Department of
Primary Industries and
Regional Development

GOVERNMENT OF
WESTERN AUSTRALIA

Research Library

Bulletins 4000 -

Research Publications

2001

Soil factors influencing eutrophication. In Soilguide. A handbook for understanding and managing agricultural soils. (ed. Geoff Moore)

David Weaver
Department of Agriculture and Food, Western Australia

Robert Summers
Department of Agriculture and Food, Western Australia

Follow this and additional works at: https://researchlibrary.agric.wa.gov.au/bulletins

Part of the Agriculture Commons, Natural Resources Management and Policy Commons, Soil Science Commons, and the Water Resource Management Commons

Recommended Citation

Weaver, D, and Summers, R. (2001), *Soil factors influencing eutrophication. In Soilguide. A handbook for understanding and managing agricultural soils. (ed. Geoff Moore)*. Department of Primary Industries and Regional Development, Western Australia, Perth. Bulletin.

This bulletin is brought to you for free and open access by the Research Publications at Research Library. It has been accepted for inclusion in Bulletins 4000 - by an authorized administrator of Research Library. For more information, please contact library@dpird.wa.gov.au.

7.3 Soil factors influencing eutrophication

David Weaver and Rob Summers

Eutrophication is essentially the nutrient enrichment of waterways leading to algal growth. It must be controlled to maintain sustainable agricultural systems and the main mechanisms of control are stabilising catchment processes and reducing nutrient output.

Eutrophication can be defined as 'the nutrient enrichment of waters which results in the stimulation of an array of symptomatic changes, among which increased production of algae and macrophytes, deterioration of water quality and other symptomatic changes, are found to be undesirable and interfere with water uses' (OECD 1982). The word eutrophic is a Greek word that means 'well fed'. The food referred to is plant nutrients, such as nitrogen (N) and phosphorus (P) and as such the definition simply means 'an undesirable addition of plant nutrients to a waterbody'. The visible sign of nutrient enrichment is the proliferation of algae in waterways. Algae flourish in nutrient rich waters, most often to the detriment of other species of aquatic plants and fauna. Algae may block light to other aquatic plants such as seagrasses resulting in reduced biomass, thus threatening parts of the ecosystem reliant on seagrass. The decomposition of algae consumes oxygen, which can lead to the death of fish and the release of nutrients from sediments into the water column.

Eutrophication is a natural aging process. Over millennia waterbodies are slowly filled with soil and other materials entering with inflowing waters. In this natural process water quality is usually good, there is a diverse biological community and little algae. Human activities accelerate these natural processes. Human settlement, the clearing of forests, development of cities, agriculture and industry have increased the addition of nutrients to catchments and increased water erosion and flow from catchments to downstream waterways at a rate exceeding that of the system to assimilate.

Eutrophication leads to social and economic problems at a local scale including visual pollution for residents and recreational users and declining property values because of the stigma of pollution. An increase in nutrients can increase fish productivity, however algae fouls fishing nets making fish catching difficult. Algae decomposition results in the release of foul smelling gases (including hydrogen sulphide) which can be a problem for some residents. At an international scale overseas consumers demand products that are produced in a sustainable manner and this generates barriers to trade.

The nutrient most implicated in eutrophication in Western Australia is phosphorus (P) which generally limits algae growth to the greatest extent. However, just as the supply of other nutrients influences pasture growth, the addition of other micro- and macro-nutrients may also influence algal growth. The major areas of concern are the coastal zones, particularly in the south west and along the south coast (Figure 7.3.1) (Hodgkin and Hamilton 1993). These are also the most heavily populated and developed areas of Western Australia. Some waterbodies that have received particular attention, both in the media and by research organisations are the Peel Inlet and Harvey Estuary, Leschenault Inlet, Princess Royal Harbour and Oyster Harbour, Wilson Inlet and Swan Estuary. There are also numerous reports of the effects of nutrient enrichment of many wetlands, lakes and rivers throughout the south-west of WA.

Soils are closely linked to eutrophication processes because soil characteristics influence the delivery of soil and nutrients to waterways. This section describes some of the principles of eutrophication and then elaborates on some soil criteria influencing the problem.

Principles of eutrophication

Some features of our waterbodies and environment encourage algae to grow. These include limited exchange between waterbodies and the ocean restricting the flushing of nutrient-rich waters, warm water temperatures, high light intensities and shallow waterbodies and ample supplies of nutrients from external and internal sources (nutrients are released from sediments into the water column under anaerobic conditions).

Our catchments also have unique features that encourage the loss of nutrients to waterways. Some of the most commonly cited reasons for nutrient loss include a high percentage of catchment clearing, extensive areas of sandy surfaced soils with little capacity to retain nutrients, drainage of waterlogged soils to remove excess water, the application of fertilisers with high water solubility (e.g. superphosphate) to correct nutrient deficiencies and soils which often support pastures with limited root systems resulting in a limited uptake of applied nutrients.

Aquatic flora may respond differently to additions of nutrients than do agricultural pastures and crops. A small loss of nutrients from agricultural land may not hinder crop growth in the paddock, but may greatly influence the growth of algae in waterways. Waterways generally have low nutrient levels and contain flora that are adapted to efficient scavenging, hence when excess nutrients are available, algal blooms can occur. Nutrients entering waterways come from a variety of sources and have their origin in two main categories, diffuse and point sources.

Diffuse sources

Diffuse sources of nutrients are those that come from a wide area (spread throughout the catchment). Broadacre agriculture, including areas under pasture or crop are diffuse sources. Diffuse sources may contribute a large proportion of the total amount of nutrient discharged into a waterway because of the extensive nature of most catchments. The quantity of nutrient exported on a per unit basis (say kg/ha) is usually quite small relative to application rates and the amount stored in the soil, and ranges from about 0.05 to 4 kg/ha/yr. Usually less than 20 kg/ha of phosphorus is applied to areas of broadacre agriculture.

It is difficult to compare nutrient loss rates in kg/ha from catchments of different sizes because smaller catchments appear to lose more nutrient per unit area than large catchments. In-stream losses and variable source areas lead to scale effects which may confuse the interpretation of nutrient loss data.

Other major diffuse sources of nutrients are urban areas. Urban nutrient sources include fertilizers applied to domestic gardens, parks and golf courses, as well as septic tanks, sewerage disposal and waste disposal sites. The proportion of the total input from these sources will depend on the extent of the urban area in comparison to other sources and the current nutrient management strategies in place in urban areas.

Point sources

While diffuse sources are mainly associated with extensive agriculture, point sources are usually associated with intensive agriculture and discharges at a particular point. Point sources include intensive forms of agriculture such as piggeries, sheep holding yards, dairies and horticulture, meat processing plants, vegetable processing plants, and fertilizer factories and other industries.

Intensive animal industries often produce large quantities of wastewater and nutrients. Nutrient concentrations in these wastes are often much higher than those measured leaving diffuse sources. Many of these industries currently combine ponding, irrigation and diversion to waterways to dispose of nutrient rich wastewater.

Table 7.3.1 shows approximate quantities of N and P excreted by different animals over a year. Where many animals are housed together and the waste is discharged over small areas, nutrient losses by leaching and runoff can be large because areal application rates of nutrients are high and soils have limited capacity to retain applied nutrients. Nutrient losses from point sources are usually expressed as quantities (kg or tonnes) for a specific industry rather than kg/ha.

Table 7.3.1 Nitrogen and phosphorus output (kg/animal/yr) in some animal wastes (Vanderholm, 1984)

Animal	Nitrogen	Phosphorus
Broiler Chickens	0.3	0.07
Laying Hens	1 - 2.4	0.1 - 0.2
Sheep	5.5	0.9
Pigs	3.7	0.7 - 3
Feedlot Beef	18 - 32	6.4
Dairy Cows	64	13

For the satisfactory production of horticultural crops, the application of large quantities of nutrients and water is often required. Nutrients are often applied in excess. They may be lost from the system before the plants can use them or the amounts applied may be in excess of the plant requirements. The excess nutrients are lost from the system by leaching, runoff or soil erosion (Table 7.3.2). Often two or more crops are grown in a year and recommended nutrient application rates are not always adhered to.

Table 7.3.2 The fate of nitrogen and phosphorus fertilizer (in kg/ha/crop) after application to five major vegetable crops on the coastal sands. (After McPharlin and Luke 1989).

Crop	Status of Land	Applied		Crop Removal		Remaining	
		N	P	N	P	N	P
Carrots	New	372	74	100	15	272	59
	Old	300	50	100	15	200	35
Lettuce	New	850	250	100	20	750	230
	Old	370	90	100	20	270	70
Cauliflower	New	1050	280	119	25	931	255
	Old	570	120	119	25	451	95
Onions	New	800	280	90	26	710	254
	Old	320	120	90	26	230	94
Potatoes	New	740	280	132	15	608	265
	Old	360	120	132	15	228	105

Humans discharge the equivalent of 1 kilogram of phosphorus annually as a result of domestic activities. The detergents that we use make up approximately 50% of the P that we dispose of. Disposal through septic tanks or improperly constructed or sited sewerage works can lead to nutrient contamination of ground and surface waters. Table 7.3.3 shows the difference in annual nutrient input in sewered and unsewered areas of Perth.

Table 7.3.3 Annual input of nitrogen and phosphorus in urban residential areas of Perth, Western Australia (10 residences per hectare). (After Gerritse *et al.* 1990).

	Nitrogen ($kg\ ha^{-1}$)	Phosphorus ($kg\ ha^{-1}$)
Sewered	80	40
Unsewered	260	70-80

The nutrient exported to a waterbody from point sources will depend on the location of the source in relation to the waterbody, the size of the source, the soil on which it is sited, groundwater proximity and direction of flow, seasonal and other environmental factors and the management strategy employed to deal with the nutrients.

Factors affecting nutrient loss

A commonly observed feature of nutrient transport is that it is dependent on rainfall and flow. Figure 7.3.2 shows P loss and flow data for a subcatchment on the south coast in 1990. Most of the nutrient was lost in one period of high flow.

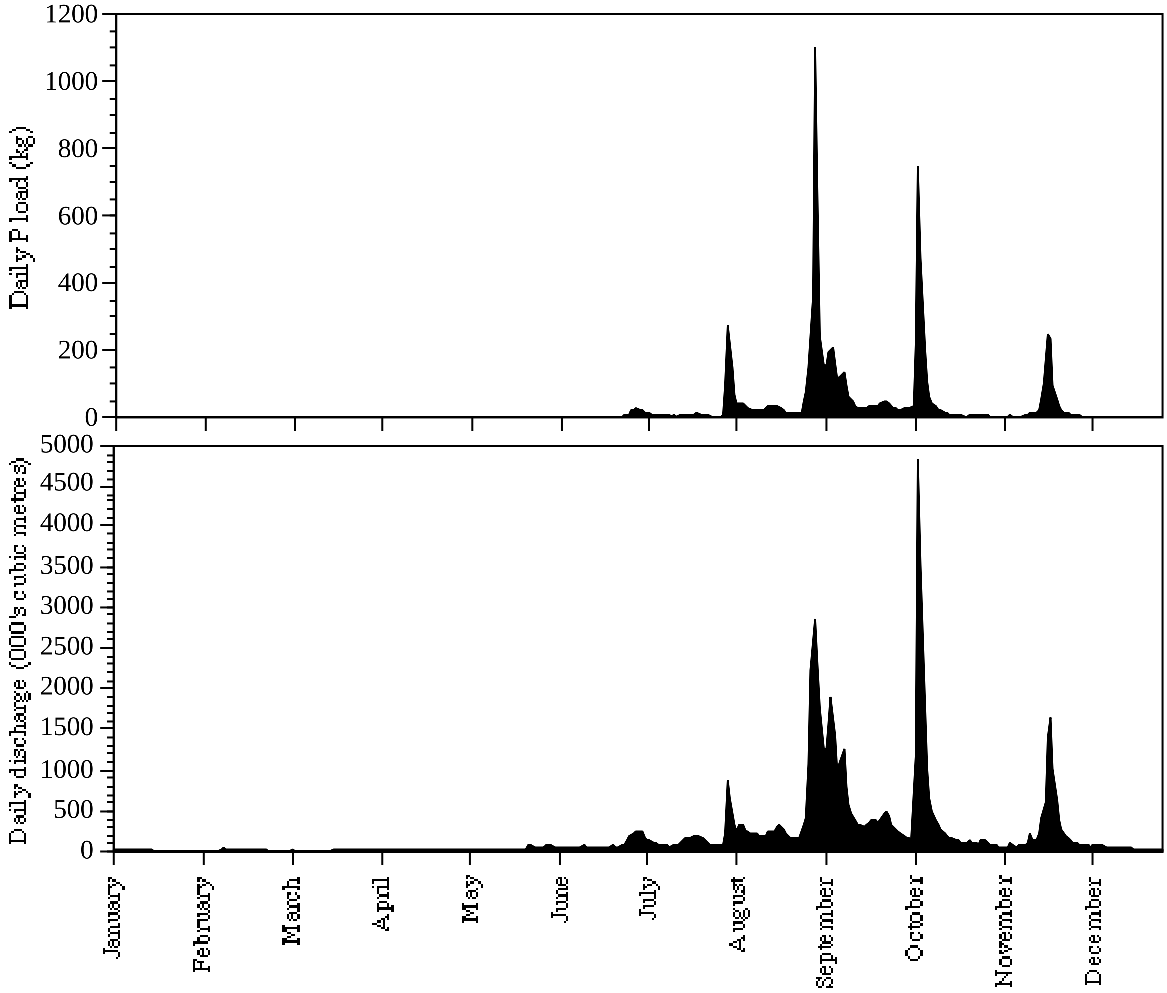

Figure 7.3.2 Timeseries of daily phosphorus load (kg/day) and daily river flow during 1992 (thousands of cubic metres/day) for the Kalgan River near Albany.

Table 7.3.4 summarises a range of factors that influence P loss and P concentrations in streams. It also illustrates whether the factor is linked to an increased or decreased risk of P loss with a brief explanation, and whether soil, hydrology or other factors (such as management or inherent natural features) are most dominant in influencing the magnitude and direction of the change in risk. Many of the factors in Table 7.3.4 are generalisations and there may be exceptions to them in specific situations. It is not an exhaustive list.

Table 7.3.4 A list of the factors that influence P loss and P concentrations in streams.

Factor	Risk of P loss	Soil	H_2O	Other
years of fertiliser application	risk increases with increasing number of years of fertilisation	✓	✓	✓
	risk increases or decreases between adjacent water years depending on management and environmental factors		✓	
time since fertiliser application	risk decreases as time of contact with soil increases	✓		
fertiliser application rate	risk increases with increasing application rate	✓		
streamflow	risk increases with increasing flow rate		✓	
dominant flow mechanism (runoff vs subsurface vs groundwater	risk increases with dominance of surface runoff	✓	✓	
	risk decreases with dominance of subsurface and groundwater flow, but depends on P retention of soil	✓	✓	
seasonal effects	risk increases in winter and spring, decreases in summer and autumn, generally decreases annually	✓	✓	
catchment size	risk of high concentrations and high unit area loss rates decreases with increasing catchment size			✓
catchment shape	risk to downstream waterways decreases with elongate catchments			✓
	risk to downstream waterways increases with shapes that favour short distances to waterbody			✓
travel time in a stream	risk decreases with increased travel time in a stream		✓	✓
riparian (streambank) vegetation condition	risk decreases with improved riparian vegetation condition		✓	✓
river/creek/stream/drain length	risk decreases with increased river/creek/stream/drain length		✓	✓
spatial position - where sample is collected in a stream (laterally, vertically and longitudinally)	†concentration increases towards centre of watercourse and decreases towards edges, increases as streambed is approached		✓	
	concentrations and unit area loss rates increase as headwaters are approached		✓	✓
stream order	risk of high concentrations and high unit area loss rates decreases with increasing stream order		✓	✓
soil P retention	risk of high concentrations and high unit area loss rates decreases as soil P retention increases if leaching is dominant	✓	✓	
	risk of high concentrations and high unit area loss rates increases with increasing P retention if soil erodes	✓		
	risk increases or decreases depending on dominance of subsurface and groundwater flow	✓	✓	
	sandy soils store little P and leach more P than clay soils which store more and lose P mainly by erosion			
soil fertility	risk increases with increasing soil P status	✓		
depth to impeding layer	risk increases with shallow soils mainly because of greater runoff and decreases with deep soils	✓	✓	
grass height	risk decreases with increasing grass height	✓	✓	✓
grazing pressure	risk increases with increasing stocking rate			✓

proximity to point source		†risk decreases with increasing distance from source	✓		
soil moisture		risk increases as soil moisture increases	✓	✓	
rainfall intensity		risk increases with increasing intensity if erosion is dominant	✓	✓	
		risk decreases if high rainfall intensity causes dilution		✓	
amount of previous rainfall event		risk decreases as amount of previous rainfall increases	✓	✓	
land use		risk increases with intensity of land use, but depends on the level of management	✓	✓	✓
land management		risk decreases as land management includes greater emphasis on soil conservation measures	✓	✓	✓
effective vegetation cover		decreases as effective vegetation cover increases			✓
drainage		risk increases with increasing surface drainage	✓	✓	✓
		risk decreases with increasing subsurface or tile drainage	✓	✓	✓
		risk decreases with increasing surface drainage if the drainage causes increased contact of water with soil, improved P retention from oxic conditions and improved pasture growth	✓	✓	
distance to waterway		risk decreases as distance from source to waterway increases			✓

† more likely to produce a measurement error or effect rather than identify a factor influencing nutrient loss

Soil factors affecting nutrient loss

Nutrients usually get to waterbodies from our soils, through the movement of water. Some nutrients are discharged directly into waterways in the form of wastes but most often the nutrients are applied to our soils first, in the form of fertilizers or wastes. The nutrients stored in the soil can be lost by leaching from sandy soils or by erosion from heavier soils.

Nutrient loss depends on soil characteristics, the form of nutrient applied, rainfall, uptake by plants and water movement. Some of these factors, such as uptake by plants and form of nutrient applied, are dependant on management decisions which can control to a certain extent the amount of nutrient lost. Rainfall we cannot control, whilst our soils have natural characteristics (P sorption capacity) that influence both how much is exported to waterbodies and how much is available to plants. Some natural characteristics influencing a soils sorption capacity include the soil texture and the presence and amount of iron, aluminium and calcium compounds.

Phosphorus loss by leaching depends on the soil type, the rate of P application and the throughput of water. For sandy soils (3 and 4 in Table 7.3.5) the time taken for P to move through the soil is short in comparison to lateritic soils (1 and 2 in Table 7.3.5). The capacity of each of these soils to sorb P can be determined by measuring its Phosphorus Retention Index (PRI). The higher the value the greater the capacity to sorb P.

Table 7.3.5 Calculated times (years) for phosphate to travel through 1 metre of some soils of the south-west of Western Australia for different rates of accumulation of phosphorus and recharge. (After Gerritse 1990).

Phosphorus accumulation (kg/ha/yr) -	20		100		500	
Recharge (cm/yr) -	20	100	20	100	20	100
1. Surface soil of the Darling plateau	38000	15000	11000	4500	3000	1300
2. Clay subsoil of the Darling plateau	250	170	60	45	15	11
3. Subsoil of a yellow Spearwood sand	45	30	12	7.5	4.5	2.5
4. Surface soil of a Gavin sand	6	2.5	3	1.5	1.5	<1

However, soil P retention is irrelevant if management does not aim to retain soil on-site. Soils with high P retention reduce P loss by leaching and increase P loss by erosion. Soils with high P retention have a tendency to store large amounts of P in the soil which can then be lost through erosion when surface runoff removes soil particles that have been enriched with nutrients (Figure 7.3.3).

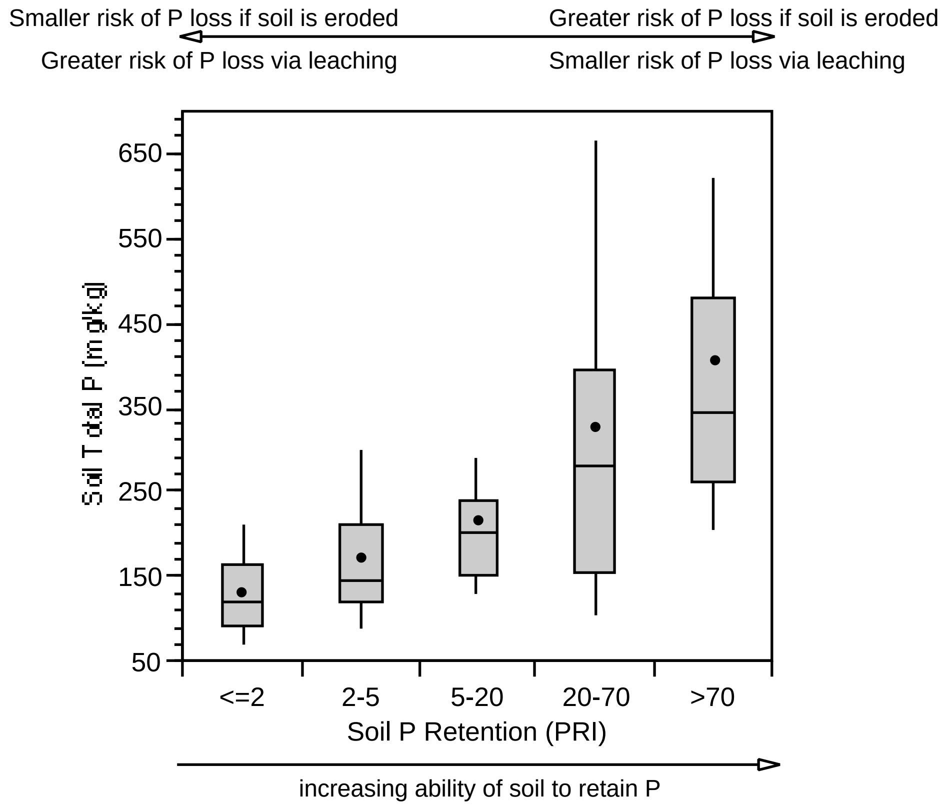

Figure 7.3.3 Box and whisker plot showing the relationship between soil P retention and soil Total P indicating which soils are most likely to contribute to P loss via leaching or erosion.

(Filled circles represent the mean, bottom of box represents 25th percentile, middle of box represents 50th percentile, top of box represents 75th percentile. Top whisker represents 90th percentile and bottom whisker represents 10th percentile).

The effect of time (surrogate for cumulative P application) on increased risk of P loss via surface runoff is shown in Figure 7.3.3. Phosphorus accumulates in the topsoil after many years of application of fertiliser (Figure 7.3.4). Enriched topsoils have the greatest potential to lose P from surface runoff and erosion. In the short term (within a season) the risk of P loss decreases with time of exposure to soil. The risk of P loss in soluble forms from sandy soils also changes between rainstorms as P is leached from the soil solution. Phosphorus cycles between pools in the soil and increasing the amount of pre-leaching decreases losses from subsequent rainfall (Weaver *et al.* 1988).

Under leaching conditions where there is sufficient P carried over from the previous year to start germinating plants, the best time to apply P is after the plants have germinated. As a rule of thumb, the later the fertiliser can be feasibly applied (up to about a month after the break of the season) to established plants the less chance there is of loss of P and the greater the efficiency of fertiliser use.

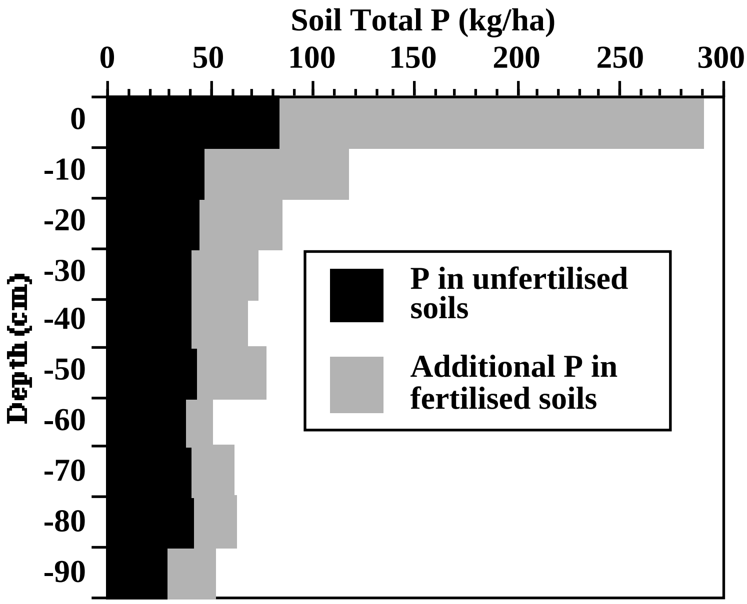

Figure 7.3.4 Average change to soil P storage with depth for soil profiles on the south coast of WA post clearing.

A common measure of P retention used in WA is *reactive iron*. Reactive iron in a soil is constant, while soil PRI will decrease as cumulative fertilizer inputs increase over time and sorption sites in the soil become saturated. PRI tells us about the soils current ability to retain phosphorus whilst reactive iron level will reflect the PRI it had before any fertilizer was applied. The PRI of some soils and red mud (bauxite mining residue) is given in Table 7.3.6.

Table 7.3.6 Phosphorus retention index of some virgin Western Australian soils and amending materials. (After McPharlin *et al.* 1990).

Soil type/amendment	PRI
Joel sand	0
Grey Karrakatta sand	0.3-0.4
Wongan Grey sand	2.7
Yellow Karrakatta sand	3.2-4.1
Spearwood sand	7.0
Wongan yellow loamy sand	13.0
Gingin red loam	70.0
Red Mud	310.0

Management options

There are a number of options for reducing nutrient loss. These are based on minimising nutrient inputs and maximising nutrient retention.

Fertilizing for need

Fertilizing according to the requirements of pastures rather than tradition can go a long way towards reducing nutrient applications in catchments. There are models available (e.g. PHOSUL-K) to predict nutrient requirements. Fertilizing for need requires regular soil testing, so that fertilizer applications are optimised. Reactive iron, in combination with other soil measurements such as bicarbonate-extractable P are used to determine how much P is required by annual pastures in high rainfall areas. There are standards to determine P requirements of pastures depending on the soils P status (Table 7.3.7). The South Coast Estuaries Project survey showed that more than 50% of the soil samples taken in the area had a high P status and could go without applications of P for at least one year. Further soil testing may indicate that some high P status soils may be able to do without P applications for more than one year.

Table 7.3.7 Soil phosphorus status standards for the South Coast

Reactive Iron (ppm)	Bicarbonate P (ppm)		
	Low	Medium	High
1-100	<10	10-12	>12
101-200	<12	12-15	>15
201-400	<15	15-20	>20
401-800	<20	20-25	>25
801-1600	<25	25-30	>30
>1600	<30	30-40	>40

Using alternative fertilizers

An alternative fertilizer that supplies phosphorus in a slow release form, more suitable to the needs of pasture in coastal high rainfall areas may be available. It is known as coastal super and also has a high sulphur content in a slow release form. In addition, particularly for soils with high phosphorus status, other nutrients, such as sulphur and potassium, can be used to achieve the most economic level of production.

Treating point sources

Point sources of nutrients, particularly where an effluent is discharged, can be treated to remove a large proportion of the nutrients before the effluent is discharged. There are many methods of treating effluent to remove nutrients. There are passive biological treatments and more active chemical treatments available. Some of these relevant to soils include irrigation over soils with high nutrient retention in conjunction with tree plantations. It is best to site point sources as far from watercourses as possible so that the opportunities for removal of nutrients by soil contact and biological removal is increased.

Soil amendment

Amending sandy soils with waste products from industrial processes or with soils with high capacities to adsorb phosphorus can reduce nutrient losses. Red mud (the residue produced in the process of extracting aluminium from bauxite) is one material that has been used and tested. Rates of application of red mud up to 4000 tonnes/ha have been tested. Applications of 80 tonnes/ha reduced the amount of P lost by 70% (Summers *et al*. 1993). In addition pH of the soil increased and productivity increased. Other materials such as the wastes from synthetic rutile plants are now under scrutiny as amendments for sandy soils. For very sandy soils, amendment with high PRI loams may significantly reduce P losses (Gilkes *et al.* 1992)

Water control

The mechanism by which nutrients make their way to our waterbodies is water. Water carries nutrients in both dissolved and particulate forms. By putting in place erosion control measures, much of the particulate nutrient problem can be overcome. For example, in Western Europe it has been shown that a 50 metre wide buffer strip of vegetation along streamlines can filter out 50-100% of P (Isermann 1990). Other devices such as detention basins or structures that slow water movement are effective in reducing nutrient loss through sedimentation and biological processes.

Some land degradation problems such as salinity and waterlogging may be overcome by removing water from the land through drainage. This may, however, be to the detriment of nutrient enrichment problems. It would be appropriate to use methods of water control that attack these problems in unison. Subsurface drainage may reduce nutrient loss by allowing intimate contact between percolating water and soil, whilst surface drainage may contribute to increased nutrient loss if it does not improve soil water contact (Skaggs *et al*. 1994). Removal of excess soil moisture may reduce the risk of P loss from erosion.

Pasture species that use more water and have more extensive root systems can also help. Perennial pastures have root systems ready to take up nutrients applied soon after the first rains of the season. They may also assist in reducing the effects of erosive summer storms.

Planning and other control mechanisms

The above mechanisms are mostly used for existing sources of nutrients. It is important, however, to plan for the future. One control mechanism involves assessment of the capability of the land and ensuring that the lands capability for nutrients is not exceeded.

In some environmentally sensitive areas, proposals for nutrient intensive activities may need tsome form of environmental assessment. Proponents may need to provide detailed information on the soils ability to retain nutrients and management measures to control nutrient loss.

References

Gerritse, R.G. (1990) Impact of horticultural landuse on water quality in the Darling Range and Coastal Plain of Western Australia. In Proceedings of "Horticulture and the Environment", Western Australian Department of Agriculture, Division of Horticulture Seminar, Mandurah, June 7-8, 1990, Miscellaneous Publication No 20/90

Gerritse-RG, Barber-C and Adeney-JA (1990) The impact of residential urban areas on groundwater quality: Swan Coastal Plain, Western Australia. Water Resources Series No. 3,CSIRO

Gilkes, R.J., Mosquera-Pardo, A.C., Newsome, D. and Watson, G. (1992) Iron oxide wastes from synthetic rutile manufacture: A comparison with bauxite red mud as ameliorants for P-leaching sandy soils. In proceedings of "International Bauxite Tailings Workshop" 2-6 November 1992. Perth Sheraton Hotel, WA. pp 345-354

Hodgkin-EP and Hamilton-BH (1993) Fertilisers and eutrophication in southwestern Australia: setting the scene. Fertiliser Research, 36, 95-103

Isermann-K (1990) Share of agriculture in nitrogen and phosphorus emissions into the surface waters of Western Europe against the background of their eutrophication. Fertiliser Research, 26, 253-269

McPharlin-I, Delroy-N, Jeffery-B, Dellar-G and Eales-M (1990) Phosphorus retention of sandy horticultural soils on the Swan Coastal Plain. Journal of Agriculture, Western Australia, 31, 28-32

McPharlin-I and Luke-G (1989) Irrigation and fertilizer management for horticultural crops on the Swan Coastal Plain.. Journal of Agriculture, Western Australia, 30, 91-96

Organisation for Economic Cooperation and Development (1982) Eutrophication of waters: Monitoring, assessment and control. Final Report. OECD cooperative program on monitoring of inland waters, Environment Directorate, OECD, Paris, 154 pp

Skaggs-RW, Breve-MA, Gilliam-JW (1994) Hydrologic and Water Quality Impacts of Agricultural Drainage. Critical Reviews in Environmental Science and Technology, 24, 1-66

Summers-RN, Guise-NR and Smirk-DD (1993) Bauxite residue (Red Mud) increases phosphorus retention in sandy soil catchments in Western Australia. Fertilizer Research, 34, 85-94

Vanderholm, D.H. (1984) Agricultural Waste Manual. NZAEI Project Report No. 32. NZAEI, Lincoln College, Canterbury, New Zealand.

Weaver- DM, Ritchie-GSP, Anderson-GC and Deeley- DM (1988) Phosphorus leaching in sandy soils. I. Short-term effects of fertilizer applications and environmental conditions.. Australian Journal of Soil Research, 26, 177-190