Implications of stubble retention

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The original objective of stubble mulching was to control soil erosion in the American Great Plains. However, North American experience, gained over almost four decades, has exposed the many interactions which occur between soils, plants and micro-organisms where stubble retention is practised.

In the light of this experience, Parr and Papendick (68) commented on the need for multidisciplinary approaches to elucidate the implications, positive and negative, of stubble retention in cropping systems.

Positive aspects, particularly related to the original objective of erosion control, are well documented and not treated at length in this review. They are primarily physical in nature, encompassing, for example, reduced run-off, improved regulation of soil moisture and temperature, and improved soil structure. Chemical effects of stubble retention are less well understood. They also may be positive: for example, improved soil nutrient status. However, there is considerable evidence for negative effects associated with phytotoxin production during leaching and decay of stubble and consequent decreases in yield of subsequent crops.

Stubble retention in Australia, initially adopted in areas of high erosion risk, is finding increasing acceptance in a range of climatic zones and cropping systems. Each presents its own problems; each will experience differing combinations of the positive and negative effects of stubble retention. This review attempts not to specify these combinations but to elucidate the implications of stubble retention for plants and soils in Australian cropping systems.

Physical effects of stubble retention

Retained stubble itself presents a physical obstacle to wind and water, promoting stability at the climate/soil interface. Although these effects are modified through stubble decomposition and ultimate incorporation into soil organic matter, long-term implications for physical properties of the soil remain.

1. Soil Physical Properties

(a) Bulk density

As with other soil properties, changes in bulk density that accompany stubble retention are determined to some extent by environmental conditions and tillage practices.

In humid temperate regions, a combination of high clay content and high soil moisture at the time of sowing predisposes increases in bulk density where direct drilling is practised, compared to conventional tillage (14).

Cannell at al. (14) considered such increases would restrict root growth which, in turn, may restrict nitrogen uptake. Working with sandy loam and clay loam soils in temperate zones, Turelle and McCalla (87) and Pidgeon and Soane (72) found that under no-till conditions bulk density increased for the first three years owing to natural compaction and vehicular traffic, with little change thereafter.

Throughout a five-year experimental period Blevins, Thomas and Cornelius (9) found little difference in bulk density between conventional and no-tillage systems but, under a system of minimum tillage in Nigeria, Juo and Lal (37) reported that bulk density generally decreased with increasing amounts of residue. These workers considered that for these soils bulk density was increased by raindrop impact and soil dispersion owing to exposure when no residues were present. In low-rainfall areas such effects may not influence bulk density relationships.

The general pattern of bulk density changes, or the inversely related property porosity, is an initial increase (decreased porosity), followed by a period of stabilization. With continued stubble inputs and crop root activity, a slight decrease (increased porosity) may occur in some soils. The extent of the latter phases depends on the accumulated residue input, the type and frequency of cultivation and soil micro-organism and macro-organism activity.

(b) Soil aggregation

Compared to conventional tillage, stubble retention systems, with time, promote improvements in soil aggregation that are related to the level of residue inputs (8). Comparing stubble management systems on swelling soils Hewitt and Dexter (34) found greater soil aggregation where stubble was retained than where it was burnt. Later work (Dexter et al., in press) indicates that, as might be expected, the extent of changes in soil macro-structure varies with site, amounts of stubble returned and other factors.

Marston and Hird (62), working with black cracking clays, reported no significant structural differences between stubble treatments. Such variable responses may be a consequence of clay levels and type of such soils and of organic matter levels before the introduction of stubble retention. Further, for some Australian soils, structural changes are slow to occur (31), indicating that longer periods of monitoring are required for definite conclusions on some soil types and environments.

The prime aim of stubble retention systems is at least to contain soil erosion losses. Structural improvements are an added bonus in reducing the erodibility of soils. With time, structural improvements associated with residue inputs lead to higher infiltration rates and hydraulic conductivity (37,41), in turn resulting in higher water content in the profile.

2. Moisture Relations

(a) Reduced evaporation and increased infiltration

The retention of surface stubbles has given improved surface soil moisture levels both in Australia (22) and overseas (10). However, increases in overall soil water status have proved much more variable and depend on soil moisture status, soil type and climatic conditions. McCall and Army (57) have suggested that stubble mulches can reduce evaporation only as long as the soil surface remains wet. Thus in regions of high rainfall stubble may be more efficient in reducing evaporation than in low or irregular rainfall areas. When the soil near the surface dries, the rate of evaporation loss becomes increasingly independent of stubble mulches on the surface.

(b) Improved moisture storage

Under Australian conditions the value of straw retention in improving water storage in the whole soil profile has shown great variation between locations. In northern New South Wales Doyle and Forrester (22) found similar levels of profile water storage to 135 cm depth under both burnt and retained stubble systems. Certainly, large amounts of stubble (17.5 t/ha) have proved capable of improved water storage, increasing the recharge of soil moisture below 45 cm even at higher temperatures (82). This increased water storage produced yield increases that were proportionally greatest in a dry year.

Overseas data have also shown major increases in stored soil moisture which were related to the method by which the straw mulch was applied (46, 48). The results of much of the experimental work with water storage under straw residues suggest that, while surface infiltration is usually increased, there may be little long-term value unless longer term evaporation can be reduced, allowing deep penetration of water.

(c) Reduced run-off

Erosion control remains the prime function of stubble retention in much of the Australian cropping belt. On light soils, for the reduction of wind erosion, standing stubble is more effective than stubble mulching (60), while surface mulching has a greater effect in reducing raindrop impact and water erosion. In much of Australia, wheat straw residues of only 1.5 to 2 tonnes/ ha are common and this level of stubble may be insufficient to protect the soil adequately. Even with adequate stubble levels run-off may still occur once the plough layer is fully saturated. However, this slow rate of run-off will greatly reduce erosion risks.

The quantity of stubble required to protect the soil will vary depending upon soil type, slope and rainfall intensity. A strong relationship exists between the quantity of stubble retained and soil losses; Loch and Donnollan (51) showed that an increase from 1-3 t/ha of stubble will produce an almost proportional reduction in run-off.

Recent Queensland data (26) illustrate the value of both retained stubble and standing crops for reducing both water run-off and soil loss (Table 1).

Table 1. Run-off and soil loss under four surface conditions. (After Freebairn and Wockner, 1980).

	Stubble Burnt	Stubble Incor-porated	Stubble Mulched	Sorghum Crop
Surface cover %	5	35	50	80
Surface run-off (% of rainfall)	28.7	17.3	9.7	3.2
Soil loss t/ha	20-40	5	Negligible	Negligible

Such data show major effects of stubble on single-storm losses over a short time period; in northern Australia it is frequently these events which cause rapid soil degradation.

3. Temperature

Stubble mulching with summer-growing crops such as maize has proved valuable in moderating the adverse effects of high soil temperature (45, 46, 59). Lal (46), using light residues of 2 t/ha, produced differences of up to 8?C between mulched and bare soils at 5 cm depth. Minimum soil temperatures in his experiments were lower for the unmulched treatment and this produced a greater diurnal temperature fluctuation. Daily maximum temperatures were reached one hour earlier for the bare soil: the mulch treatment also retarded the rapid cooling which occurred after the 3 p.m. peak temperatures on the bare soil. In the two years of this experiment, yields were significantly increased by stubble mulch application (Table 2).

Table 2. Effects of stubble mulch on yield of maize. (After Lal, 1974).

Treatment	Grain Yield t/ha 1970	1971
Mulched	0.78	5.4
Unmulched	0.53	3.6
L.S.D. (P = 0.05)	0.32	0.7

In later work, Lal (48) showed that maximum soil temperature in unmulched plots was supra-optimal for between 3 and 6 hours per day in the initial period of maize growth.

Straw mulching has been found to increase root weight and lateral root growth in maize in a year of above-average soil temperatures and moisture stress (3). Lal (48) also found a concentration of maize roots in the surface soil layers directly under the mulch, and suggests that preferential root growth was occurring in the cooler damper areas under the stubble mulch.

Under winter conditions straw also has the capacity to reduce major temperature decreases in bare surface soils. McCalla and Army (57) showed that while soil was cooler in spring and summer under a mulch, a reversal occurred in late summer and that temperature fluctuations were less under the straw-mulched plots. Cool conditions under mulch in early spring growing seasons can reduce crop growth in cooler areas (88).

Allmaras, Burrows and Larson (3) determined an optimum root temperature for corn growth and showed that reduced soil temperatures resulting from stubble retention either stimulated or depressed growth depending on whether bare soil temperatures were above or below this optimum. These results could be extrapolated to other crops.

4. Enrichment of Soil Organic Matter Content

Increased organic matter content of soils improves nutrient status, influences soil water, air and temperature relations, makes tillage easier and improves soil structure, thus reducing erodibility (50). Following the introduction

of stubble retention in a cropping system, changes in soil organic matter levels are influenced by several factors.

(a) Previous history

Where natural vegetation exists or where productive pastures have been maintained for long periods the introduction of cropping usually results in a decline in organic matter levels (25,9,49,63). However, where soils were cropped before the introduction of stubble retention, a maintenance of or increase in soil organic matter levels is possible (47).

(b) Levels of organic matter input

The higher the input to a system the lower the rate of decline, or the faster the build-up of organic matter. Lal et al. (49), for a tropical situation, reported that the rate of organic matter decline over an 18-month period was 0.103% per month where no residue was returned but 0.076% per month where

12 t/ha of rice straw was mulched. Rasmussen et al. (77) considered that an input of 5 t/ha/yr of residue was required to maintain soil organic matter levels in the temperate wheat-growing areas they studied, while Juo and Lal (37) considered 16 t/ha/yr was required for a tropical environment.

(c) Cultivation

Tillage reduces soil organic matter levels while increasing aeration, and consequent oxidation, and increasing the potential for leaching and erosion (2).

Comparing no-tillage and conventional tillage for maize production, Blevins et al. (9) found that, after 5 years without nitrogen addition,soil organic matter levels were 3.68% and 2.37% respectively. For a treatment receiving 336 kg N/ha the respective values were 4.53% and 2.79%.

Soil organic matter changes apart, the placement of residue is important in soil erosion control, consideration of which may assume greater importance than preference for a particular form of tillage. Brown and Dickey (13), studying the effectiveness of wheat straw in erosion control, found that, after 18 months, loss of straw was dependent on its position relative to the soil. The loss for standing material was

22% and 34% for two locations, the latter the warmer of the two; for straw lying on the soil surface 31% and 40% and for buried straw 93% and 98%. The amount of stubble remaining above the ground can be manipulated with various tillage implements (24, 61). Incorporation of residues generally accelerates decomposition.

Curbing the rate of decline, maintaining a constant level, or even increasing the levels of soil organic matter, are achievable provided sufficient stubble is available. In many wheat-growing areas of Australia, particularly in poor seasons, the amount of stubble available is not sufficient to meet such aims.

However, there are indications that mulched straw increases the organic content of the soil more so than incorporated material (18). This suggests that residue placement may he an important management tool in the manipulation of soil organic matter levels.

Chemical and biological effects of stubble retention

1. Changes in Soil Nutrient Status

(a) Nitrogen immobilization

Residue placement and nitrogen content are important determinants of the rate of decomposition and extent of nitrogen immobilization associated with retained stubble. When residues with a low nitrogen content (wide C:N ratio) such as cereal straws are incorporated into soil, nitrogen immobilization and subsequent yield reduction can occur. Such effects are intensified in soils with low nitrogen status. In general, applications of fertilizer nitroger are required to rectify such a deficiency. However, the application of nitrogen does not always result in yield increases where phytotoxins, released during residue decomposition, are present (40).

The period of immobilization depends on the time required to decompose the residue. Heavy, clay-textured soils, while generally having a high initial organic matter level, also have slower rates of organic matter decomposition than soils with a sandy texture (1, 43). Such results are a consequence of the better aeration of sandy soils and the protected organic matter associated with clay colloids. Ladd, Parsons and Amato (44) have demonstrated a similar relationship for differential nitrogen immobilization rates between calcareous clay and calcareous sandy soils.

Following the addition of residues with wide C:N ratios some soils have shown overall gains of nitrogen, reportedly as a result of the activities of non- symbiotic nitrogen fixers (1). Presumably, a soil environment deficient in readily available nitrogen gives a competitive advantage to this group of micro-organisms.

Total soil nitrogen increases under stubble retention systems, but initially available mineral nitrogen is less compared to systems where stubble is burnt before sowing (79). While the burning of stubble may overcome nitrogen immobilization problems, such benefits have to be weighed against the increase in potential soil erodibility (80) and the volatilization loss, during combustion, of nitrogen and carbon (76). Biederbeck et al. (7) considered that burning of stubble would reduce the potentially available nitrogen in time as well as inducing other deleterious declines in soil properties. For these reasons, it is considered that under most Australian conditions stubble retention should be favoured over burning and minimal incorporation of stubble practised to reduce the sudden impact of nitrogen immobilization following sowing.

(b) Other nutrients and pH

Studies by Withee and McCalla (93), Triplett and Van Doren (86) and Blevins et al. (9) indicate that, under stubble retention systems, phosphorus and potassium tend to be more concentrated in the first few centimetres of the soil profile than on conventionally-tilled sites. This distribution essentially indicates the site of organic matter accumulation and subsequent mineralization. Brown and Dickey (13) reported that phosphorus immobilization was maximized after three months but that this could vary with soils and location. Such observations on the build-up of nutrients imply associated increases in numbers and diversity of microbial populations. Withee and McCalla (93) point out that the availability of such nutrients would also make conditions more favourable for decomposition of crop residues. However, Doran (21) found that no-tilled soils were less oxidative compared to conventionally-tilled soils. In wet areas this could mean a larger proportion of facultative anaerobes and, in particular, denitrifiers. For some soils this may be an early phase and, in time, more favourable aeration may develop in association with decomposition of roots and the development of larger soil fauna populations (5).

The introduction of stubble retention, together with reduced or zero tillage, will change nutrient levels and availability over time. Increased mineralization rates of both inorganic and organic nitrogen sources can have an influence on pH levels. Blevins et al. (9) reported a decline in pH level that was influenced by nitrogen fertilizer and residue additions in no-till plots. This depression of pH was larger than that for conventionally-tilled plots. Hence, in the long term, nutrient availability and toxicities of aluminium and manganese could be potential problems. Such problems might be countered with appropriate additions of lime.

2. Production of Residue Phytotoxins

Stubble-mulch practices result in the addition of a wide variety of both organic and inorganic compounds to the soil system. These compounds may be leached directly from stubble residues, liberated during decomposition, or synthesized by micro-organisms utilizing the residues as a nutrient source. The production, accumulation, transformation and, ultimately, destruction of such chemicals is influenced by a large number of factors and the dynamic nature of the soil system ensures that their concentration varies over space and time.

(a) Leaching

Before their decomposition, most crop residues contain water-soluble substances able to inhibit the germination and growth of other crops (11,29,38, 30,39,42). Inter- and intra-specific variation influences the extent of this inhibition and the period of weathering required to remove it. Guenzi and McCalla (29) demonstrated that cold water extracts of standing residues of wheat, oats, soybeans, corn and sorghum significantly depressed the germination and growth of wheat, corn and sorghum. Eight weeks of weathering in the fields was sufficient to reduce the toxicity of wheat and oat stubbles, while corn and sorghum required 22-28 weeks weathering (30).

The amount of rain falling on standing straw will modify such time scales.

In southern Australia, where dry conditions usually prevail in summer, Kimber (38) demonstrated that wheat straw taken from the field after several months of weathering still contained water-soluble toxins. In the wheat belt of northern New South Wales and Queensland, summer rainfall is probably sufficient to allow weathering of cereal stubble to proceed beyond this stage. However, the greater resistance of corn and sorghum residues to leaching suggests that even in high rainfall areas water-soluble toxins may be active during the establishment phase of crops sown into these stubbles.

Intra-specific variation in the occurrence of water-soluble toxins in stubbles is also apparent. For example, Guenzi et al. (30) tested water extracts from stubbles of nine wheat varieties collected immediately after harvest and found differences in their ability to depress the germination and early growth of wheat.

(b) Aerobic decomposition

A diverse range of phytotoxic products is associated with the decomposition of residues. These are probably of far greater significance than water- soluble toxins leached during the normal weathering process.

Given favourable moisture and temperature levels, microbial activity and synthesis is high where residues are decomposing in aerobic soils (28,69). Under such conditions, soil type, temperature, pH, residue type and treatment, and the type and population density of micro-organisms associated with the decomposition will largely determine the organic compounds produced and their subsequent effects on plant growth.

Stubble-mulch practices significantly increase the number of bacteria, actinomycetes and fungi on the top few centimetres of soil (66). These micro-organisms have been implicated both as primary decomposers of plant residues, releasing inherent phytotoxins or precursors of phytotoxins previously bound in plant tissues, and as intermediaries in the transformation of primary decomposition productions into secondary phytotoxic substances. Furthermore, they often synthesize other substances that influence the growth and metabol- ism of higher plants.

Chatterjee and Nanci (15) determined that stubble residues were degraded most quickly and completely when a large variety of micro-organisms was assoc iated with the decomposition. Under these conditions, decomposition products underwent sequential breakdown; that is, one species utilized the breakdown products of another until only simple and usually beneficial breakdown products such as soluble carbohydrates and nitrogen remained. When a restricted number of micro-organisms was involved in the decomposition process the likelihood of phytotoxin accumulation was greater, as products were not further decomposed.

When conditions favour microbial activity, phytotoxins are formed during the early stages of the decomposition process and subsequently inactivated (70, 71, 85, 38, 39, 83).

If concentrations of organic matter are sufficiently high and the necessary micro-organisms are present, antibiotics are produced in appreciable quantities in soil (94,12). Nearly all antibiotics can be taken up and trans- located by plants. Even though the half-life of such absorbed antibiotics is only several days, they are metabolic inhibitors of great specificity and potency (12). Many have been shown consistently to inhibit seed germination and root growth at concentrations of 5 pg/ml or less (12,64,81) (Table 3).

Table 3. Repression of root growth by antibiotics. (After Norman, 1959).

Antibiotic	Concentration causing 50% repression of root elongation of *Cucumis sativus*	Concentration causing 50% reduction of dry weight of *Hordeum vulgare* roots
	µg/ml	µg/ml
L-cycloserine	0.2	0.6
Azaserine	2.6	2.3
Sulfocidin	2.9	2.7
Magnamycin	4.0	50
Oligomycin	4.7	6.2
Terramycin	5.2	2.5 (caused 42%)
D-cycloserine	8.5	3.5

Persistence of antibiotics is dependent on soil pH, levels of biological activity and the presence of exchange sites (36,12,74,84,73). In general, lighter soils probably favour antibiotic activity (58).

The existence of other naturally-occurring compounds capable of influencing the growth of higher plants at extremely low concentrations is highly probable. Compounds elaborated by soil micro-organisms have been shown to react with the plant's natural hormones to produce synergistic responses. Norstadt and McCalla (65) observed that corn, grown in stubble-mulched soil, exhibited loss of geotropism, shortening of the first internode, and emergence of leaves from the coleoptile while still below the soil surface, symptoms strongly suggestive of a plant hormone imbalance. At present, the identification of growthregulating substances in soil is dependent on their being present in sufficient quantity to be detectable with available technology and stable under extraction conditions.

Incorporated stubble decomposes more rapidly than that on the surface (55).

Rather than producing an even distribution of phytotoxins throughout the soil mass, such incorporation results in the accumulation of toxins in the micro- sites directly associated with fragments of decomposing plant material (69). The extent of root injury and the physiological effects on the plant as a whole are primarily dependent on the frequency of chance encounters of exploring roots with these pockets of toxicity. When abnormally large quantities of plant residue are added to soil, effects can be widespread and severe (71).

(c) Anaerobic decomposition

Many researchers have demonstrated phytotoxin production during decomposition of plant residues in poorly-aerated soil, a condition induced by compaction, waterlogging, high clay content, or any combination of these or other factors. Excessive residue loadings can also lead to soil anaerobiosis if the oxygen demand of micro-organisms exceeds that which can be supplied by diffusion (68).

Under anaerobic conditions the pathways of decomposition of organic compounds, the types of intermediate products formed, and the rate of metabolism of these products differ markedly from those under aerobic conditions (69). Microbial activity and synthesis is depressed where oxygen concentrations are below 3×10^{-6} M, and decomposition of organic residues occurs slowly (28). Many of the specific organic compounds detrimental to plant growth have been identified under such conditions, especially VFA's and other organic acids which, despite slow residue decomposition, can accumulate in appreciable quantities (28,69,53,90). Products of wheat straw degradation in the presence and absence of oxygen are shown in Table 4.

Table 4. Effect of aeration on the degradation of wheat straw[a] and the subsequent action of the products on the root extension of barley seedlings. (After Lynch, 1977).

	Anaerobic	Aerobic
Products of decomposition		
Total soluble carbon products[b] (g)	2.92	0.50
Organic acids (g)	2.01	<0.01
Methane (mg)	0.078	–
Ethanol (mg)	64.5	49.5
Loss in dry weight of straw (g)	8.7	11.9
pH at termination	5.5	8.0
Concentrations of organic acids produced (mM)[c]		
Acetic	15.0 ± 0.9	0
Propionic	3.8 ± 0.1	0
Butyric	1.8 ± 0.1	0
Hydrocinnamic	0.037 ± 0.003	0.043 ± 0.003
Effect of straw solutions on the root extension of barley seedlings (% of control)[c]	75 ± 8	126 ± 5

[a]35 g of straw in 1.5 litres, degraded for 33 days.
[b]Assuming that the mean content of elemental carbon in the products is 40%.
[c]Means and standard errors of 7 determinations made during days 13-32 of incubation of the straw.

Hemicellulose and cellulose, which together account for approximately 76 per cent of the weight of undegraded cereal straw, are the principal substrates for the formation of simple organic acids by facultative and obligate anaerobes (55). The potential for residues to produce VFA's declines during decomposition in parallel with reductions in these two cellulosic components (33). The rate of such decomposition is influenced by soil temperature, with reduced VFA production and lower phytotoxicity at lower temperatures (53,90).

Soil pH, although not directly influencing the production of VFA's, affects their threshold concentration, that is, the minimum concentration at which they become inhibitory to plant growth (53,90).

Lynch (54) demonstrated that the concentration of acetic acid produced by barley, wheat, oat and rape residues under anaerobic conditions increased in the order of listing and correlated with their degree of inhibition of the root extension of barley seedlings. Acetic, propionic, butyric and valeric acids display synergistic effects (91).

Patrick and Koch (70) found that residues of timothy, rye, corn and tobacco decomposing in saturated soil produced substances inhibitory to the respiration of tobacco seedlings. The authors noted that high soil moisture levels did not need to be maintained in order for plytotoxic decomposition products to be formed. Flooding the soil for 3-5 days was sufficient to produce toxicities comparable to those resulting from a 20-day saturation period. Therefore, it seems probable that anaerobic conditions predisposing phytotoxin formation often prevail following heavy rain or irrigation.

Not only can fluctuations between aerobic and anaerobic conditions occur rapidly but point-to-point variations occur in the soil environment. Anaerobic microsites are often widespread in otherwise aerobic soils, favouring the production of localized pockets of toxic decomposition products (69). The prevalence of such microsites provides an explanation for the universal occurrence of obligate anaerobes (28).

Substances that form when residues are decomposing under anaerobic conditions have been shown to predispose plants to root-rot and to increase root-rot severity. Increased pathogenesis seems related to root injury, which has been observed in the laboratory less than one hour after exposure to residue extracts (70), and is also evident in plants growing in close proximity to residues under field conditions (71).

3. Effects of Residue Phytotoxins

(a) Crop plants

The documented effects of stubble phytochemicals on field crops are almost always negative. They include delay or complete inhibition of seed germination, reduced plant populations, stunted and deformed roots and tops, deranged nutrient absorption, lack of seedling vigour, reduced tillering, chlorosis, wilting, and predisposition to root-rots and other diseases (64, 71,30,65,85,35,40,16,53,42). These effects have been observed with residues from a wide range of crops, including cereals, oilseeds and grain legumes (52).

In the Palouse region of the Pacific Northwest, USA, crops are commonly sown directly into stubble residues to improve erosion control and reduce energy requirements. Wheat yield reductions of 25% (16) and as high as 40% (67) have been reported under such systems in comparison to conventional seedbed preparation. The greatest yield reductions occur where residue levels are high, in the order of 9 to 13 tonnes ha^{1} (16).

Yields of winter cereals direct-drilled into straw residues in Britain are often reduced when wet conditions prevail at the time of sowing. Lynch et al. (56) found that under such conditions germination was not affected, but reduced tillering resulted in fewer fertile ears per plant and a lower grain yield of wheat (Table 5).

In environments where stubble residues have produced adverse chemical effects, both inter- and intra-specific variations in phytotoxin production must be an important consideration in the determination of cropping sequences.

Table 5. Effect of method of oat straw disposal on yield of winter wheat on a clay soil. (After Lynch et al., 1981).

Straw treatment	Furrow opener	Soil water content at drilling (0-5 cm) ($g\ 100\ g^{-1}$)	Yield of grain t/ha^{-1} at 85% D.M.
Burnt	Triple disc	33	8.51
	Single disc	33	8.14
Chopped and spread			
(a) left *in situ*	Triple disc	38	3.77
(b) disced	Single disc	39	5.37
(c) rotovated	Single disc	40	4.50
LSD	(P = 0.05)		0.35

Growers in Canada have reported poor cereal yields under a fallow-rape-cereal cropping sequence. Horricks (35) demonstrated that rape (*Brassica campestris*) stubble residues of 7-8 tonnes ha $^{-1}$, of which 50-60 per cent remained at the time of sowing, significantly reduced the dry matter production of wheat, barley and oats.

In south-east Asia, both Chinese cabbage (*Brassica campestris* spp. *pekinensis*) and mungbean (*Vigna radiata* (L.) Wilczek) are widely grown. Kuo et al. (42) demonstrated that substances evolving during the decomposition of Chinese cabbage residues were toxic to mungbeans, significantly inhibiting germination, root length, plant height, leaf area and dry matter production. In one experiment, all mungbean seeds planted in soil obtained from a field of Chinese cabbage failed to germinate. Results suggest that mungbean should not follow Chinese cabbage although such a sequence may be beneficial to other crops.

Kimber (38) noted that while decomposing Gabo wheat straw significantly inhibited the germination of Gabo wheat and inhibited subsequent root growth by more than 60 percent, Kondut straw had no effect on germination and actually stimulated root growth by 40 percent.

(b) Weeds

Natural plant products play important roles in plant resistance to pathogens and, to a lesser extent, insects and nematodes (75). Results from the limited research undertaken to date indicate that selection for capability to inhibit weeds could be worthwhile.

In studies undertaken to evaluate the weed-suppressing potential of natural toxins released from decomposing crop residues, DeFrank and Putnam (19) found that no-tillage plots with sorghum residues as a surface mulch provided better weed control than plots where conventional tillage practices were used in conjunction with a standard herbicide application. The sorghum mulch was effective not only in controlling weeds but also in improving the growth of a crop of snap beans. Sorghum (*Sorghum bicolor* (L.) Moench s. lat.) and sudan grass (S. *sudanense* (Piper) Stapf), planted in late summer and allowed to freeze over winter, reduced weed biomass in the following spring-summer growing period by 90 and 85 percent respectively compared to non-residue controls (75).

In a recent field trial conducted at the University of New England, Lovett, Jessop and Purvis (unpublished data) found that residues of field pea, wheat and oilseed rape displayed significant differences in weed-suppressing ability, reducing weed populations by 71, 53 and 33 percent respectively in a crop of Songlen wheat.

Stubble residues can impede herbicide application but dependence on such application would be reduced if the residues themselves possessed inherent weed-suppressing ability.

4. Ecological Changes

A change as significant as that from conventional tillage/stubble incorporation to minimum tillage/stubble retention will undoubtedly have ecological consequences, particularly for weed flora composition and the incidence of plant diseases. Current methods of dealing with these problems require modification in response to such changes.

(a) Weed populations

Herbicide selectivity may become more apparent with increased dependence on chemical weed control in reduced tillage systems. Continuous use of the same herbicides over several years can result in shifts in weed populations. In particular, a trend away from annual broadleaved species and towards perennials and annual grasses becomes evident (27,92).

Greater reliance on herbicides requires careful evaluation of their use, involving consideration not only of the weed species to be controlled but also of likely interactions between herbicide and surface organic matter. While some pre-emergent chemicals are known to be less effective under stubble-retention systems, the triazine herbicides are not readily absorbed by undecayed plant material (89,23). Further research to provide quantitative data on the amounts of trash which can be tolerated by the major herbicides, particularly the pre-emergent chemicals, would be most useful. As an example, Bateman and Walker (6) have suggested that 21 percent of stubble cover can be tolerated using trifluralin.

(b) Plant diseases

The carry-over of several cereal fungal diseases has been associated with stubble remains. In particular, yellow spot (Pyrenophora tritici-repentis) and Septoria are regarded as serious pathogens in stubble retention systems (78). Their data indicate a strong association of disease severity and the method of stubble management (Table 6).

Table 6. Influences of stubble on yellow spot in wheat. (After Rees and Platz, 1979).

Stubble Treatment	Stubble remaining at crop emergence t/ha	Yellow Spot lesions per leaf at Feekes Scale 2
Retained		
Zero cultivation	1.53	11.75
Mechanical cultivation	0.32	2.43
Burnt		
Zero cultivation	0.13	0.83
Mechanical cultivation	0.09	0.62

In spite of such examples to the contrary, there is other evidence to suggest that the incidence of plant diseases will be reduced in the longer term in line with accumulation of soil organic matter (17). In the short term, standard approaches to disease control such as the use of resistant cultivars and crop rotations will probably assume greater importance in stubble- retention systems. Burning has proved ineffective as a control measure (32), resulting only in large organic matter losses and insufficient removal of pathogenic inoculum.

Conclusions

In Australia the effects of stubble retention on soil properties are likely to be, in general, beneficial. The possibility that short-term increases in bulk density may restrict root growth is a negative feature but cumulative gains in soil quality and crop productivity appear the likely long—term result. Mechanical problems imposed by retained stubble are being countered by the development of a specialized range of cultivation and sowing equipment.

Changes in environmental factors and cultural practices associated with stubble retention and minimum tillage result in shifts in weed populations and alter patterns of disease incidence. Potential problems are accentuated by the current lack of crop or herbicide rotation. More widespread adoption of stubble retention techniques should foster the development of improved management systems in which such rotations will play a significant part.

Effective immediate counter-measures to chemical problems, such as pH change and nitrogen immobilization, already exist. Longer-term solutions are required for phytotoxic aspects, themselves still imperfectly understood. It is clear that, under the influence of the modifying factors discussed in this review, phytotoxins differing in identity and concentration are produced from decomposing stubble residues. Not only are there differences in the phytotoxins produced but there are large variations between species, and between individuals within species, in their responses to these chemicals. It is significant that roots are particularly sensitive to toxic products of stubble decomposition and that root development in field crops is not detectable by casual inspection. Yet impaired efficiency of the root system renders the plant more vulnerable to other stress factors.

Problems of phytotoxicity associated with stubble retention are likely to be encountered more frequently in Australia as diversification of crop species and their management continues. Although residues of wheat have caused toxic effects in no-tillage and conservation tillage systems in the United States, wheat has, in our experience, one of the least toxic residues of the major Australian field crops. In the short term, direct drilling into standing stubble might circumvent phytotoxicity problems encountered with other crop residues while maintaining some of the beneficial effects of retained stubble. In the longer term, it is difficult to escape the conclusion that taking advantage of variation in susceptibility to phytotoxins through selection and plant breeding offers the best solution to these problems.

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