Managing soil water and nitrogen to minimise land degradation

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Abstract

Inadequate use of water and nitrogen by agricultural plants has caused significant land degradation through soil acidification and salinisation. Whilst agronomic solutions exist to counter the incomplete use of water, the lack of control of nitrogen supply in legume systems is hard to handle. In the cropping zone, phase farming based on lucerne offers substantial potential to restore the hydrologic balance. Alley farming offers less potential because of the limited ability of trees to capture water from beyond the root zone; applications are discussed. Perennial pasture species alone will not be sufficient to counter the hydrologic imbalance in southern Australia where rainfall exceeds 600 mm/year: there, increased tree cover is needed, and agroforestry offers considerable potential. Acid soils and the importance of catchments as suppliers of water downstream must be taken into consideration. There are large economic and social implications of the landscape changes that are needed for the adoption of perennial based farming systems.

Key Words

water, nitrogen, salinisation, acidification, perennials, phalaris, lucerne, trees, agroforestry

Introduction

Two of the main forms of degradation of Australian agricultural land are dryland salinity and soil acidity. Both arise largely from the mismatch in timing between the supply of water and nitrate to, and the demand by, crops and pastures. In southern Australia, winter rain substantially exceeds evaporation during the growing season of annual crops or pastures thereby resulting in considerable flows of water beyond the reach of the annuals' roots. The recharge under annual agricultural species typically ranges from 10 to 100 times that occurring under the original native vegetation, from an average of 20-40 mm in semiarid or dry subhumid areas (with annual rainfall less than 600 mm) to 200 mm or more in high rainfall areas (800-900 mm). The native vegetation of temperate and mediterranean southern Australia commonly comprised open woodland and/or shrublands where annual rainfall is 400-600 mm (<10-30% crown cover of tallest shrub or tree species), and woodland to open forest (30-70% tree crown cover) in rainfall zones of 600-800 mm/year (2). This native vegetation had deep roots and was able to use, during the summer, the water that had penetrated deeply into the soil during the winter - that is, wellbelow the root zone of most annual agricultural plants which commonly have a rooting depth of 1 m or less (11,19,29,31).

Whitfield (33) and Bond et al.(11) have analysed the temporal mismatch between rainfall supply and plant demand, and have highlighted how its size, which increases with the amount and preponderance of winter rainfall, circumscribes possible strategies for managing its hydrologic consequences. This paper broadens their analysis to include design principles for agriculture based on perennial species, outlines problems associated with supply and demand of nitrogen in legume based systems and discusses agronomic solutions in light of economic and social considerations.

Table 1 shows selected data for rainfall and potential plant water use for eight locations and two rainfall zones (above and below 600 mm/yr, which roughly delineates the boundary between cropping and permanent pasture zones). To allow easy comparison between locations we have presented (a) annual rainfall, (b) the amount of rain which falls during May-August , the period when soil water is commonly repleted (33), and (c) the average excess of rainfall over evaporation from soil and plants during this period. A further complication in predicting the ability of an agricultural system to use rainfall effectively is the large variability in rainfall between years. As a result, drainage losses can be highly episodic and agronomic solutions that reduce drainage will not always be possible (1, 25).

The temporal mismatch in water supply and use is paralleled by, and in part causes, a temporal mismatch in the supply and use of nitrogen. Leguminous pastures create labile fractions of soil organic matter that mineralise and nitrify at the start of the growing season at rates that may substantially exceed the requirements of the establishing crops and pastures. A mole of hydrogen ions results for every mole of nitrate formed. Nitrate with accompanying cations leaches readily, with hydrogen ions being left behind where nitrification occurred. This process is the single largest contributor to soil acidification (22, 27).

Soil acidity can severely limit agricultural production and plant water use. Where rainfall is less than 600 mm in south eastern Australia, soil acidity is either not a problem, or is confined to the top 10-20 cm, and can be economically corrected by liming. At approximately 600 mm/yr rainfall soils in this region commonly have a strongly acid A horizon (20-40 cm deep), with the B horizon being non limiting (in terms of acidity) to plant growth. With increasing rainfall, deep soil acidity is more common; at 800 mm/yr soils are sometimes strongly acid throughout the B horizon. Deep soil acidity is also a problem in many sandy soils in Western Australia. Where it exists, amelioration may be technically feasible but is rarely economic.

In south eastern Australia over 100 kg N/ha can be stored in the soil profile in autumn, mainly in the nitrate form. By May, over 40% of the mineral N can be below 20 cm (Table 2) - largely because of leaching, although there will be some mineralisation of nitrogen from dead roots.

Designing agricultural systems which use water and nitrogen more effectively and reduce accessions to groundwater is a fundamental requirement for solving the major agricultural land degradation problems. The rest of this paper explores design principles and their practicality, both technically and in terms of their implementation.

Principles for countering the temporal mismatch: water

a) dynamics - trees

The mismatch has always been there. The seasonal excess of water moves slowly through the soil, at speeds ranging from perhaps a few centimetres to a metre per month, depending on the storage capacity and hydraulic conductivity of the soil. Roots of the original perennial vegetation penetrated the soil (and sometimes fractured rock) for up to tens of metres, and thus were positioned to take up almost all of this slowly draining water before it escaped.

The problem is thus best viewed as a dynamic one: it is solved if the rate of uptake exceeds the rate of drainage. Stirzaker et al. (32) have highlighted the consequences of this dynamic behaviour in studying the ability of the roots of isolated trees or alleys to capture water that escapes the roots of nearby annuals. The capture zone (Fig.1) is small, only one or two metres wide, where the trees do not have access to a water table. Outside this zone, lateral gradients of suction in the soil, induced by the tree roots, are insufficient to counter the vertical flows generated by gravity. It is not possible, in these circumstances, for tree roots to capture the water from under the annuals without their roots occupying most of the land area.

Trees with access to an essentially unlimited supply of water, such as in a fresh water table, behave differently. They can use a lot of water, up to 1000 mm, during the year (although their water use during the southern winter is, if anything less than that of annuals (13). In contrast to that in unsaturated soil, sideways flow is rapid through a water table (Fig.2). But for the trees to maintain large transpiration rates, the water table must be fresh. Alley farming may then be highly effective. Rules for the spacing of the alleys are discussed by Stirzaker et al. (32). If the water table is saline, however, as it commonly is, the roots face the danger of salinity: when they take up the water they leave the salt behind, where it will concentrate to toxic levels unless frequent flushing takes place. The circumstances that may lead to flushing are not well understood.

b) dynamics - perennial pastures

While trees are always in place to capture most of the winter excess of water each summer before it escapes their roots, it is feasible that deep-rooted perennial pastures, such as lucerne or phalaris, could be used to chase and capture a few years' accumulation of excess water that has escaped the roots of annual crops and is transiently stored in the deep subsoil.

This possibility depends on the extent of the temporal mismatch, which in turn depends on the rainfall. Where the rainfall is less than 600 mm, the deep subsoil, say between 1 to 3 m, may have an effective storage capacity of 90 mm (31). It could hold, on average, about 3 years worth of drainage beyond one metre in much of the southern Australian cropping zone. Depending on the run of seasons, though, the storage could range from 1 year (a wet one) to perhaps 5 years (a run of dry ones). Perennial pasture plants may be able to mop up much of this water during a pasture phase, thereby regenerating the storage capacity of the deep subsoil.

In areas of higher rainfall, the water lost by annuals each year greatly exceeds the storage capacity of the subsoil and thus the return of very deeply rooted permanent perennial vegetation to such areas is the only way of stabilising the hydrology. In relation to local dryland salinity, the 600-800 mm rainfall areas are most at risk because of the combination of substantial recharge coupled with substantial salt loads. Areas with rainfall above 900 mm are unlikely to have large salt loads because the soil profiles are likely to have been well leached even under native vegetation (20). However, recharge from these areas may enter confined aquifers and eventually emerge perhaps a hundred kilometres away, where it may bring salt to the surface.

c)dynamics - duplex soils with perched water tables

Many agricultural soils are duplex, often with sodic B horizons with very small hydraulic conductivities. Thus they are prone to having perched water tables during the winter. On sloping land, there may be substantial lateral flow ("throughflow") of such water, especially where native vegetation has been cleared. These water tables tend to reach the surface at breaks of slope, where trees may be able to use the water effectively.

Previously, roots of native vegetation created sparse but essentially permanent channels (biopores) through the B horizon. The roots were thus in position to dry the subsoil during the summer, thereby creating storage for excess water during the next winter. It is likely that this storage delayed the onset of a perched table. Current management of annual crops has destroyed these original subsoil biopores, thus making it difficult for annuals' roots to colonise the subsoil and therefore worsening the hydrologic imbalance.

Table 1: Comparison of rainfall amounts and distribution in the cropping and high rainfall zones of southern Australia

Rainfall 600 mm/yr or less				
Location	Merredin, WA	Longeronong Vic.	Walpeup, Vic.	Wagga Wagga NSW
Annual rainfall (mm)	315	423	327	590

May-Aug rainfall (mm)	170	178	135	211
May-Aug Et[A] (mm)	110[B]	109	125	110[B]
Winter excess of rain over Et[C]	60	69	10	101

Rainfall over 600 mm/yr

Location	Albany, WA	Hamilton, Vic.	Corryong, Vic.	Tamworth, NSW
Annual rainfall (mm)	808	695	825	674
May-Aug rainfall (mm)	436	298	325	185
May-Aug Et[A] (mm)	148	113	111	184
Winter excess of rain over Et[C]	288	185	214	0?

[A] estimated as pan evaporation by a pan coefficient of 0.6, except for:
[B] Bowen ratio measurements (Frank Dunin, pers. comm.)
[C] If we take Whitfield's (33) estimate of about 135 mm storage capacity at the beginning of the season in the soil accessible to annual crops, then the "excess" minus 135 mm gives the "average" deep drainage. That this average is negative in some cases does not mean that there is negligible deep drainage, because variability in rainfall will result in substantial drainage in wet years.

Principles for Countering the Temporal Mismatch: Nitrogen

Our reliance on legumes severely limits the ability to match supply of nitrogen with plant demand. Because of the high concentrations of nitrate at the start of the growing season and the mobility of nitrate in soil water, reducing water loss will also reduce the nitrogen mismatch. However, with annual species it is almost impossible to match supply and demand, because the major supply of nitrogen occurs when annual plants are germinating.

Acidification rates can be calculated for different agricultural systems (23), and depend on the potential for nitrate leaching and the productivity of the system. Common soil acidification rates typically require 100-200 kg lime ha^{-1}year^{-1} to balance acid addition; however rates of approximately 400 kg lime ha^{-1}year^{-1} may be needed in intensive enterprises (such as productive lucerne stands cut for hay).

Another issue concerning nitrate in water is that of contamination. If nitrate enters streams, eutrophication is possible and will raise public concerns about the environmental acceptability of agriculture. The emergence of more intensive systems, such as that of Scammell *et al.* (30) in the cropping zone, and the high input Victorian Grasslands Productivity Program (8) in the high rainfall zone, may generate serious risks of groundwater pollution. With duplex soils nitrate may enter streams not only from surface runoff but also from subsurface flow along the top of the B horizon which eventually becomes surface runoff in the lower part of the landscape. Nitrate-N concentrations in soil water measured at Book Book in southern NSW are generally low in surface flow (<5 mg g m^{-3}) but can be substantial in subsurface flow (commonly 10-50 g m^{-3} at the beginning of the season) and deep drainage (commonly 5-20 g m^{-3}

throughout the drainage period) (28). World Health Organisation (4) standards for drinking water are less than 10 g m^{-3}. However, acceptable levels of N entering streams are much lower (0.5 g m^{-3}) (3).

Table 2. Mineral N stored to 100 cm depth under crop and pasture treatments in May

?	Treatment	Mineral N (kg N/ha)? to 100 cm depth	% Mineral N stored at 20-100 cm depth
Reference	Rutherglen, Vic. - average of 3 years data		
Haines et al.	Annual pasture (40% legume)	166	50
(1997)	Continuous crop	137	51
?	Lucerne	74	43
?	2nd crop following lucerne	164	34
?	Rutherglen, Vic. - average of 2 years data		
Scammell et al.	Annual pasture (40% legume)	188	62
(1997)	Annual pasture (100% legume)	269	62
	Book Book (Wagga Wagga) - average of 3 years data		
Ridley et al. (1997)	Annual pasture - lime (40% legume)	108	40
?	Annual pasture + lime (40% legume)	102	43
?	Phalaris/cocksfoot/sub. clover - lime	81	35
?	Phalaris/cocksfoot/sub. clover + lime	88	43

Fig 1 Schematic representation of flow of water to tree roots through unsaturated soil. The capture zone delineates a part of the soil in which water will flow to the root zone of the tree and therefore be available to it; it is typically about one to two meters wide. Outside this zone trees

cannot catch water that escapes the roots of the crop. Values for recharge below the tree and the crop are rough averages for the southern Australian cropping zone. Adapted from Stirzaker et al. (32).

Fig. 2. Schematic illustration of the flow of water to the roots of trees through a water table. The mound of water under the crop spreads sideways thus replenishing water removed by the trees. If the water table is saline, though, salt is transported in the flowing water to the tree root zone, where it may build up to toxic levels as the roots extract the water leaving the salt behind. Adapted from Stirzaker et al. (32).

Possible Solutions

In developing solutions for balancing the water mismatch, the first consideration needs to be at a regional level, for excess water in one part of a region may travel underground to another part of where it induces a rise in the watertable that mobilises salt contained in a previously stable part of the profile. Furthermore, some areas of the high rainfall zone are crucial catchment areas. The Ovens, Kiewa, Upper Murray and Murray catchments on the Victorian/NSW border alone supply over 50% of fresh water for the entire Murray Darling Basin (5). In such areas it is important that agricultural systems shed water of good quality while allowing little more recharge than occurred under the native vegetation Solutions which minimise runoff as well as deep drainage may not be ideal in this situation.

a)Water: solutions in cropping areas

One of the most promising systems for controlling recharge is phase farming - alternating a series of crops with a few years of perennial pasture. This system may be able to exploit the storage capacity of the deep subsoil as we discussed earlier, allowing it to fill during the cropping years, and then emptying it with the perennial pasture (see also (33)). Lucerne is the most attractive of the pasture plants for this purpose, although its sensitivity to acidity restricts its use generally to soils with pH_{CaCl2}> 4.8. Also there are many other agronomic problems that could inhibit its widespread adoption.

The targeted use of trees may also help. As well as alley farming in areas where there is a fresh water table accessible to the roots of perennial shrubs or trees, there are two other promising possibilities for using trees in the lower rainfall areas to help manage the hydrology:

- in sloping land with a poorly permeable B horizon that produces perched water tables, alleys of trees along interceptor drains may succeed in drying the subsoil during the summer thereby creating a buffer that will absorb substantial lateral flow. This will simultaneously reduce both waterlogging and vertical flow of water through the B horizon that may end up as recharge. This use would augment that of the reverse interceptor bank (24) which is often successful in diverting both surface runoff and throughflow in the perched water table to streams, thereby reducing both waterlogging and recharge downhill from the bank.
- accumulating experience with yield monitoring is identifying chronically poor yielding parts of given paddocks whose use for cropping may be so unproductive that it leads to negative gross margins. Such areas presumably produce more recharge than the higher yielding areas nearby, and they also often have large amounts of available nutrients, as years of uniform application of fertilisers coupled with low rates of removal lead to accumulations (Simon Cook and Jon Medway, pers. comm.). These areas, if they are large enough not to disrupt the operation of sowing and harvesting machinery, offer the opportunity of establishing perennial vegetation which could both overcome the putative leakiness of these poorly productive areas and improve the profitability of cropping.

b) Water: solutions in high rainfall areas

Much of the high rainfall zone (rainfall exceeding 600 mm/yr) is hilly and geology is mixed. Many soils are duplex and acid to depth. Meat and wool production are the major enterprises and generally have such low gross margins that many farmers are unable to pay for environmental improvements.

Acid soils are a major problem for improving efficiency of water use in the high rainfall zone. Reducing recharge is important at the larger catchment level, but reducing recharge on farms will commonly not benefit the landowner. Lime responses are often less predictable and/or lower than in the cropping zone. Common reasons are that soils are highly variable, subsoil acidity commonly limits responsiveness of lime applied to surface soils, and reliance on acid tolerant species has masked the declining production associated with soil acidification. Maximal lime responses in the high rainfall zone are in the order of 3 DSE/ha.

In terms of agronomic solutions to reducing recharge, soils are commonly either too acid or too poorly drained for lucerne. Phalaris has the most potential of the exotic perennial grasses, and can reduce drainage losses by 50-100 mm/yr compared with annual grass based pastures (where drainage losses are in the range 80-250 mm/yr) (11, 17, 29). However, soil acidification threatens phalaris, as a number of lighter textured soils are now too acid and/or infertile for phalaris persistence (27).

Deep drainage losses under native pasture grasses are unknown. Native species are commonly conservative users of water compared with exotics (9) and thus have limited potential for creating a large soil water storage capacity. However, higher runoff is likely under native pastures compared with exotics (14, 26), and it is therefore possible that deep drainage from native pastures may not be as high as their partially full soil water profiles may suggest. In catchments where supply of high quality surface runoff is a priority, native pastures may offer greater potential than exotics.

Leading livestock producers see increasing production as a major solution to maintaining or increasing profitability, thus enabling them to afford environmental measures such as lime to balance soil acidification. The Victorian Grasslands Productivity Project (GPP) has shown that stocking rates of 1.3 DSE/ha for every 25 mm above 250 mm average annual rainfall can be run in the high rainfall zone (8, 18). Stocking rates of 20-25 DSE/ha have been carried on GPP paddocks for over 5 years. This production is suited only to land of relatively high agricultural capability (gentle slopes, high fertility, exotic perennial pastures). Whether such a system results in increased or decreased water use and nutrient losses is unknown. Improved growth of perennials may increase water use, but increased pasture utilisation could reduce water use. With higher stocking rates, nitrate leaching losses are likely to be at least as high as under conventional systems. Increased production on the generally lower parts of the landscape has potential to increase nutrient losses to waterways.

Agroforestry is an attractive way of reducing recharge. Saline groundwater is commonly not a major problem within the root zone of trees where rainfall exceeds 600 mm/yr on sloping land. Alley plantings along breaks of slope can be used where subsurface flow is substantial, as outlined earlier. Furthermore, livestock production is less constrained by machinery requirements than cropping, and growing low densities of spaced trees provides the maximum tree/pasture interface to maximise water use. Major constraints however are the initial costs of protecting trees from livestock damage in such a system or the lack of grazing until trees are well established.

Forestry is also being actively promoted where rainfall exceeds 600 mm/yr. Forestry production however will directly compete with livestock production in many cases because timber trees do not grow well on the problem soils. Forestry can be especially economically attractive if there is secure tenure of tree ownership separate from land ownership, as can occur in Victoria and Tasmania (6). Whilst forestry will undoubtedly reduce recharge compared with agricultural production, it also has the potential to substantially reduce runoff (12, 20). Whether forestry has a positive or negative effect in improving hydrologic stability on a regional scale remains moot.

c) Nitrogen solutions

If acidification is the only issue regarding nitrate leaching in agricultural systems, then lime can fix the problem. Farmers can calculate acid addition rates under different farming systems (23) and apply lime accordingly. Where acidity problems exist below 10 cm depth (pH_{CaCl2} less than 4.5 and with aluminium or manganese toxicity), maintaining pH at 5.0-5.5 in the surface soil slowly ameliorates deeper layers (Keith Helyar, pers. comm.). Such a solution involves applying more lime than is needed to balance acid addition, commonly in the order of 400 kg lime $ha^{-1}yr^{-1}$, depending on soil type and rainfall (20). Amelioration of deep soil acidity is generally uneconomic, particularly where the profitability of enterprise is low and/or production systems are extensive.

Increased use of phase farming in the cropping zone through lucerne pastures is a promising option to both increase effective use of water and to achieve potentially low nitrate leaching losses whilst in the lucerne phase. Once lucerne is removed, nitrogen mineralisation can be high, and it is possible that under the cropping phase leaching losses will be high. Phase farming needs to be economic, however, and given the low profitability of livestock enterprises relative to cropping, specialised profitable systems based on lucerne (such as producing out of season lambs, or niche haycutting) need to be developed. It is also not clear whether water use of grazed lucerne approaches the water use achieved in ungrazed field and lysimeter experiments. Lucerne establishment and grazing management also need higher management skills than the conventional annual pasture based system.

If the loss of nitrate from the agricultural system causes other environmental problems, either real or perceived , then agriculture faces much more complex social and political issues - as in parts of Europe. The high legume system used by Scammell *et al.* (30) illustrates an important point regarding the potential irreconcilability between maintaining high profitability and environmental goals with respect to nitrogen in an annual legume based system. This system is extremely profitable, generating high protein and grain yields in addition to high livestock profitability. However, the extremely large concentrations of mineral N stored in this system, particularly at depth (Table 2) suggest that nitrate leaching losses are likely. The balance between high grain protein (obtained partly through cereals accessing deep soil N) and risking substantial nitrate leaching appears be difficult to reconcile with the limited control over N supply in a legume based system.

Given the situation which has developed under intensive agriculture in parts of Europe, and given that, to maintain profitability in Australia, some leading farmers are increasing the intensity of production through increased stocking rates or increased reliance on fertiliser nitrogen, we need to be aware of the hidden costs of legume-based agriculture and high intensity agriculture.

Social, political and economic considerations

Widespread changes in land use are required if the hydrologic balance is to be restored (10, 20). The question of how to pay for such change is fundamental. At present, farmers are expected to pay for such measures, but few are able to do so. This means that only the top few percent of farmers are likely to be able to adopt the solutions outlined in this paper. Intensive production in areas of high agricultural capability, improved grazing management, ability to identify plants, precision farming, phase farming, flexible cropping systems based on available soil water at sowing, and incorporation of trees with agricultural systems, require complex decision making and an understanding of environmental issues and business management. In future most farming operations will need to have the decision making frameworks used today by only the top 5-10% of producers.

Given the level of adoption of current technology, widespread changes in land use are unlikely to occur fast enough. The environmental degradation in Australia caused by inadequate use of water shows that the market-driven economy has failed to protect the environment, as has also been found elsewhere (7).

Designing environmentally acceptable ways of using of water and nitrogen effectively involves catering for economic, social and environmental goals. Australian agricultural policy needs to be developed within this context, as occurs in Europe. To achieve faster change in land use a combination of voluntary incentives, and legislative measures such as the control of land clearing in South Australia, are required.

Planning should be driven from the regional scale (32), and must include classification of catchments (16) in terms of regional importance. At the farm level, property management planning is essential, but for maximum benefit this must be linked with catchment management plans. Particular parts of the landscape that are evidently contributing large amounts of recharge may have to be taken out of agriculture to protect fertile land elsewhere. For this to occur appropriate cost-sharing mechanisms need to be developed, as there is often no benefit to the landowner involved.

Regardless of scientific efforts, widespread change in land use is inevitable in some areas where social, economic and political issues may make agronomic solutions irrelevant. The high price of land in the high rainfall zone in relation to its agricultural capability can result in small parcels of land being purchased by people who do not depend on agriculture. Population is increasingin areas within an hour’s drive from regional centres in Victoria and NSW. Appropriate land use planning, and provision of services to such landholders may provide a low cost opportunity to retire agricultural land on fragile parts of the landscape and thereby to reduce recharge.

Conclusions

There are a number of technical solutions to balancing the temporal mismatch between water supply and demand. Much of the landscape needs to have perennial vegetation, either through phase farming techniques, or permanent perennial cover. In cropping areas technical solutions are feasible, particularly where phase farming can be used. In the high rainfall zone, technical solutions to handling the water mismatch will be more complex, because of high soil acidity, low profitability of livestock enterprises, and the varying importance of catchments in supplying water for downstream use. Sites which are evidently contributing large amounts of recharge may eventually have to be taken out of agricultural production and it is unlikely that a profitable alternative can be found in many situations. Incentives and cost-sharing mechanisms will be needed.

It is difficult to balance the temporal mismatch between nitrogen supply and demand in legume- based agriculture. Where it is economic, lime can be applied to balance the soil acidification caused by agricultural production. If nitrate loss results in contamination of groundwater or streams, or lime application is not economic, then some political decisions need to be made about the role of legumes and intensively fertilised systems.

Development of more sustainable agricultural systems will involve substantial change in land use and possibly large social change in some parts of the landscape.

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