Soil biology and crop production in Western Australian farming systems

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Introduction

Agricultural management practices ultimately seek to optimise plant and animal productivity within the overriding constraints of both climate and the capacity of the soil (physical, chemical and biological attributes) to support plant growth (Abbott, Murphy 2003). While optimal physical and chemical conditions of the soil for plant growth are often well defined, we have a much poorer understanding of the control that biological factors, particularly non-pathogenic associations, have on plant growth. The objective of this paper is to examine the relative contribution of soil biological attributes to crop production in Western Australian farming systems. Once these key attributes have been identified, management practices can be selected that take into account the potential for enhanced soil biological fertility and improved yield.

Western Australian farming system

The grain production zone (wheat belt) in Western Australia covers an area of more than seven million ha. Grain production is primarily restricted to areas where average annual rainfall is between 325 and 750 mm, the majority of which falls during the growing season (late autumn-late spring) in the south-west of Australia. Major soils in this region (Chromosols, Sodosols, Kandosols) are highly weathered with low surface clay and soil organic matter contents. The summer weather pattern is typified by hot dry conditions with infrequent storm events, largely restricting production to an annual winter cropping phase. Low winter rainfall and dry summers therefore constitute the primary constraint to organic matter production and accumulation. A lack of new plant residues and root exudates to provide a carbon food source in the soil, and problems associated with desiccation over summer as surface soil temperature peaks above 40°C, present significant challenges to the buildup of biological components in soil compared with temperate environments. However, this does not mean that soil biology is not important. Indeed, the Western Australian farming system is reliant on a cyclic pattern of biological activity which 'explodes into action' with rainfall and then slows at the onset of soil drying.

The relatively low growing-season rainfall and the inherently low capacity of major soil types in WA to retain water and plant nutrients are realised in poorer crop growth. Low potential yields have thus resulted in relatively low input systems, and these systems are therefore more reliant on biologically fixed nitrogen and organic matter decomposition to supply plant available nutrients and support crop production. In southern Australia for example, Angus (2001) calculated that, on average, 80% of crop uptake was supplied via biological processes, so the amount of nitrogen cycling through a WA soil during the growing season can be more than enough to satisfy crop nitrogen demand (43-122 kg/N ha, Murphy et al 1998), even where no fertiliser is applied. The exceptions to this are soils with a high leaching potential, which can result in the loss of both water and mobile nutrients below the rooting zone, and soils where microbial immobilisation of nitrogen out-competes plants for nitrogen availability (eg decomposing plant residues with high carbon:nitrogen ratio). Strategically timed or split

fertiliser applications (generally 20-80 kg N/ha) are therefore used to overcome the difficulties of matching biological nutrient supply with plant demand. Developing management strategies to improve asynchrony (microbial nutrient supply occurring when plant demand is low) and synlocation (plant-available nutrients being located in the soil matrix where there are no plant roots) is often difficult but essential for future sustainable production (Murphy et al 2004, Ridley et al 2004, Hoyle, Murphy this proceedings).

Identifying soil constraints to crop production

From 1960 to 1990, the average wheat grain yield in 62 WA shires was 1.9 t/ha, with less than 5% of shires assessed in 1990 having reached 50% of their rainfall-limited yield potential (Hoyle, Anderson 1993). In our current research we have used the WA-Wheat model (Department of Agriculture), which has been developed as a front-end system for the APSIM model, to target districts that consistently under-perform. To do this, WA-Wheat was used to initialise (seeding date, varietal maturity, fertiliser application, actual rainfall, soil type) model simulations (1960-2001) on a shire basis for comparison against actual historical yields. Where potential yield is not achieved our approach has been to assume that this is the result of inappropriate management practices and/or soil physical, chemical or biological constraints to crop production (Figure 1).

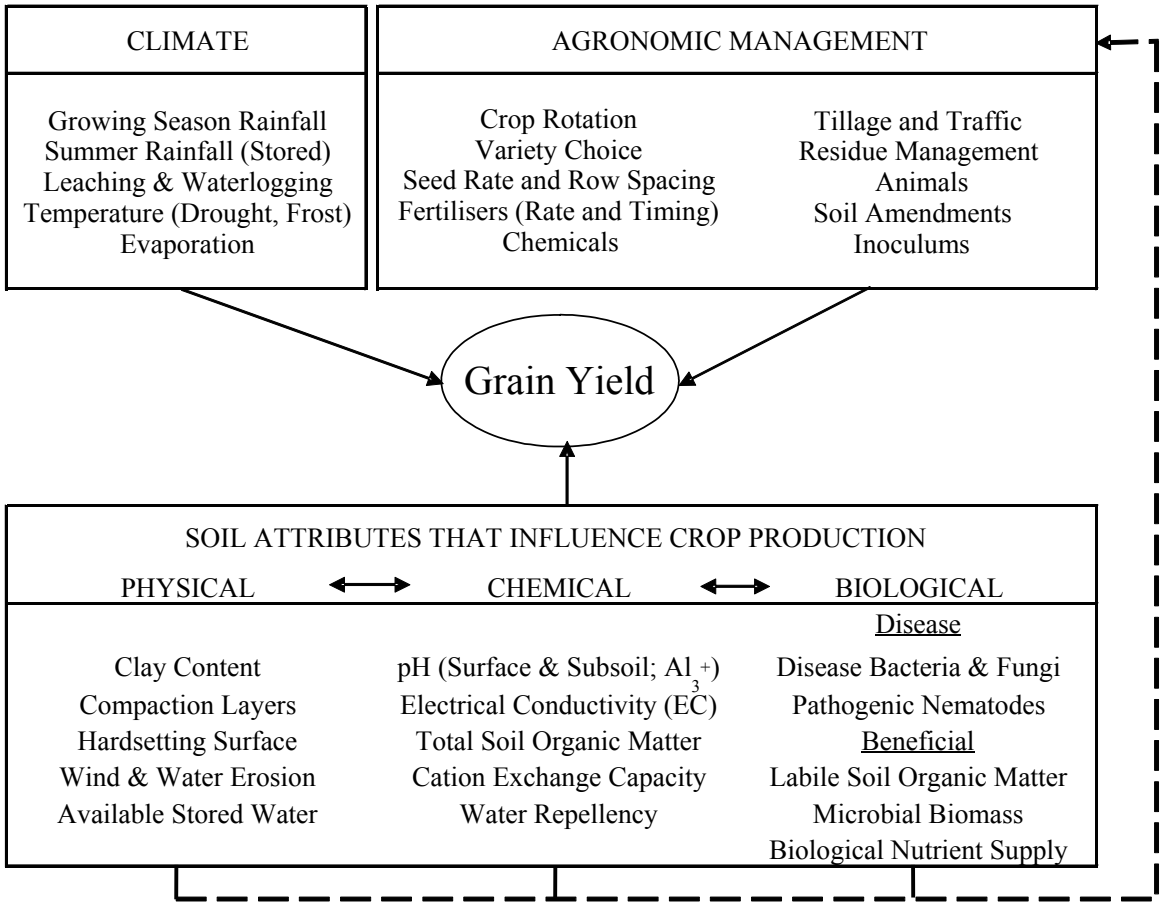

Figure 1. A conceptual model of climatic and agronomic factors along with key soil physical, chemical and biological constraints to yield production in Western Australian farming systems.

Once soil constraints are identified their economic importance can be assessed, so that the cost and practicality of removing the constraint versus potential yield benefit is known before implementing changes in agronomic practice. This approach focuses on discrete soil attributes that have a known direct impact on crop production, and can be measured and interpreted in the context of management solutions. This approach provides an economic evaluation of 'cause' and 'effect', enabling prioritisation of high return solutions to overcome major agronomic and soil limitations instead of placing effort in further detailed site characterisation which is not feasible over a large scale.

Identifying soil constraints to crop production: a case study

Evaluation of the 'soil indicator' package described in Figure 1 was achieved by collecting climatic, agronomic and soil data from 40 paddocks on 20 farms in two adjoining catchment groups (named 'A' and 'B' for simplicity). Paddocks were located within a 10 x 20 km region and were chosen in consultation with growers to either compare high and low yielding areas, or encompass soils that consistently under/over performed against expected yields. Within each paddock three field replicates were established, and within each replicate area soil was collected in 0-5, 5-10, 10-30, 30-60 and 60-90 cm layers for laboratory analysis (in triplicate). Rainfall was recorded at each farm and agronomic data supplied through a one-on-one interview and questionnaire process with the principal grower in each farming unit. Grain yield cuts were taken by hand within a few days prior to machine harvest.

Using figures from the shire that includes A and B catchments, we compared the WA-Wheat model's predicted achievable grain yield against historical records (1960-2001) of actual average grain yield (Figure 2). In approximately 50% of years, we observed good agreement between actual and predicted yield, but in 20 of the 43 years there was a difference of greater than 0.8 t/ha in predicted yield compared with actual yield. Given the low average historical grain yield for wheat in this region (1.58 t/ha), this would represent a significant yield benefit if obtainable. Actual yield data from the 40 paddocks illustrate that on a site by site basis actual yield can vary considerably (mean = 2.5 t/ha, min = 0.44 t/ha, max = 4.74 t/ha) within a season (Figure 2) and can reach the same upper range as predicted by the model .

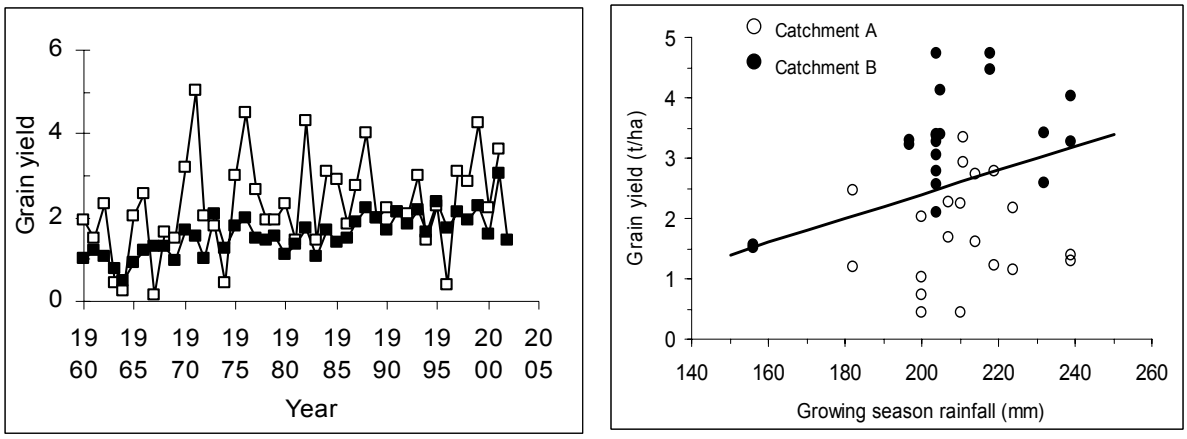

Figure 2. Left: Actual (filled squares) and modelled (open squares) grain yield (t/ha) for the shire that contains catchments A and B. Right: Measured grain yield from the 40 paddocks plotted against growing season rainfall for each site. The solid line represents an achievable grain yield. Paddocks below this line are underperforming and those above the line are above reasonable expectation.

The independent influence of rainfall, inorganic nitrogen fertiliser and soil constraints (as listed in Figure 1) on grain yield was determined using bivariate regression analysis (Table 1). In this regression analysis data for diseases (take-all, rhizoctonia) and pathogenic nematodes (*Pratylenchus neglectus*, *P. thornei*) were excluded as their occurrence was below detection limits or low in 38/40 paddocks. Biological nutrient supply was assessed solely as potentially mineralisable nitrogen in the regression analysis. Mycorrhizal bioassays were performed to determine their importance to plant nutrient supply. More than 30% of root length colonisation is required to obtain benefits of plant nutrient acquisition from mycorrhizal associations (Abbott, unpublished critical value). However, mycorrhizal root length colonisation in the plant bioassays performed was between 0-30% as the paddocks were sufficient in bicarbonate-extractable phosphorus.

Table 1. Mean values for attributes determined in catchments A and B and results of bivariate regression analysis whereby climatic, agronomic and soil physical, chemical and biological attributes were assessed for their individual influence on wheat grain production across the 40 paddocks. Average grain yield was 1.76 and 3.24 t ha/ in catchments A and B respectively. All significant attributes have been presented; most non-significant attributes assessed have been removed. (The same letter denotes no significant difference between catchments for that attribute.)

	Attribute	Catchment		Coefficient[a]	P-value[b]	Variability
		A	B			Explained[c]
Climate	Rainfall (mm)	211a	206a	-	ns	3.7
Agronomy	N fertiliser (kg N/ha)	20a	24a	0.02	0.055*	9.4
Physical	Clay content[d] (%)	11.0a	10.4a	0.08	0.062*	9.1
Chemical	Total carbon (t C/ha)	9.0a	10.8b	-	ns	0.2
	pH ($CaCl_2$)	5.7a	5.6a	-	ns	0.4
	EC[d] (mS/m)	80a	63b	-	ns	0.1
Biological	Labile C (kg C/ha)	83a	118b	0.01	0.041**	10.5
	Microbial biomass C (kg C/ha)	107a	183b	0.01	0.001***	30.3
	PMN (kg N/ha)	7.0a	10.1b	0.14	0.003***	21.2

[a]The coefficient can be interpreted as t/ha grain yield change per unit change in attribute.
[b*] = significant P<0.10; ** = significant P<0.05; *** = significant P<0.01; ns = not significant.
[c]The variability explained has a maximum of 100% and is not additive between individual attributes.
[d]clay and EC data were assessed using robust regression analysis due to unusual data points. EC = Electrical conductivity. .

Measured yields from catchment B were significantly higher than in catchment A, which is reflected in some, but not all of the soil attributes used in the regression analysis (Table 1). It is notable that the biological attributes explained the greatest amount of variability in yield between the 40 paddocks. For example nitrogen fertiliser and clay content each explained 9% of the variability. Potentially mineralisable nitrogen, an index of biological nitrogen supply, explained 21%. Microbial biomass explained 30% (Table 1). Growing season rainfall was not significantly related to grain yield, although we have already argued that rainfall is the primary driver of production in this environment. However, this was not surprising as we would only expect a strong relationship between growing season rainfall and yield if there were no other constraints to crop production. Over a 10 mm growing season rainfall gradient (200 to 210 mm), there was a grain yield variation from 0.5 to nearly 5.0 t/ha (Figure 2). Thus there was

certainly either poor agronomic management and/or the influence of soil constraints on crop production.

Combinations of significant factors that influenced grain yield were then determined using ordinary least square multiple regression analysis. Using a multiple regression model that included all nine parameters listed in Table 2 we were able to explain 42% of the yield variability (regression model not shown).

Several soil attributes were identified that did not have a significant direct influence on grain yield; but may have had an indirect influence through their effect on the size of the microbial biomass (Figure 3). In this case, 66% of the variability in microbial biomass could be explained by clay content (log transformed data), pH and labile carbon. In other words, providing an optimal physical and chemical soil matrix along with an available carbon (food) source was the primary basis for improving the mass of soil microorganisms in these soils. This is logical given microorganisms, like all other living organisms, function more effectively within an optimal environment and provided with a suitable food source. Removing attributes that were either directly related to microbial biomass, or those that were not significantly affecting grain yield from the initial model, resulted in the development of a simpler model to explain the variability in grain yield (Figure 3). This model, which consisted of growing season rainfall, nitrogen fertiliser and microbial biomass as the only three attributes used, still explained 40% of the variability in grain yield. This means that by removing six attributes from the initial model we only lost 2% of explained variability; but removed a considerable amount of the analytical measurements that would be required.

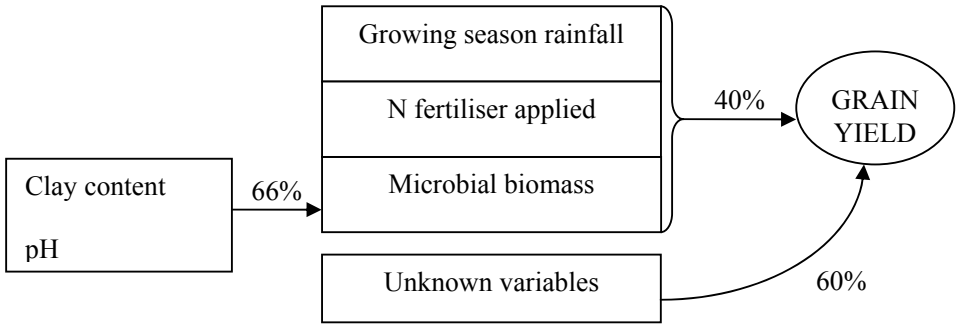

Figure 3. A schematic representation of the multiple regression analysis models used to describe microbial biomass (explanatory variables: nlogClay content*pH*Labile Carbon) and grain yield (explanatory variables: Growing season rainfall*N fertiliser applied*Microbial Biomass).

Further analysis indicated that the influence of the microbial biomass on yield was predominately due to the strong relationship ($r^2 = 0.77$) to potentially mineralisable nitrogen. Thus the model used to describe grain yield could alternatively be expressed as growing season rainfall, nitrogen fertiliser and potentially mineralisable nitrogen with a similar percentage of the grain yield still being explained (data not shown). This provides a simple water and nitrogen availability story as the key drivers of grain production in this environment, which is supported by the fact that water is essential for plant growth and that nitrogen is the primary nutrient limiting crop production throughout the world.

Rapid prediction of potentially mineralisable nitrogen using mid infrared technology

Our current research has demonstrated that potentially mineralisable nitrogen (PMN) can be successfully predicted using mid infrared technology (Murphy et al 2004, Murphy, Milton this proceedings). The major advantage of mid infrared prediction over conventional laboratory analysis of PMN is that it enables rapid (two minute) and cost efficient analysis of a soil biological attribute that has a direct impact on yield production. For example, a one unit increase in PMN caused a 0.14 t/ha yield increase, Table 1. The accuracy of mid infrared to predict the within-paddock variability in PMN is illustrated in Figure 4.

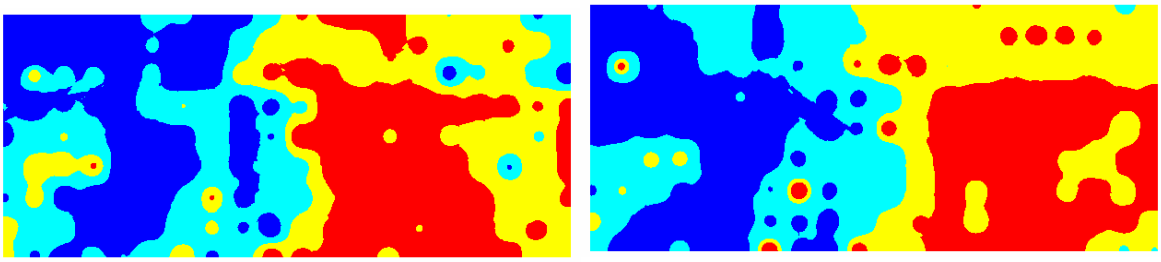

Figure 4. Spatial maps (10 ha) of potentially mineralisable ntirogen determined analytically using traditional biochemical analysis (left) and predicted using mid infrared technology (right) for the 0-10 cm layer of a Western Australian agricultural soil. Data categorised into four categories (Murphy et al 2004).

Soil was collected using a 25m x 25m sampling grid (180 sampling points over 10 ha) from one of the 40 paddocks. Over this 10 ha area PMN ranged from 4-32 kg N/ha. PMN was determined using conventional biochemical laboratory analysis and also predicted (on the same soil samples) using a mid infrared calibration curve that was developed from an independent data set. There was good agreement between mid infrared predicted and measured PMN ($r^2 = 0.70$) which is illustrated by the degree of similarity in the measured and mid infrared predicted spatial maps (Figure 4). While mid infrared is not 100% accurate at predicting PMN, it is of sufficient accuracy for categorising soils or zones within a paddock into poor, low, moderate and high biological soil nitrogen supply, which could be used to adjust for inorganic nitrogen fertiliser application rates.

Management options to enhance soil biological fertility

Despite the identification of known soil constraints to grain yield, 60% of the variability in wheat grain yield is still not explained within these catchments. This highlights the complexity of soil-plant-microbe interactions and the difficulty in identifying drivers of grain yield within different environments. However, the fact that biological attributes had a greater quantifiable influence than chemical or physical attributes on yield variability in this case study provides justification to the development of agricultural farming systems that encourage soil biological fertility (Abbott, Murphy 2003). However, there are few, if any, quick fix solutions to improving soil biological fertility. Research trial data from WA (Table 2) demonstrates that it can take many years for differences in attributes of soil biological fertility to occur upon implementation of management practices. Soil biological attributes are generally highly variable spatially over small distances (see Case study 4, Table 2), with changes in the chemical and physical attributes of the soil often having a greater influence than imposed agronomic management practices on soil biological fertility. Therefore, it is difficult to measure

significant differences between treatments even when changes seem quite large (eg Case study 3 microbial biomass, Table 2).

Table 2. Impact of agronomic management practices on microbial biomass, biological soil nitrogen supply (PMN) and diversity (catabolic diversity, range possible 0-24 with higher number indicating more diverse population) of microorganisms in four trials from WA that represent the major soil groups (Chromosols, Sodosols, Kandosols). Values with the same letter are not significantly different (P<0.10) within the same trial for the biological attribute specified.

Case study #	Agronomic management	Microbial biomass	PMN	Catabolic diversity
		kg C/ha	kg N/ha	min = 1 max = 24
1	Harvest stubble burnt	98a	No data	14.5a
	Harvest stubble retained	153b	No data	15.5b
2	Continuous wheat rotation	308a	30a	15.8a
	Faba beans:Wheat:Canola:Wheat	317a	30a	16.4a
	Medic (grazed) : Wheat	421b	25a	18.0b
	Annual pasture - Ryegrass (grazed)	417b	45ab	16.5a
	Perennial pasture - Lucerne (grazed)	421b	67b	16.5a
3	Lupin - brown manure	140a	13a	15.9a
	Oat - brown manure	76a	14a	17.6b
	Mustard - brown manure	119a	15a	19.4c
4	Variability within 10 ha; n = 220 pts	22 to 1000	4 to 32	No data

1: Data collected after 17 years of imposed treatments, 0-5 cm, Chromosol, Merredin WA.
2. Data collect after 4 years of imposed treatments, 0-5 cm, Sodosol, Mindarabin WA.
3. Data collected after 2 months of imposed treatments, 0-10 cm, Kandosol, Meckering WA.
4. Minimum and maximum data from 220 composite bags of soil collected under a barley crop on a 25 m grid over 10 ha; 0-10 cm; Dangin WA.

Seasonal variability in the data collected is also a major issue in deciding when to sample soil for biological attributes. This is illustrated in Table 3 where it can be seen that the seasonal (sowing, tillering, flowering, harvest) differences in measured soil biological attributes are considerable.

Table 3. Impact of season on the microbial biomass, potentially mineralisable nitrogen (PMN) and the actual daily rate of inorganic nitrogen release through microbial decomposition of soil organic matter and residues (gross nitrogen mineralisation). Six conventional farms were paired with two farms of each of the other farming systems listed. S = sowing, T = tillering, F = flowering, H = harvest.

Farming system	Microbial biomass-N (kg N/ha)					PMN (kg N/ha)					Gross mineralisation (kg N/ha/day)			
	S	T	F	H		S	T	F	H		S	T	F	H
Conventional	52	42	20	12		42	34	40	36		7.1	6.6	1.2	1.0
Integrated	60	32	17	11		58	44	54	47		5.8	6.1	1.2	0.8
Organic	72	46	19	10		54	44	53	48		3.6	6.4	1.6	1.0
Bio-dynamic	72	37	26	11		54	46	58	54		5.3	5.5	1.3	1.1

However, it should be noted that PMN was more stable through the season than measurement of microbial biomass or microbial activity (gross nitrogen mineralisation), suggesting that it is an easier soil biological attribute to interpret between and within seasons. Data in Table 3 also illustrates that seasonal changes in the measured biological attributes are greater than measured differences between farming system type. Thus the capacity to alter soil biological fertility within a region is primarily constrained by water and temperature with agronomic practice as a secondary factor.

Conclusion

Soil biological fertility was significantly correlated to grain production in WA. The benefit was predominately associated with the size of the microbial biomass, which was directly related to their capacity to decompose soil organic matter and fresh residues to release plant available nitrogen. These findings confirm our view that WA farming systems are highly reliant on biological nitrogen supply and that farming systems need to be modified where possible to fully benefit from water availability and microbial nutrient supply. However to achieve this, limitations associated with both the asynchrony and synlocation of water and nutrients need to be further addressed. This will require improved soil management to identify and remove soil constraints to plant growth and rooting depth, new plant breeding to improve plant root architecture in order to capture water and nutrients, a flexible fertiliser strategy (type, split applications, delivery), developing an economic role for deep rooted plants and improved plant residue management (carbon:nitrogen ratio of decomposing material, level and timing of incorporation) and identifying novel methods for manipulating microbial processes.

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