by fauna is slower, but it still contributes to reduced bulk density (Kladivko, 1994). The presence of residues, however, does not always improve the pore system. Karlen et al. (1994) studied the effect of three types of corn stover management (removal, retention, retention and returning) in a 10-year no-tillage system in Wisconsin. No significant difference among treatments was found for total porosity, bulk density or penetration resistance.

The effect of residue use in a given tillage practice depends on several parameters, including soil type and the depth of investigation. In Lithuania, Feiza et al. (2015) compared bulk density and pore size distribution at three depth ranges (5-10, 15-20 and 30-35 cm) in no-tilled soils with straw removed or retained (chopping and returning) on two soil types: Cambisol and Planosol. Although no change in bulk density between straw removal and retention was found in the Cambisol, they observed a decrease in bulk density with residues in the Planosol. In addition, the amount of macropores and mesopores increased in the Cambisol in the 5-10 cm depth range, but decreased at all three depth ranges in the Planosol. The authors concluded that the mesopores and macropores in the Planosol were obstructed by the residues. Application rate can also affect the extent of compaction. Blanco-Canqui et al. (2007b) studied the effect of three wheat mulch rates on soil physical properties in central Ohio. The mulching significantly reduced the bulk density with increasing mulch rates, but no significant effect on penetration resistance was found.

Tillage practice has a great influence on soil compaction, whether or not residues are present. In a long-term study in Germany, Tebrügge et al. (1999) found lower bulk density at the surface layer in no-tilled treatments due to the accumulation of crop residues on the surface. They observed higher bulk density (at 0-30 cm) in a no-tilled treatment than in reduced and conventional tillage treatments, particularly in the upper layer (0-10 cm). Under the tilled layer, the opposite effect was observed. Rasmussen (1999) observed persistent high density in the previous plough pan after reducing the ploughing depth. In that study, an increase in bulk density in the newly ploughed layer was also reported. Vogeler et al. (2009) reported that after 5 years of conversion from conventional to reduced tillage, the bulk density was higher in a conservation treatment than in the conventional one, and after 8 years the bulk density in the reduced tillage treatment was lower at 10 cm but higher at 20 cm.

3.2. Soil hydraulic properties

Water retention curve. Tillage practices combined with crop residue application not only influence cover rate at the soil surface, but also modify organic matter content and total soil porosity. Mulumba et al. (2008) applied wheat straw as mulch at different rates on untilled and uncropped soils and determined the water retention and available water capacity of soil samples at a depth of 0-10 cm. After 11 years of this field experiment, they reported higher water content at low suction with high rates of residue application. No significant difference was found, however, among the different treatments at high suction.

Bescansa et al. (2006) compared the available water capacity and water retention curve of the top 15 cm of untilled soil with and without stubble burning, reduced tillage and conventional tillage in a 5-year experiment in Spain. In their study, soil structure and water retention were more affected by the tillage practices than by the presence of residues at the soil surface. Water retention at saturation was 13% higher in tilled than untilled soil and 11% lower in tilled than untilled soil at higher suction (from -33 kPa). The authors explained this difference by the higher amount of small pores in untilled plots than tilled plots, which were likely to retain more water under dry conditions.

Hydraulic conductivity function. Hydraulic conductivity at the soil surface generally decreases with residue removal or incorporation into the soil because of the destabilization of soil aggregates (Duley, 1939[2] in Green et al., 2003; Turmel et al., 2015).

In addition, repeated ploughing can damage the pore network at depth and create a plough pan. For example, Wahl et al. (2004) showed that the maximum depth of infiltration was 50 cm under conventional tillage and 120 cm under reduced tillage. Compaction can also occur, however, under reduced tillage. Pagliai et al. (2004) compared saturated hydraulic conductivity at varying levels under reduced tillage (10 cm depth), conventional tillage (40 cm depth) and ripper subsoiling (50 cm depth). The saturated hydraulic conductivity was higher under reduced tillage than under conventional tillage at a depth of 0-10 cm, but it was lower or not significantly different from conventional tillage at 10-40 cm.

3.3. Assessing the effects of crop residue management in the spatio-temporal dynamic context

Several authors have studied the influence of crop residue management on soil hydraulic properties. Crop residue management, however, is not the only variable that differs among studies. First, temporal dynamics can overshadow punctual differences among treatments. Alletto et al. (2009) studied the parameters influencing the spatial and temporal variability of soil bulk density and hydraulic conductivity near saturation in France. They pointed out that the time of sampling was the first factor of variability for bulk density and for hydraulic conductivity function, whereas crop residue management was identified as the second or fourth factor. Some authors have reported a two-stage effect of tillage practices. Just after tillage, the soil surface structure of tilled systems is improved due to large open pores created by tillage (Messing et al., 1993). These newly formed pores, however, are relatively unstable, especially with conventional tillage. Under the influence of wetting/drying cycles and gravity, tilled soils tend to exhibit a decline in the number of macropores and their connectivity at the soil surface. This reduced macropore connectivity ultimately leads to a decrease in saturated hydraulic conductivity (Green et al., 2003). Alletto et al. (2009) observed that the most important increase in bulk density occurred between the two first measurements campaigns (between 10 and 51 days of measurement). Saturated hydraulic conductivity decreased by a factor 10 during the first month under conventional tillage at a depth of 15 cm. After this initial decrease, saturated hydraulic conductivity increased under both tillage practices over the cropping season, but the rate of increase was slower for conservation tillage. These seasonal changes

[2] Duley F.L., 1939. Surface factors affecting the rate of intake of water by soils. *Soil Sci. Soc. Am. J.*, **45**(1979), 851-856.

also affect the water retention curve. While studying the temporal variation in soil physical properties in a spring ploughing in France aimed at managing maize residues, Alletto et al. (2015) also observed a decrease in the saturated water content during the growing season under conventional maize monoculture.

Spatial heterogeneity also needs to be included when studying the influence of crop residue management on soil physical and hydraulic properties. First, fields with a different precipitation history can produce different results (Müller et al., 2009). Second, soil type can have an important influence, with clay content and coarse elements in particular being shown to be important sources of heterogeneity (*e.g.*, Alletto et al., 2009; van Es et al., 1999). The differences related to soil type can also be observed at the field scale (*e.g.*, da Silva et al., 2001). At this scale, the agricultural operations create additional heterogeneities. The rows and inter-rows can be a major factor of variability in soil water dynamics (da Silva et al., 2001; Starr et al., 2004; Alletto et al., 2009). Da Silva et al. (2001) found higher bulk density in the inter-rows, whereas Alletto et al. (2009) measured higher bulk densities in rows, related to lower saturated hydraulic conductivity. As different tillage practices affect different depths of the soil, the depth at which an investigation takes place is also a factor that can lead to variability (*e.g.*, Pagliai et al., 2004).

4. IMPACT OF CROP RESIDUE MANAGEMENT ON CROP PRODUCTION

The influence of residue management on crop production is complex and variable, and results from direct and indirect effects and interactions. A direct effect is, for example, the presence of residues on the soil surface, which constitutes a direct obstacle to crop emergence. Indirect effects include residue mineralization, which leads to more nutrients available for the plants or the presence of organic matter from residues modifying the soil structure and therefore modifying the root system development.

Crop production depends greatly on environmental factors. These factors range from soil water, organic matter content, nutrient availability, cover diversity and microbial life activity through to soil structure. All these variables evolve over time, as does the sensitivity of the crop to these variables. The effect of residue management can therefore vary at different times in the plant development process. For example, differences in nutrient uptake and storage can be observed from germination to yield in different parts of the plant. It is also important to note that not only do the presence and position of crop residues matter, but also that the type of crop residues and the subsequent annual crop matter. Each crop type needs a specific type of management. For instance, harvesting sugar beet under reduced tillage is much more challenging than harvesting wheat.

As noted earlier, climate and weather conditions need to be considered in studying the impact of crop residue management on crop production. Hot and dry years will not have the same effect as cooler or wetter ones. Although studies on the effects of crop residue management have been conducted in different parts of Europe and across the world, the need to obtain results for specific contexts remains. A recent meta-analysis using 610 studies comparing conservation tillage with conventional tillage showed that the use of conservation agriculture is beneficial under rainfed conditions in a dry climate, but, at best, it is not particularly important in temperate climate crop production (Pittelkow et al., 2015).

4.1. Germination and crop growth

For crop emergence, it does not only matter whether or not residues are applied, but also where they are located in the soil profile. Soil crusting in the absence of residues at the soil surface, coupled with high air humidity and frequent rainfall, reduces germination quality (Gallardo-Carrera et al., 2007). In addition to the effect of raindrop impact, crusting is more likely when the soil contains less organic matter (Pagliai et al., 2004), which is the case when crop residues are continuously exported.

Residues at the soil surface, however, can be an obstacle during soil preparation and crop emergence. In their review of non-invasive tillage in the UK, Morris et al. (2010) showed that surface crop residues are an obstacle for drilling machines, especially when residues are lying on the ground unattached to roots. A blockage in the drilling machine can cause lower crop density and therefore impede crop yield from the outset.

Crop emergence can be slowed and even impeded by the presence of crop residues above the seeds, with the seedlings having to go around the physical obstacle (Arvidsson et al., 2014). In a glasshouse experiment in Oregon, Wuest et al. (2000) showed that residues above winter wheat seeds (as in no-tillage) or mixed around the seeds (as in reduced tillage) delay crop emergence by obstructing the coleoptile's route to the surface. Soane et al. (2012), in their review of no-tillage in Europe, noted that spring-sown crops can be delayed in cold and wet conditions because of increased soil humidity and cold temperatures resulting from the presence of crop residues on the soil surface. Soil temperatures can be up to 2.5 °C lower when there is residue cover (Børresen et al., 1990) because of increased solar reflection, less evaporation and the insulating effect of a residue cover (Shinners et al., 1994[3] in Morris et al., 2010). The opposite is true in southern Europe under dry conditions, however, where residue cover allows more soil water retention and therefore greater water availability during crop growth (Van den Putte et al., 2010; Soane et al., 2012). Nevertheless, bad seed-to-soil contact can delay crop emergence under dry conditions (Soane et al., 2012), which makes it difficult to predict its effect.

In addition to abiotic factors, the biotic environment influences seed emergence. Residue cover provides a favorable habitat for slugs (Christian et al., 1986) and possibly for plant pathogens. Straw can be a source of plant pathogens (Arvidsson et al., 2014). When applying reduced or no-tillage (Van den Putte et al., 2010) with residue retention, rotation must be included. Problems with pathogens are more likely to occur with monoculture or with cereals-only crop rotation because the cycle of pathogens is continuous. Seeds in direct contact with straw can fall victim to phytotoxicity (Soane et al., 2012). In their pot experiment, Wuest et al. (2000) concluded that when crop residues were placed below the seeds of winter wheat, growth could be impeded because the roots had access to the residues (source of pathogens or phytotoxins). Morris et al. (2010) reported that the time between residue decomposition and crop sowing determines the phytotoxic effect: the longer the time, the less the effect.

In the case of residue retention in reduced or no-tillage systems, several authors (Morris et al., 2010; Soane et al., 2012) have suggested moving residues away from the sowing line in order to avoid drilling blockage, seed-to-residue contact, root-to-residue contact, physical obstacles faced by the seedlings and a potential source of phytotoxicity. Shinners et al. (1994)[3] in Morris et al. (2010) showed that a residue-free band of 20-30 cm around the sowing line can produce a yield equivalent to that from soil without residue cover. Given this, strip tillage could be a solution for row crops such as sugar beet or maize. Strip tillage is not suitable for cereals, however. For these crops, in no-tillage systems, it is now believed that residues need to be chopped and spread very evenly, although it has been shown that chopped straw results in 16% lower yields than conventional tillage or reduced tillage with residue exportation (Soane et al., 2012).

4.2. Nutrient uptake

In this section, we focus on two main nutrients essential for plant growth: N and phosphorus (P). So far as we know, the relationship between residue management and potassium (K) uptake by plants has not yet been studied. The impact of crop residue management on soil chemical properties (and specifically N and P in soils) was discussed in the first section of this review (Lemtiri et al., 2016, same issue). Here, we focus on the indirect effect on crop production. An important aspect, alongside residue composition, is the type of crop planted after residue application.

Research results on N uptake by plants related to crop residue management are fairly divergent. In a 10-years field experiment in Ireland, Brennan et al. (2014) observed almost no effect on N uptake in a 3-year study comparing conventional tillage with reduced tillage with or without wheat straw incorporation. Other studies have shown a positive effect of residue retention on N uptake. Malhi et al. (2011) compared straw retention with straw removal under conventional tillage in Canada. They reported that total N uptake in seed and straw was greater with straw retention. Grain N uptake, however, can be reduced by cereal straw retention after the repeated application of a treatment (3-year experiment, Dfb, Grey Luvisol [CSSC]) due to probable net N immobilization (Soon et al., 2012).

As for P, Noack et al. (2014) showed that 0-15% of P uptake by shoots comes from crop residues and therefore that these residues could be the source of some of the subsequent crop's P requirement. Noack et al. (2014) reported that the retention of residues increased plant P uptake regardless of residue placement in the soil profile. Residue incorporation tends to increase root access to P, due to the increased rate of release and decomposition of organic matter. In zero-tillage systems, when residues are retained only on the soil surface, decomposition is slower. Nevertheless, P uptake by plants can also be reduced in the short term when crop residues are incorporated into soil due to the immobilization of soil P (MacLeod et al., 1997, in chamber experiment, Dfb climate).

4.3. Yield

In their meta-analysis, Pittelkow et al. (2015) showed that in humid climates (aridity index more than 0.65) yield decreases with zero-tillage regardless of residue retention, whereas in dry climates (aridity index less than 0.65) zero-tillage in combination with residue retention and crop rotations increases the productivity of rainfed crops. They also reported that residue retention is essential in the adoption of conservation agriculture and that the adoption of zero-tillage without residue retention will lead to a yield decrease regardless of climate. In a meta-analysis of crop growth under conservation agriculture in European conditions, Van Den Putte et al. (2010) showed that reduced or no-tillage with residue retention generally

[3] Shinners K.J., Nelson W.S. & Wang R., 1994. Effect of residue-free band width on soil temperature and water content. *Trans. Am. Soc. Agric. Biol. Eng.*, **37**(1), 39-49.

affected crop yields negatively (by 4.5%, on average). This effect was more pronounced under zero-tillage, reducing yield by 8.5%, on average, regardless of crop type. They also showed that sugar beet was not economically viable when no-tillage was applied. In reduced tillage with residue retention, only maize and winter cereals produced lower yields.

A study conducted in Minnesota by Blanco-Canqui et al. (2007a) showed that corn stover removal is harmful for grain yield. A 50% stover removal induced a loss of 1.94 $t \cdot ha^{-1}$ of grain yield and 0.94 $t \cdot ha^{-1}$ of stover yield. They concluded that only a small part of corn stover could be removed without reducing grain yield (< 25%). As stated earlier, however, when residues are combined with wet weather, these conditions favor plant infection, which in turn has a direct effect on crop yield. This can be counter-balanced by adopting crop rotation schemes.

Yield reduction is sometimes caused by a combination of unfavorable weather conditions (wet years) and residue retention (Riley, 2014). The opposite is true in drier years, when crop residue retention can enhance water conservation in soils, ultimately producing better yields (Linden et al., 2000; Riley, 2014).

Although the negative and positive effects of crop residue management on yield have been reported, other studies have reported no effect of crop residue management on crop production (Swan et al., 1994; Dam et al., 2005; Soon et al., 2012; Brennan et al., 2014; Riley, 2014). They identified weather conditions as the main factor influencing crop production, over and above other factors such as the type of crop residue management (Linden et al., 2000; Dam et al., 2005; Soon et al., 2012).

5. CONCLUSIONS

In this review we have highlighted the diversity and contrasting effects of crop residue management on soil physical properties, soil functions and crop production. We discussed the importance of the environmental context (soil and climate) and the complex relationships among the various compartments of the soil-water-plant system.

Crop residue retention offers several environmental and ecological benefits for the soil-water-plant system, including improved soil structural quality, which ensures optimum soil functions. Generally, the incorporation of crop residues increases soil porosity (especially the large pores) and reduces soil bulk density, regardless of tillage operations. The application rate can affect the extent of compaction. The effect of crop residues in a given tillage practice also depends on soil type and depth. Conservation tillage with the incorporation of crop residues increases SOC content near the soil surface, whereas in conventional tillage soil C is distributed throughout the ploughed area. Soils with higher organic matter content tend to have higher aggregate stability and therefore less risk of compaction and soil erosion.

Organic matter added to the soil, as provided with a catch crop, is also beneficial. A study in France by Chenu et al. (2014) concluded that in terms of increasing the stock of C it is better to add organic matter (such as cover crops) than to reduce the mineralization rate by reduced or no tillage.

With regard to soil hydraulic properties, the presence of crop residues on the soil surface tends to increase hydraulic conductivity at the surface, whereas tillage affects soil hydraulic properties both at the soil surface and below it. The effect of crop residue management on soil hydraulic properties, however, remains unclear. One of the main reasons for this is the lack of studies in which the crop residue management factor has been isolated from other influencing factors. More systematic experimental approaches would facilitate a comparison among studies. In particular, the frequency of measurement and the time between management operations and sampling appear to be crucial parameters in order to be able to compare results. Soil hydraulic properties can change just a few weeks after crop residue management. Their determination, however, is generally time-consuming and destructive, which often limits the number of samples taken during the growing season. Although soil type and weather conditions appear to be important factors of variability among different sites, the effect of crop residue management at the field scale can be overshadowed by soil type, position between rows and inter-rows or measurement depth. In some cases, the investigation techniques used can also affect the precision and accuracy of the results.

It is clear that residue retention has a positive effect on long-term soil quality, but it is also clear that in terms of its effects on crop production it is not suitable for all agroecosystems. Soil type, crop rotation and, in particular, weather conditions have a great impact on the effect of crop residue management on crop production. It has been shown, for example, that the combination of wet weather and residue retention can induce plant diseases by harboring plant pests and pathogens and thus endangering crop yields. In drier years, residues can enhance water conservation, ultimately leading to better yields. Residues on the soil surface, however, might be problematic for good seed-to-soil contact and they can represent an obstacle for seedlings trying to reach the surface. In order to avoid endangering crop yield, it is advisable to clear residues away the sowing lines. Crop rotation also appears to have a great influence on the soil-water-plant system and therefore should be taken into account when choosing a crop suitable for residue management (and therefore tillage). For example, cereal-based crop rotation should be avoided when residues are incorporated into the soil, regardless of soil tillage. The effect of residue management on N uptake by crops in temperate climates is not yet clear, but it has been shown that residue retention can increase the P uptake of the subsequent crop.

The literature review showed that studies on soil physical properties usually do not take account of crop production, and *vice versa*. Studies of the whole soil-water-plant system should be conducted, instead of separate studies on separate soil functions, in order to disentangle the web of interactions and distinguish direct from indirect effects.

Given the importance and variability of the experimental context and the lack of cross-disciplinary approaches in most studies, it would be worth adopting a holistic approach in crop residue management studies. Although many studies have been conducted on the impact of crop residue management on various aspects of the soil-water plant system around the world, more are needed that adhere to high experimental standards and take account of spatio-temporal variability.

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