Allelopathy: a possible contributor to yield decline in sugar cane

John V. Lovett[1] and Alan P. Hurney[2]
[1]Department of Agronomy and Soil Science, University of New England, Armidale, NSW 2351, Australia.
[2]Bureau of Sugar Experiment Stations, Tully. Qld 4854, Australia.

Summary

Yield decline in sugarcane bears similarities to the problem of "soil sickness", reported since at least the early nineteenth century, and with the "long fallow disorder" described more recently in Queensland and northern New South Wales. One component of the syndrome may be allelopathy, since phytotoxicity resulting from compounds produced from living plants and from their residues is widely recognized as contributing to previously unexplained phenomena of this type. In this paper analogies between the yield decline syndrome and known examples of allelopathy are identified and the likelihood of allelopathy contributing to the phenomenon is assessed.

Introduction

Allelopathy, biochemical interactions between plants of all levels of complexity, has been identified with secondary metabolites released by plants during life, and from their residues after death. In Australia, allelopathy has been associated with indigenous and introduced plants, marine species such as corals, and microorganisms (Lovett 1989). Typically, in agricultural situations, allelochemicals are washed from foliage or plant residues by rainfall or irrigation, or may be released into the rhizosphere. For the most part their destination is the soil, where they may accumulate to concentrations not found in plant material itself. Ultimately, these biologically active compounds break down, but at varying rates according to ambient conditions.

In part, allelopathy may account for "yield decline" in sugarcane, a term used within the Bureau of Sugar Experiment Stations to describe a situation where soils which have grown sugarcane over several years produce well below their known potential (Croft et al. 1991). Observations of yield decline bear strong similarities to the "soil sickness" described by De Candolle (1832). In essence, soil sickness means that a crop will not continue to produce successfully in the same soil over extended periods. De Candolle made the interesting observation that crop rotation provided at least a partial solution to the problem. Leslie and Whitehouse (1965) reported on "long fallow disorder", a term used to describe poor growth of a range of crop species following fallows in excess of twelve months on cracking clay soils in parts of Queensland and northern New South Wales. Plant nutrition, effects of nematodes (Thompson et al. 1980) and decline in populations of vesicular-arbuscular mycorrhizae (Thompson 1987) may all contribute to long fallow disorder.

Yield decline in sugarcane has been recognized in, for example, Hawaii (King 1959), and Taiwan (Chou 1987) for many years. Like long fallow disorder, its causes are recognized as being complex. In Queensland, evidence from field trials indicates that soil-borne factors are implicated in a syndrome which has been estimated to cost the industry $300–600m per annum. Yield decline has been linked with plant nutrition, fungal pathogens, nematodes and soil physical properties but unknown contributing factors are also acknowledged (Croft et al. 1991)

In the specific context of sugarcane, although Evans (1934) reported on studies of root-exudation, no references to allelopathic activity during life of the crop have been located. However, the adoption of green trash blanketing (see, for example, Wood 1986) in which some 16–24 tonnes ha⁻¹ (fresh weight) of plant residues remain on soil surfaces after harvest, prompts comparison with other systems in which allelopathy resulting from compounds produced from plant residues has proved to be a factor of significance, and raises the possibility that allelopathy also contributes to the yield decline syndrome.

Allelopathy and plant residues

The possibility of phytotoxicity occurring where plant residues are retained on the soil surface or incorporated into soil has been increasingly noted as the practice of conservation farming has become widespread (Lovett and Jessop 1982). The benefits of conservation farming are recognized in many cropping areas of Australia and have been rapidly adopted by farmers in the recent past. These benefits are principally physical in nature. Chemical effects associated with residue retention in conservation farming systems have not been studied as extensively.

Retention of plant residues results in the addition of a wide variety of organic and inorganic compounds to the soil system. These compounds may be leached directly from stubble and straw, liberated during decomposition, or synthesized by microorganisms utilizing the residue as a substrate.

The work of Kimber (1967, 1973a,b) in Western Australia pointed to wheat stubble as a possible source of toxic chemicals which might affect the germination of following crops. An important finding was that length of the rotting period for crop residues was related to possible toxic effects. In general, the longer the crop residues were allowed to decompose, the less was the risk of an accumulation of chemicals to toxic levels in the soil.

Subsequently, much attention has been focused on this topic in North America and Europe and the production of organic acids (especially acetic acid) from wheat residues has been implicated in toxic effects by Lynch (1977) and colleagues in the United Kingdom. They, like other workers, have shown that the production, accumulation, transformation and ultimate destruction of such chemicals is influenced by a large number of factors, including moisture, availability of oxygen, pH and temperature.

The modifying effect of temperature on residue decomposition is exemplified in Table 1, which shows that more than three times as much acetic acid was formed at 20°C as at 8°C.

Table 1. Effect of temperature on concentrations of organic acids produced from decomposing wheat straw (From Lynch 1977).

Concentrations of organic acids produced (mM)		
Temperature	20°C	8°C
Acetic acid	22	7
Propionic acid	2	0.8
Butyric acid	2	0.8

Phenolic acids, well known in the context of release from living plants (see, for example, Einhellig and Rasmussen 1978, 1979) may also be found as residue phytotoxins. P-coumaric, ferulic, caffeic, p-hydroxybenzoic, syringic and vanillic acids have all been identified from this source (Guenzi and McCalla 1962, McCalla and Haskins 1964, Hoagland and Williams 1985). Members of this group of allelochemicals have been identified when residues of wheat, corn, sorghum and oats have been left to decompose on the soil surface.

Phytotoxicity is also associated with the residues of crops other than cereals. For example, in a field experiment, emergence and 1000–grain weight of wheat were reduced by residues of sorghum, rapeseed, lupin, pea and wheat itself when applied at a rate equivalent to 3 t h⁻¹, Table 2.

Table 2. Effects of crop residues on emergence and 1000–grain weight of wheat grown in the field. (From Lovett and Jessop 1982).

Species	Emergence (plants per 1 m length of row)	1000–grain weight (g)
Control	28.0 a	30.3 a
Sorghum	9.3 b	26.8 b
Rapeseed	17.7 ab	28.7 ab
Lupin	19.7 ab	29.1 ab
Pea	6.3 b	25.7 c
Wheat	11.3 b	28.9 ab

(Means identified by the same letter are not significantly different at the 5% level, Studentized Range Test).

These findings were of particular significance because they showed that not only could emergence of the wheat crop be affected by toxins produced from crop residues but that some effect persisted through to final harvest, as shown by effects on the 1000–grain weight. The most toxic residue in this experiment was that of field pea, indicating that legumes may not always be beneficial components of farming systems.

Pea residues, at least, decompose rapidly. Durable residues, more comparable to those of sugarcane, include those of sunflower, sorghum and rapeseed. In work of Mason-Sedun et al. (1986), when compared to water controls, water extracts of residues from thirteen different Brassicas, representing six species, all inhibited root and shoot growth of wheat, although germination was not affected, Table 3.

Table 3. Effect of aqueous extracts from Brassica residues on seeds of Triticum aestivum L. cv. Songlen. (From Mason-Sedun et al. 1986).

Brassica cultivars	Extract pH	Extract conductivity (mmhos cm⁻¹)	Germination percentage %	Radicle length % Inhibition	Coleoptile length % Inhibition
Distilled water	7.25	0.10	87.5 a*	0.0 a	0.0 a
B. campestris cv. Torch	6.02	3.79	87.5 a	59.1 b	56.7 b
B. juncea cv. Zem 1	6.62	3.73	89.6 a	71.4 c	74.9 c
B. hirta cv. Winchelsea Vic	6.33	3.50	87.5 a	81.8 d	79.1 d
B. napus cv. Wesroona	5.91	3.26	91.3 a	84.4 d	80.0 d
B. hirta cv. Yellow Mustard	6.36	3.41	89.4 a	81.3 d	83.3 def
B. napus cv. Bronowski	6.23	3.07	87.5 a	95.8 ef	81.3 def
B. napus cv. Wesway	6.41	3.12	89.4 a	91.1 e	85.9 defg
B. napus cv. Westar	6.29	3.15	89.4 a	92.5 ef	88.1 efg
B. juncea cv. Lethbridge 22A	6.58	3.82	91.3 a	94.5 ef	84.5 defg
B. juncea cv. Zem 2	6.53	3.81	91.3 a	94.9 ef	81.7 def
B. nigra cv. 81802	6.15	3.24	91.9 a	95.2 ef	83.8 def
B. nigra cv. Vince	6.07	3.25	89.4 a	97.5 f	89.0 fg
B. kaber cv. Jabra	6.32	3.53	86.9 a	97.8 f	91.4 g

*Germination percentage, radicle and coleoptile lengths having the same letter are not significantly different at the 5% level, Studentized Range Test.

Table 4. Influence of the metabolites of Fusarium oxysporum and Trichoderma harzianum on the germination and growth of sugarcane. (Modified from Kao 1989).

Treatment[a]	Time of incubation (wk)	Germination[b] (%)	Length of bud (cm)	Growth rate (cm/day)
F. oxysporum	3	100	6.8b	1.3a
T. harzianum	3	100	4.4a	0.8a
Hs medium (control)	–	100	9.0c	1.6b
Sterile H₂0 (Control)	–	100	9.4c	1.6b

[a] Inoculation with the spore suspension (1×10⁴ spores ml⁻¹ medium) of F. oxysporum or T. harzianum into Hs medium (Hoagland nutrient solution + 1.5% sucrose) and shaking at 25 ± 2°C.

[b] Germination and growth of sugarcane measured at the 12th day after sowing. Numbers followed by the same letter in each column are not significantly different (p = 0.01) according to Duncan's Multiple Range Test.

Residues of six representatives of four Brassica species were subsequently deployed at a rate of 5.5 t ha⁻¹ in field trials where grain yield, plant dry weight, plant height and tiller production of wheat were all reduced. The greatest reduction in yield, from the equivalent of 2.92 t ha⁻¹ to 1.30 t ha⁻¹ (a loss of 55%) occurred with residues of B. juncea cv. Zem 2.

Typical effects of chemicals produced from decaying plant residues are poor emergence, reduced plant populations, stunted roots, reduced tiller number (of cereals), reduced dry weight and grain yield. Many of these features are similar to those induced by allelochemicals produced during active plant growth.

It is important to emphasize that the many benefits of retaining crop residues are not negated by the possibility of damage from chemicals produced from plant residues. Management options must, however, be considered. On the basis of available data, residues decomposing on or near the soil surface seem less likely to lead to chemical toxicity problems than residues which are fully incorporated into soil, especially where the soil is cold and wet, leading to a possible build-up of chemicals such as organic acids. The data also suggest that the possibility of toxic effects occurring should be taken into account when planning a sequence of crops in a rotation. This may benefit crops directly, by reduced risk of toxicity, and indirectly through suppression of weeds by the compounds produced (Worsham 1989).

Allelopathy and sugarcane residues

Chou (1987), working in Taiwan, reported that yield reduction in ratoon crops of sugarcane may be attributed to autointoxication as noted with, for example, wheat (see Table 2). Five phenolic acids, p-hydroxybenzoic, ferulic, p-coumaric, syringic and vanillic, together with several aliphatic acids, including acetic acid, were identified from decomposing sugarcane leaves in waterlogged soil. In preliminary work we have confirmed the presence of ferulic, vanillic and p-hydroxybenzoic acids in extracts of sugarcane residues from Tully, North Queensland, together with gallic, chlorogenic and protocatechuic acids. As noted, above, these compounds have been identified with allelopathic activity resulting from the presence of residues of a number of other crops.

In later work, Kao (1989) noted that yield decline of monoculture sugarcane in Taiwan could be related to a number of causes, including injury by soil insects, soil-borne pathogens and soil compaction by heavy harvest machinery. He observed, however, that recent workers have considered that imbalance of soil microorganisms and the accumulation of

phytotoxins in soil contribute to growth inhibition of monoculture sugarcane. Both of these latter effects, by definition, may be classified as allelopathic.

Kao (1989) concluded that, in his experiments, retardation of the growth of sugarcane was not attributable to phytotoxins produced from cane residues themselves, but from inhibitory metabolites of the fungi *Fusarium oxysporum* and *Trichoderma harzianum* which flourished in residue-treated soil, Table 4. While germination of sugarcane buds was not affected, length of buds and growth rate were reduced by fungal metabolites, which inhibited respiration and metabolic processes of sugarcane cells, resulting in retarded cell division and reproduction.

Conclusion

The work referred to in this paper illustrates the interactions between residues, the environment and microorganisms, which make the study of allelopathy so complex. It emphasizes that allelopathy is one of many stress factors which operate in the crop environment. Allelopathic effects, as shown in Tables 1 and 4, frequently do not affect germination *per se* but may disable the affected plant to some degree, impairing its ability to deal with other stresses. At times, allelopathy may be dominant, at others of minor significance. However, the Taiwanese work, in particular, suggests that allelopathy is a factor which should not be ignored in attempts to elucidate the phenomenon of yield decline in Australian sugarcane.

References

Chou, C.H. (1987). Allelopathy in subtropical vegetation and soils in Taiwan. *In* 'Allelochemicals: Role in Agriculture and Forestry', ed G.R. Waller, pp. 102-17. (American Chemical Society Symposium Series No. 330, ACS, Washington DC.)

Croft, B.J., Magarey, R.C., Hurney, A.P. and Reghenzani, J. (1991). Soil constraints to productivity improvement. Bureau of Sugar Experiment Stations Report, 23 pp.

De Candolle, M.A.-P. (1832). Physiologie vegetale. III. Bechet Jeune, pp. 1474-5. Library of the Faculty of Medicine: Paris.

Einhellig, F.A. and Rasmussen, J.A. (1978). Synergistic inhibitory effects of vanillic and p-hydroxybenzoic acids on radish and grain sorghum. *Journal of Chemical Ecology* 4, 425-36.

Einhellig, F.A. and Rasmussen, J.A. (1979). Effects of three phenolic acids on chlorophyll content and growth of soybean and grain sorghum seedlings. *Journal of Chemical Ecology* 5, 815-24.

Evans, H. (1934). Studies on root-exudation and root-types in sugarcane. Department of Agriculture, Mauritius Sugar Research Station Bulletin No. 5, 3-13.

Guenzi, W.D. and McCalla, T.M. (1962). Inhibition of germination and seedling development by crop residues. Soil Science Society of America Proceedings 26, 456-8.

Hoagland, R.E. and Williams, R.D. (1985). The influence of secondary plant compounds on the associations of soil microorganisms and plant roots. *In* 'The Chemistry of Allelopathy', ed A.C. Thompson, pp. 301-25. (American Chemical Society Symposium Series No. 268, ACS, Washington DC.)

Kao, Ming-Muh. (1989). Fungal metabolites as growth inhibitors of sugarcane and the mechanism of phytotoxicity. *In* 'Phytochemical ecology: Allelochemicals, mycotoxins and insect pheromones and allomones', eds G.R. Waller, and C.H. Chou, pp. 329-41. (Academic Sinica Monograph Series No. 9, Taipei.)

Kimber, R.W.L. (1967). Phytotoxicity from plant residues. I. The influence of rotted wheat straw on seedling growth. *Australian Journal of Agricultural Research* 18, 361-74.

Kimber, R.W.L. (1973a). Phytotoxicity from plant residues. II. The effect of time of rotting of straw from some grasses and legumes on the growth of wheat seedlings. *Plant and Soil* 38, 347-61.

Kimber, R.W.L. (1973b). Phytotoxicity from plant residues. III. The relative effect of toxins and nitrogen immobilization on the germination and growth of wheat. *Plant and Soil* 38, 543-55.

King, N.J. (1959). The varietal yield decline problem. Proceedings of the International Society of Sugar Cane Technology, Xth. Congress, Hawaii, pp. 62-5.

Leslie, J.K. and Whitehouse, M.J. (1965). Investigations on the long fallow disorder. Queensland Wheat Research Institute Annual Report 1964–1965, pp. 9-10.

Lovett, J.V. and Jessop, R.S. (1982). Effects of residues of crop plants on germination and early growth of wheat. *Australian Journal of Agricultural Research* 33, 909-16.

Lovett, J.V. (1989). Allelopathy research in Australia: an update. *In* 'Phytochemical ecology: Allelochemicals, mycotoxins and insect pheromones and allomones', eds C.H. Chou, and G.R. Waller, pp. 275-91. (Institute of Botany, Academia Sinica Monograph Series No. 9, Taipei.)

Lynch, J.M. (1977). Phytotoxicity of acetic acid produced in the anaerobic decomposition of wheat straw. *Journal of Applied Bacteriology* 42, 81-7.

Mason-Sedun, W., Jessop, R.S. and Lovett, J.V. (1986). Differential toxicity among species and cultivars of the genus *Brassica* to wheat. *Plant and Soil* 93, 3-16.

McCalla, T.M. and Haskins, F.A. (1964). Phytotoxic substances from soil microorganisms and crop residues. *Bacterial Reviews* 28, 181-207.

Thompson, J.P. (1987). Decline of vesicular-arbuscular mycorrhizae in long fallow disorder of field crops and its expression in phosphorus deficiency of sunflower. *Australian Journal of Agricultural Research* 38, 847-67.

Thompson, J.P., Mackenzie, J. and McCulloch, J.S. (1980). Nematodes – a major factor in crop sequence effects on Darling Downs wheat. Proceedings of the Australian Agronomy Conference, Lawes, 194.

Wood, A.W. (1986). Green trash management in the Herbert Valley. Preliminary results and research priorities. Proceedings of the Australian Society of Sugar Cane Technologists 8, 85-94.

Worsham, A.D. (1989). Current and potential techniques using allelopathy as an aid in weed management. *In* 'Phytochemical ecology: Allelochemicals, mycotoxins and insect pheromones and allomones', eds C.H. Chou, and G.R. Waller, pp. 275-91. (Institute of Botany, Academia Sinica Monograph Series No. 9, Taipei.)