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Review/Overview Article

The role and value of crop residues in dryland agriculture

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ABSTRACT

The major reasons advanced for the retention of crop residues in rainfed systems include increased water infiltration, reduced evaporation from the soil surface, increased soil organic carbon, reduced soil erosion and ultimately the yield of following crops. The residues of crops are valued in various ways in the cropping systems of the dryland regions of the world, including feed for livestock, protection against soil erosion and for maintenance of soil organic matter. Minor uses include building materials, bio-energy production and fuel. Retention of crop residues forms a major part of the system of conservation agriculture along with zero tillage and diverse crop rotation, but retention of crop residues has not been as widely adopted as the other components. This review discusses some of the reasons that crop residues are valued in various agro-ecological environments. It reveals some gaps in knowledge about the short and longer term effects of retaining or removing crop residues and the need to clearly separate the contributions of the components of conservation agriculture. There may be a trade-off between the value of crop residues for livestock feed and the value for soil protection and fertility maintenance. It is suggested that the relative values for different purposes and in a variety of situations requires further elucidation of the impact of residue retention on soil water storage, organic matter content, grain yield increases, and reduction of soil erosion in relation to the potential gains from animal production and survival.

Key words : Crop residue, Rainfed cropping systems, Stubble

The portions of crops remaining in the field after the grain has been harvested-crop residues (sometimes referred to as stubble, straw or stover)-may have a direct monetary value to the farmer for livestock feed as well as a value for soil and yield improvement that varies widely according to the environment. Additional uses may include erosion control, industrial products or building materials. The crop residues consist of stems, leaves and roots, some fallen grain, and often some weeds.

Farmers can place a value on the residues for reasons that vary according to whether livestock forms part of their farming system, local customs that permit grazing by nomadic flocks, and/or whether straw is used as a building material (in bricks, for thatching or for bale-type construction), for industrial purposes such as paper or ethanol production, or even for heating fuel. In addition, there may be values in crop residues that can be harder for the farmer to estimate in monetary terms. These might include reducing or controlling wind and water erosion or incorporating into the soil to improve or maintain soil fertility (Bessam and Mrabet 2003; Lal 2010) which presumably increase or maintain crop yield in the longer term.

Crop residue retention is one of the components of conservation agriculture (CA), along with zero or minimum mechanical disturbance and crop rotation, (Verhulst *et al*. 2010; Kassam *et al*. 2012; Serraj and Siddique 2012) and is assumed to have value in both erosion control and in building soil organic carbon (SOC) (Prasad and Power 1991; Farooq and Siddique 2015). Where use of residues for animal feed is customary (Saud *et al*. 2011), there may be a trade-off between the value for grazing and the value for soil improvement or soil protection (Magnan *et al*. 2011; Mrabet *et al*. 2012; Scott *et al*. 2013; Valbuena *et al*. 2012). The adoption of zero tillage, and the presumed desirability of returning crop residues to the soil, has renewed focus on the value of residues for purposes other than animal feed. It has been inferred that CA should be a fixed system (FAO 2011) but it has also been suggested that there is scope to adapt it to fit various farming systems

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or environmental conditions (Keinsler *et al*., 2012; Serraj and Siddique 2012; Pannell *et al*. 2013; Kirkegaard *et al*. 2014) including complete or partial removal of residues by burning or cutting (Scott *et al*. 2010). Understanding the separate impacts of zero tillage, residue retention and crop rotation components of the CA system in dryland environments is needed.

Adoption of zero tillage and other components of the CA system has varied in different systems (Knowler and Bradshaw, 2007; Farooq and Siddique, 2015). For example, following the development of small, affordable zero-tillage seeders, and extension programs that demonstrated significant cost savings and yield advantages of zero-tillage plus early sowing, adoption since 2007 has increased rapidly to more than 30,000 ha in the northern drylands of Syria, and 10,000 ha in northern Iraq (Haddad *et al*., 2014; Yigezu *et al*. 2015). Similar adoption has been reported in the rice-wheat cropping belt in India (Singh *et al*. 2014). This has been partly due to the impact of regional wars and high fuel prices, and has not been accompanied by large-scale adoption of residue retention. Even where the adoption of zero tillage has been widely accepted (Loss *et al.* 2013a), the absence of retained stubble has not been a barrier to the adoption of other improvements that can provide benefits: such as early sowing, and can lead to significant cost savings and yield increases.

There is some evidence from Western Australia of increased yield benefits in wheat crops following 'break' crops (lupin, peas, canola and oats) where zero tillage has been widely adopted (Seymour *et al*. 2012) and where crop residues are also retained. This tends to support the inclusion of crop rotation in the 'package' of practices that are commonly included in CA. This finding needs to be further examined across a range of soil and agro-ecological conditions as the response of wheat yields in various rotation systems can vary widely (Ryan *et al*. 2008a, b). Crop rotation has been a component of dryland cropping systems for thousands of years but the benefits and possible interactions need to be reaffirmed periodically as other production practices are adopted.

The assessed value of residue retention for improving cropping systems through soil improvement, animal feed, and increased crop yield appears to vary from positive (Krull *et al*. 2012; Farooq and Siddique 2015) to neutral or even negative (Scott *et al*. 2010, 2013). A modelled assessment of the factors that influence the adoption of CA (including reduced tillage, residue retention and crop rotation) by small holders in Africa (Pannell *et al*. 2012) found that the key factors might include: "...the opportunity cost of crop residues for feed rather than mulch, the short-term reduction in yields under zero tillage plus mulching in some cases, combined with short planning horizons and/or high discount rates of farmers, farmer aversion to uncertainty, and constraints on the availability of land, labour and capital at key times of year".

This paper however, highlights the separate effects of residue retention on the soil, crop and animal components of farming systems and the need to understand the possible reasons for adoption or non-adoption of residue retention as part of a CA system. The scope of this review includes systems that contain the winter cereals such as wheat, barley and oats that are grown under rainfed conditions in various combinations with legume crops and pastures. Our review largely relates to dryland environments with winter-dominant rainfall, or Mediterranean-type environments. The aim is to evaluate the importance of crop residues in the dominant cropping systems in dryland environments. Its purpose is to assess gaps in existing knowledge of the impacts of residue retention on soil water storage, soil organic matter and crop yield and to suggest areas for future research. While reference is necessarily made to the principles of CA our main purpose is not to evaluate the CA system *per se* but to evaluate the value of the stubble retention component of the system in order to understand why crop residues are retained in some systems, but not in others.

Description of the systems

Traditional crop/livestock systems often rely heavily on crop residues to maintain livestock over the dry, summer period (Nordblom 1987). In North Africa and West Asia, livestock are often not owned by the farmers that produce the crops but by nomadic herders who enjoy customary rights to graze crop residues in return for payment either by barter or cash (Kassam *et al*. 2012). In such situations, the extent of residue removal by grazing varies according to the rainfall zone and stocking pressure and thus the degree of protection against soil erosion varies considerably. This situation is a variant on the system in parts of Africa where nomadic flocks have the customary right to graze crop residues without payment to the farmer (Mazvimi and Twomlow 2009; Sibanda *et al*. 2011; Erenstein *et al*. 2012). In some dryland environments where there are no nomadic herders, livestock are usually owned by the crop producers as in Australia, but the range of residue removal by grazing is similar, depending often on the value of livestock products and the extent of previous soil erosion. For example, where grazing rights can be sold and the soils are perceived to be less prone to erosion as in North Africa and the Middle East, the residue removal can be almost complete each year. However, where there is no market for the sale of crop residues off-farm, or where the risk of soil erosion is high if the soils are left bare as in parts of Australia, the removal of crop residues is likely to be less.

Residue use for building generally constitutes a very small proportion of total crop residue production except at the local scale. Likewise, use of crop residues for making paper or ethanol (Borrion *et al*., 2012; Hansen *et al*. 2012) to date is only a small proportion of the total available residues and is sourced from more humid areas where crop yields are relatively high. In these cases, little crop residue is returned to the soil except for the roots, and there will be a need to replace the nutrients contained in the straw as well as those removed in the grain.

In modern crop–livestock systems, whether zero or conventionally tilled, grazing by livestock can remove all or part of the residue even though some nutrients are returned to the soil through faeces and urine. Experimental evidence from south-west New South Wales has shown that grazing animals consume fallen grain and green weeds before they eat dried leaves and stems (Mulholland *et al*. 1976). The applicability of this finding to other dryland cropping zones needs further confirmation. Complete stubble burning or partial burning of windrowed residues is also practised, often in crop-only systems, to reduce weed seeds or where residues are likely to block seeding machinery (Llewellyn *et al*. 2012; Scott *et al*. 2013). For example, in Australia from a survey taken in 2007-8 up to 45% of residues were burned, totally or partially, in the winter-rainfall areas (Llewellyn *et al*. 2012). In conventional tillage systems the residues are commonly turned into the soil by cultivation (Fettell and Gill 1995).

The diversity of stubble management systems is illustrated in Table 1 using data from a survey of 7055 farmers (Australian Bureau of Statistics 2009). The most popular treatments of crop residues were either complete retention or removal by baling or grazing. The results are indicative of systems in transition where farmers are testing various methods according to site and seasonal conditions. This diversity in broad scale farming systems of southern Australia, where the annual rainfall is more evenly distributed between winter and summer, has been discussed by Kirkegaard *et al*. (2014) who suggested that farmers have cautiously adopted components of the CA system according to their soil, climatic and financial conditions.

However, in an earlier simulation study (Kirkegaard and Hunt 2010) the potential impact of retained crop stubble was not included as a benefit for subsequent crop yield.

In all systems where residues are grazed, there is potential for soil compaction if livestock are left on the crop residue after harvest when the soil is wet (Packer *et al*. 1985; Hamza and Anderson 2005) even though this may be minimal (Bell *et al*. 2011; Hunt *et al*. 2011). Wind erosion may also occur if animals overgraze the residues leaving bare soil. Minimum levels of cover have been suggested to protect soil from wind erosion (Findlater *et al*., 1990; McTainsh *et al*. 1990; FAO 2011). In evaluating the grazing worth of residues, the possible dis-benefits of these hazards should be considered, where appropriate. The benefits of controlling soil erosion through retaining crop residues (mulching) are seldom considered by smallholders, but accrue mainly in the public domain (Williams and Young 1999; Pannell *et al*. 2013). However, in extreme cases where soil erosion threatens the viability of the farming enterprise, the benefit of residue retention will be apparent to all farmers, regardless of farm size or the adoption level of advanced technologies. Research to support the benefits of residue cover in reducing soil erosion has clearly demonstrated the benefits on vertisols in summer dominant rainfall conditions in parts of Australia (Freebairn and Wockner 1986; Sallaway *et al*. 1990).

Biological evidence for soil and crop yield improvement

The question of how to place a monetary value on improvements in soil organic matter, soil water infiltration and reduced erosion can be addressed through improved crop yields in the short or longer term. In theory, increased water infiltration and reduced soil evaporation will lead to increased crop yield which, in the absence of other limiting factors, will lead to increased return of organic matter

Table 1. Crop residue management practices in some Australian states, 2007–2008. [NB. Some farmers use more than one method, so percentages do not sum to 100].

Practice	% of area × state				
	WA	SA	Vic	NSW	Qld
Most stubble left intact (no cultivation)	62.5	50.0	37.1	44.8	32.0
Most stubble removed by baling or heavy grazing	29.2	38.9	44.2	35.8	16.9
Stubble removed by hot burn (early in the season)	6.6	2.1	2.9	3.2	4.5
Stubble removed by cool burn (late in the season)	16.1	8.9	10.1	5.6	3.6
Stubble ploughed into the soil	13.7	21.5	27.4	35.2	53.2
Stubble mulched (on top of soil)	3.4	9.7	9.0	8.8	19.8

Source: Australian Bureau of Statistics (2009).

(or SOC) to the soil, thus improving soil fertility over time and setting up a beneficial cycle of soil and yield improvement.

Soil water

The evidence for increased water infiltration (Hamblin *et al*., 1987; Marley and Littler 1989; Radford *et al*., 1992; Malinda 1995; Thomas *et al*., 1995; Schwilch *et al*. 2013) and reduced soil surface evaporation (Smika 1983; Sommer *et al*. 2012) when crop residues are retained is relatively clear, a finding confirmed for a wide range of conditions in the review of Verhulst *et al.* (2010). The amount and distribution of rainfall after harvest may have important consequences for the effectiveness of stubble retention for water conservation in some environments (Scott *et al*. 2010, 2013). In contrast, it is apparent that increased water storage where crop stubble is retained is more likely in environments where some rain falls during the summer period (eg. Marley and Littler 1989; Radford *et al*. 1992; Scott *et al.* 2010; Scott *et al.* 2013).

Soil organic matter

Data from Morocco and other locations in the West Asian and North African region summarized by Mrabet *et al.* 2012 and Loss *et al*. 2015, show some evidence that no-till systems with stubble retention increase soil organic matter more than conventional tillage and that wheat yields increased more often than not in field experiments comparing the two systems. In addition, evidence that soil organic matter increases in a range of soil types using direct drilling with residue retention in Australian rainfed crops suggests no increase even after 10 or more years unless annual rainfall exceeds about 500 mm (summarized by Chan *et al*. 2003). This is possibly due to the lower crop yields and residues that are produced under lower rainfall conditions, or to the likelihood that soil temperatures are higher in the low rainfall areas leading to destruction of soil organic matter (Hamza and Anderson 2010).

Even in cases where soil organic matter is increased only slightly by the addition of green material, other soil physical properties such as water stable aggregates and soil bulk density may improve (Hamza and Anderson 2010; Krull *et al*. 2012). Whether similar improvements can be achieved by adding dry stubble material to the soil needs clarification. Verhulst *et al*. (2010) concluded that CA systems that include residue retention can have a positive effect on soil properties other than organic matter percentage.

In higher rainfall areas (>500 mm annual rainfall) in farming systems that include a range of crop and crop/pasture combinations, soil organic matter tends to accumulate in the top 10 cm across a range of soil types in the Western Australian environment (Hoyle *et al*. 2013). If the organic matter content of the topsoil tends to reach saturation under zero-tillage systems in general but the subsoil remains low, further research is required to demonstrate overall soil improvement. In addition, data are needed for a range of cropping and farming systems that can be used to ascertain the anticipated impact of SOC on grain yield in the absence of other limiting factors.

The potential impact on soil fertility and crop yield of changes in soil physical and chemical properties due to plant roots and return of animal wastes, other than changes due to SOC, also need to be further assessed. In addition, Krull *et al.* (2012) have stated, that total SOC is often not a good indicator for assessing soil properties. Frequently, such properties are affected by specific pools with particular properties. Only by studying these pools separately and in conjunction with a specific function is it possible to understand what the key impacts of a SOC pool are.'

Crop yield

The review by Pannell *et al*. (2013) concluded that the impact of residue retention (mulching) on crop yields in central Africa and south Asia has been largely positive over the longer term. In contrast, the review by Scott *et al*. (2010) on stubble retention in cropping systems in southern Australia concluded that "the effects on grain yield of stubble retention are largely negative, using current technology." In a further review, Scott *et al*. (2013) again drew the conclusion that in the dominant cropping systems of southern Australia there is little compelling evidence that crop residue retention has resulted in reliable economic benefits. Ward and Siddique (2015) also concluded that even though the evidence for reduced soil surface evaporation under retained crop residues is clear, the evidence that this has led to improved water use efficiency in grain crops has been less evident. Further, Schwilch *et al*. (2013) in a study on stony hillsides in Morocco reported only small increases in grain yield and water use efficiency and limited effectiveness of the ground cover aspect of the CA system tested.

In addition, Farooq *et al*. (2011) found that the impact of CA (including both zero tillage and residue retention) on crop yields was mostly positive, especially at lower rainfall, but suggested that where the yield of CA crops did not exceed those of conventional systems, factors such as weeds and diseases may have been responsible. The separate impact of crop residue as distinct from the tillage effect is not reported in many of the experiments in these reviews. In any case, evidence that the SOC percentage is closely related to crop yield is not always apparent in field studies across a wide range of experiments (Howard and Howard 1990; Fettell and Gill, 1995).

The apparent lack of a robust relationship, or set of relationships, between soil organic matter percentage and crop yield may be due to some other factor or factors limiting yield such as water or nutrient availability. In general, there is some level of agreement that soil organic matter and crop yields are more or less linearly related up to about 2% organic carbon (Howard and Howard 1990; Janzen *et al*. 1992) but less agreement that a critical level exists across soil types and environments (Loveland and Webb 2003). However, the variability in these relationships suggests that the slope of the increase below 2% organic carbon is quite wide.

Given the variability among the various authors and reviewers of the benefits of retaining crop residues, it seems likely that local climatic, edaphic and technological situations should be accounted for when attempting to extrapolate experimental evidence to commercial farms.

In summary, it appears that where the soils are deep (implying that they can store more available water) and there is more than 500 mm annual rainfall with a summer or winter incidence, the benefits of residue retention on grain yield is likely to be positive. However, where the soils can store less water and the annual rainfall is less than about 500 mm, regardless of its incidence, there is less likelihood of a positive effect of retained residues on yield of the following grain crop. In addition, under the lower rainfall conditions atmospheric temperatures are likely to be higher, thus making it more likely that SOC will be destroyed over the dry periods.

The value of crop residues

One of the constraints in valuing crop residues is the difficulty of comparing cases where a direct monetary return can be obtained for the residue itself with cases where the return only comes via animal production or survival, or through preservation of the soil resource. Examples of potentially competing uses include: livestock grazing versus soil protection and fertility improvement; soil improvement versus harvest and sale off-farm; burning to facilitate sowing operations of the succeeding crop (with additional fertilizer to replace lost nutrients) versus return to the soil. Combinations of uses such as partial removal by grazing or burning with the remainder returned to the soil are also practised (Table 1).

Animal feed

Estimating the value of livestock grazing is possible through knowledge of stocking rates and number of days of grazing. The current value of livestock and their weight gain or loss will also be important determinants of monetary value. Some estimates of stocking rates, weight gains and time of grazing have been made for sheep grazing cereal stubble in Australia (Mulholland *et al*. 1976; Robertson 2006). A preliminary estimate based on a stocking rate of 10 sheep per hectare with a live weight gain of 5kg/head (based on values selected from Mulholland *et al*., 1976) can be used as a starting point in assessing the value of grazed stubble. However, detailed analysis of the economic value of stubble for various agricultural systems is needed.

In eastern Mediterranean countries, it is common that nomadic herders pay crop producers between US $ 20 and $ 60/ha for grazing rights depending on whether the land is irrigated or rainfed, and the crop residue is barley or wheat (A. Mazid, A. Haddad, personal communication). The price may include removal of the remaining straw after grazing for about 60 days. The value of crop residues for grazing in any given year may also be a function of the amount of residue and the availability of alternative feed sources. In a drought year, even though the residue amount may be small, its value for livestock feed could be high. In Morocco, for example, Magnan *et al.* (2011) estimated that grazing stubble accounts for around 25% of the total value of cereal production in a normal rainfall year and around 75% in a drought year, when many farmers harvest little or no grain.

In the final analysis, the value in the market place will be decided by supply and demand for any given situation but the cost of nutrients removed by grazing or other means needs to be taken into account. The range of values of nutrients found in wheat straw in crops in Western Australia, for example, is given in Table 2.

Table 2. The range of plant nutrients found in wheat straw in Western Australia (after Gartrell and Bolland 2000).

Nutrient	Range (kg/t)
N	2–10
P	0.2–1.5
K	6–16
S	0.4–1.5
Mg	0.5–1.0
Ca	0.6–2.0
Cu	0.001–0.003
Zn	0.01–0.03
Mn	0.01–0.06

If animals are left to graze crop residues until forced to consume stems in addition to green weeds, spilled grain and leaves, or the stocking rate is too high, or the quality or amount of residue is too low, then it is likely that they would lose weight towards the end of the summer period and the only value of the stubble would then be for survival of the animals. This is supported by the low digestibility of cereal straw (Mulholland *et al*. 1976; McDonald *et al*., 2002; Robertson 2002; Thomas *et al*. 2010) aside from other residue components, especially late in the summer or after summer/autumn rain. Similar data are required for other dominant systems that cover the range of the variables that are locally appropriate.

Controlling soil erosion

The value of erosion control is more difficult to assess. The effectiveness of residue cover for reducing soil loss by wind erosion has been asserted, measured or modelled in a range of rainfed environments (Lyles and Allison 1976; Findlater *et al*. 1990; Hansen *et al*. 2012) but the amount of soil lost and its relevance to crop yield is not clear. The relative value will depend in part on the amount and productivity of the remaining soil, which in turn is partly affected by the average rainfall if a value based on crop yield loss is used. Estimated losses of soil by water erosion at Wagga Wagga, New South Wales ranged from 0.5 to 1.4 t/ha/year for stubble retained compared to stubble burnt treatments (Barker, 1989). Losses measured due to water erosion were much greater in some North American agro-ecosystems (Hansen *et al*. 2012). However, there is considerably more summer rain at these locations than in most Mediterranean-type environments.

If the topsoil, which contains most of the crop nutrients, is eroded entirely, the cost of the loss includes the cost of extra fertilizer required to maintain the value of crop yields. An additional cost may be the partial loss of soil depth and consequent water holding capacity. The value of crop residues could be viewed in the context of preventing soil fertility loss, which will vary according to the initial and remaining soil quality, past and potential crop yields, and the possibilities for, and costs of restoration.

Further research and economic assessment under a range of agro-ecological situations is necessary to fully value crop residues. In the meantime, the only cases where actual values can be unequivocally ascertained are those where residues are sold as in the example given above for the eastern Mediterranean region. There is also a need to evaluate the possible range of returns from strategies that have, for example, a mixture of some grazing and some residue retention.

It is far from clear however, that farmers in all circumstances will respond to soil losses by retaining crop residues unless the observable erosion is severe. On the south coast sand plain in Western Australia, farmers rapidly adopted stubble retention with minimum and then zero tillage from 1970–1990, when blowing sand covered roads and fences and the livelihood of farmers was threatened (J. Lemon, personal communication). This experience of the value of stubble retention has likely been critical in the widespread adoption of residue retention in other parts of the Australian cropping zone (Ward and Siddique 2015). Various surveys of Australian farmers (Australian Bureau of Statistics 2009; Llewellyn *et al*. 2012) reported that up to 63% of crop residues were retained and about 34% burnt in the dryland areas, apparently in response to concerns about soil erosion if residues were removed completely. In contrast, in West Asia and North Africa dust storms in late summer/early autumn are widespread and the common perception among farmers is that a small amount of wind erosion has little impact on soil fertility (Loss *et al*. 2015).

Carbon sequestration

A further value of retaining crop residues lies in carbon sequestration for the purpose of reducing atmospheric carbon dioxide. Various values have been placed on soil carbon sequestration ranging from about US $ 25 to US $ 150/t (Antle *et al*. 2002: Belcher 2003). Given the relatively small amount of crop residue from dryland cereal crops, say 1–15 t/ha/year, it would take a long time to sequester each tonne of carbon. The potential for carbon sequestration in current cropping systems in Victoria, Australia has recently been questioned (Robertson and Nash 2013).

In long term trials in northern Syria comparing zero-tillage with stubble retention and conventionally-tilled treatments, Loss *et al.* (2015) measured carbon sequestration rates associated with increased soil organic matter in the range of 0.27 to 0.30 Mg C/ha/yr and they postulated that this rather modest increase was probably due to low to moderate crop productivity and a reasonable initial soil organic matter content of about 1.3%. Much of the value of carbon sequestration however, will be accrued in the form of soil structural and chemical improvements, the impact of which may be evident in the relatively shorter term (Krull *et al*. 2012).

Given the large number of variables that are known to influence the value of crop residues, and the absence or scarcity of objective measurements for many of them, it seems appropriate to use a bio-economic model such as that proposed by Pannell *et al*. (2014) to estimate some likely values. They concluded that “Key factors that would tend to discourage adoption in situations that otherwise look favourable include: the opportunity cost of crop residues for feed rather than mulch, the short-term reduction in yields under zero tillage plus mulching in some cases, combined with short planning horizons and/or high discount rates of farmers, farmer aversion to uncertainty, and constraints on the availability of land, labour and capital at key times of year. Further experimental data for some of the parameters described above will contribute to the reliability of such models.

CONCLUSIONS

Crop residues may have a substantial monetary benefit for farmers in crop/livestock farming systems where animals remove all or part of the material left after grain harvest. Many factors affect size of this benefit but it can be viewed as the opportunity cost of using the residues for another purpose such as soil fertility improvement. There are several gaps in knowledge that make it difficult to evaluate the value of crop residues to the farmer under a range of conditions. These include:

- While there is credible evidence that retention of crop residues can increase soil water storage, it is not clear whether this has increased crop yield in all cases. The reasons for this apparent anomaly need to be further elucidated.
- Addition of crop residues to the soil does not always result in increased SOC. Further, a general relationship between SOC or soil organic matter and crop yield across a wide range of conditions is not apparent. It is likely that there will be a range of responses according to rainfall zone, soil type and other environmental factors. The factors that limit such an anticipated response require further research if the value of residue retention is to be fully assessed.
- Changes in soil physical properties associated with changes in SOC need further clarification.
- Where zero tillage is practised there is scope to investigate how organic matter from crop residues can be moved further down the soil profile beyond the top few centimetres.
- The relationship between topsoil loss and crop yield for a range of agro-ecological systems needs to be clarified.
- Data on animal performance and survival when grazing crop stubbles are required for the dominant cropping systems.
- The possible range of returns from systems where some grazing is practised and some residues are retained.

Many of the published reports comparing various forms of CA with conventional systems have not clearly distinguished between the effects of residue retention and those of reduced tillage, crop rotation, or nutrition on grain yield. The lack of data and adequate analyses on this aspect makes estimating the value of residues more difficult. The experimental and analytical rigour to fully evaluate aspects of CA systems has been strongly argued by Brouder and Gomez-Macpherson (2014).Given the variation in cropping and farming systems within Mediterranean-type environments where CA has been or is beginning to be adopted, and the apparent or perceived values for a range of alternative uses of the residues, it seems inappropriate to insist on a doctrinaire recommendation that all such systems must include full residue retention.

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