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The use of bauxite residue to control diffuse phosphorus pollution in Western Australia – a win-win-win outcome

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ABSTRACT

The Department of Agriculture, Western Australia has been working with Alcoa World Alumina Australia Ltd for more than ten years investigating the potential to use bauxite refining residues as soil amendments for the poor, acidic, sandy soils of the Swan Coastal Plain in south west Australia. Regional waterways, especially the Peel Inlet and Harvey Estuary, have historically been susceptible to nuisance algal blooms fed by phosphorus in run-off from farmland and urban areas. Extensive laboratory, field and catchment-scale trials have shown the ability of soil amendment with fine bauxite refining residue (now trademarked in this context as Alkaloam™) to reduce the leaching of nutrients to sensitive regional waterways by up to 75%, whilst increasing pasture productivity by up to 25% (up to 200% in well-controlled experimental situations). This is now widely acknowledged as the only land management option developed globally which has been shown to reduce non-point-source phosphorus export immediately upon application. Alkaloam™ is now available on a commercial basis to landholders in the Peel-Harvey Catchment and is seen as an exciting solution to a significant land degradation problem. This paper examines the effectiveness of Alkaloam™ in retaining phosphorus, increasing plant production and assisting in minimising waste production from refineries – win-win-win.

KEYWORDS

Bauxite residue, Peel-Harvey, phosphorus, red mud, soil amendment.

INTRODUCTION

Location and characteristics of the Peel Harvey Catchment

The Peel-Harvey Catchment lies approximately 70km south of Perth in Western Australia and the gazetted coastal portion of the catchment covers about 190,000 ha which extends as far north as Kwinana and south to Harvey. Over 65% of the catchment has a coarse sandy surface of varying depths to impermeable layers of ironstone or clay, the remainder has clay or loam alluvium at the surface. Inundation is common during winter because of the very flat landscape and the short and intense period of rain. An extensive artificial drainage network has been constructed and, while this greatly reduces inundation, stream-flow generally rises, peaks and falls over several days because water pools and is stored on the flat landscape. The Peel Inlet and Harvey Estuarine System has been affected by eutrophication and the excessive growth of benthic algae since about 1968 (Cross 1974). Algal growth has been stimulated by phosphorus (P) from fertiliser used in the surrounding catchment, most of which (90%) comes from the coastal portion of the catchment which discharges directly into the water body (Birch 1980).

Phosphorus which is not utilised by plants is transported from the clay soils in the catchment by overland flow attached to clay particles, whilst the sandy soils discharge P initially either in a soluble form or bound to low molecular organics. The sandy soils are so poor in retaining P that only a small proportion of applied P remains after winter with most of it leaching through the soil or being washed over the surface when the soil is saturated.

In 1994, a Public Environmental Review (Summers and Bradby, 1993) was under-taken by the Department of Agriculture to assess the impact of bauxite residue application on to farmland in the Peel-Harvey coastal catchment. The Environmental Protection Authority of WA found the project acceptable with the condition that there was suitable monitoring upon the release of bauxite residue for widespread use which was to be reviewed after five years (WA EPA, 1993; WA EPA, 2000). The Department of Agriculture established a monitoring program to assess large-scale trials prior to the release of bauxite residue to determine base-line or background information about the environmental impacts of soil amendment with bauxite residue. This monitoring was to measure the long-term effectiveness of the bauxite residue to retain nutrients and was to be used to define the scope of the future monitoring commitments.

The alumina industry in the south-west of Western Australia produces 15 million tonnes of bauxite residue annually. The fine fraction (< 150 μm) of residue after the treatment of bauxite with caustic soda to remove the alumina is often called red mud. Red mud is now trademarked by Alcoa World Alumina as Alkaloam™ when used as an agricultural soil amendment after appropriate preparation. The residue is mainly silica and iron and aluminium oxides. It is composed predominantly of silt sized particles and has a pH (both 1:5 water and 1:5 CaCl2) of about 11, because of residues of sodium hydroxide and sodium carbonate. As the bauxite residue dries, it combines with the carbon dioxide from the air and the dominant alkaline material converts from sodium hydroxide to sodium carbonate and the pH falls below 9. The high iron and aluminium oxides combined with the residual alkali results in the material having a very strong affinity for P.

This paper reports the results of several studies into the effectiveness of bauxite residue to reduce P leaching and increase plant production and also discusses the results of the associated environmental monitoring programme.

PHOSPHORUS CONTROL

Laboratory trials

Laboratory trials were undertaken to assess the best application rate of Alkaloam™ to retain P applied as fertiliser and the length of time that P continued to be taken up by Alkaloam™ (Summers *et al.*,1996b). The composition of leachates from Alkaloam™ amended soils was compared with drinking water standards for humans and untreated controls. Monthly rainfall was simulated and leachate was collected from lysimeters filled with bleached grey sand representative of the region amended with 5-80 tonnes ha^{-1} of Alkaloam™. Leachates from over 12 months of simulated rainfall were tested for potential pollutants (Cd, Al, Fe, As, F, SO_4), electrical conductivity, pH, and P. The rainfall simulation was continued for the equivalent of 5 years and P levels were monitored during this time.

The ionic concentrations of the contaminants from columns treated with Alkaloam™ were similar to the concentrations in the controls, or fell to similar levels after the equivalent of 3 months of rainfall. The concentrations of these leachates were below the maximum recommended limits for drinking water. Phosphorus reductions of up to 90% were measured with Alkaloam™ amendment, with the best application rates of Alkaloam™ for the reduction of P leaching between 10 and 20 tonnes ha^{-1}. The improved nutrient retention from Alkaloam™ continued for the equivalent of at least 5 years of fertiliser application.

Catchment trials

The Meredith catchment is a sub-catchment of the Peel-Harvey, with 4360 ha monitored for P concentration and water flow for 12 years prior to the application of Alkaloam™ and six years after application. About 1600 ha of the catchment was treated with 20 tonnes ha^{-1} of Alkaloam™. This was the majority of cleared grazing land that had been fertilised. The water was sampled daily using an automatic sampler providing a composite from four samples. Every fortnight the site was sampled manually for heavy metals as well as for nitrogen and P.

The P concentration dropped significantly in the drainage water from the Meredith catchment after treatment with 20 tonnes ha^{-1} Alkaloam™ when compared with the previous ten years. The P concentration in the run-off varied seasonally with a rapid rise at the start of flow in winter and then a slow tailing off in concentration over winter and spring. Adjustment of the P concentrations for seasonal variations in run-off showed a reduction of 0.3 mg L^{-1} compared with the median level of 0.94 mg L^{-1} over the previous ten years. This was a reduction of 32%. The result was based on the Mann-Whitney test (Wilcoxon Rank Sum Test) on analysis of the median P concentrations ($P < 0.05$). The other water quality criteria measured at the Meredith drain were generally the same as or less than those measured at other sites.

The data has been analysed using monthly water quality data to allow some interpretations to be made on seasonal water quality variations before and after Alkaloam™ amendment (Figure 1).

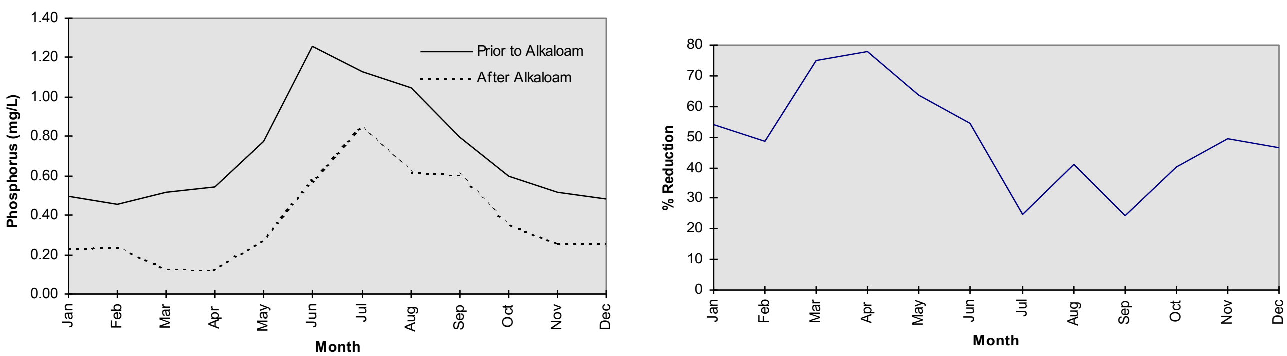

Figure 1. a) Monthly P concentrations - Meredith Drain, b) Monthly % P reductions - Meredith Drain after Alkaloam™ amendment (From Rivers, 1996).

These graphs indicate a consistent and continuing reduction in P concentration of up to 80% on a monthly basis in the water in the Meredith Drain after Alkaloam™ amendment of the catchment soils. Statistical analysis indicates significant reductions in this data set for the individual months of June and August, and a significant reduction in the overall monthly data set ($P<0.0001$) using a paired t-test.

Similar information has also been obtained for other regional drains (Harvey River, Mayfield Drain and Nambeelup Brook) for varying periods of time dependent upon data availability. Statistical analysis of these data sets does not indicate the same statistically significant reductions in P concentrations over the same time period. The reductions in water P concentration appear to be limited, regionally, to the Meredith Drain.

This data has also been compared with a number of other data series to try and gauge some understanding of any causative factors other than amendment with Alkaloam™ which may be producing a decline in the P export from the Meredith Drain. When the data is been compared with the sale price of beef over the same period (as an indicator of the potential returns gained over this period by beef farmers) and the amount of superphosphate sold in this region over this time (as an approximate indicator of the amount of fertiliser applied to farmland over this period) no statistically significant correlation has been observed (Rivers, 1996). The only causative factor for reduction in P concentration in the Meredith Drain appears to be Alkaloam™ amendment.

Also, within the Meredith Catchment, a pair of adjacent, similar catchments were monitored for nutrient discharge (Summers *et al.*, 1993). Alkaloam™ was applied to the treatment catchment (32 ha) at a rate of 80 tonnes ha^{-1} using agricultural spreaders and the control catchment (24 ha) was not treated. The P concentration of the water, collected daily by automatic samplers, and discharge rate using a sharp crested 'V' notch weir were monitored for the first year. Only the P concentration was monitored for the subsequent years monitoring to assess the longevity of the P retention by the Alkaloam™. Two fertiliser applications were made to each catchment. The total P application was 20.4 kg P ha^{-1} for the untreated catchment, and 63.4 kg P ha^{-1} for the treated catchment. The higher rate of P on the treated catchment resulted from P in gypsum applied at an equivalent rate of 41.5 kg P ha^{-1}.

The concentration of P in the streamflow from the catchment treated with bauxite residue was consistently lower (median of 0.5 mg L^{-1}) than those from the untreated catchment (up to 5 mg L^{-1}) (Figure 2). There were only two small P spikes in the streamflow from the treated catchment. The first occurred after heavy rain and the second after the second fertiliser application, neither of which reached the levels commonly measured in the untreated catchment. Phosphorus loss to surface drainage from the catchment treated with 80 tonnes ha^{-1} bauxite residue (4.2 kg P ha^{-1}) was reduced by 70% when compared with the untreated catchment (13.8 kg P ha^{-1}). A reduction in P loss of this magnitude continued for five years until monitoring ceased.

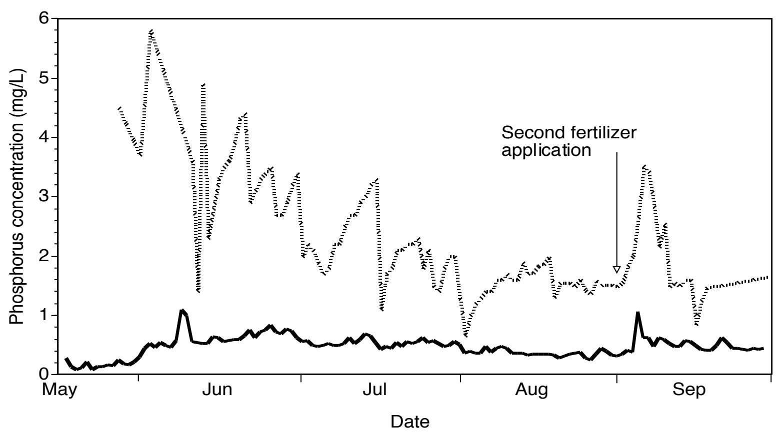

Figure 2. The P concentration in the streamflow from the catchments. The untreated catchment is represented by the dashed line.

AGRICULTURAL PRODUCTIVITY

When Alkaloam™ is applied to the acidic, sandy soils of the Swan Coastal Plain the alkalinity acts to increase pH as well as improving nutrient retention. These changes improve the soil as a medium for growing clover. Trials were established to determine the effect of bauxite residue on clover plant growth and on the effectiveness of the P fertiliser (Summers *et al.*, 2001).. This was achieved by superimposing different amounts of P fertiliser on each of the rates of Alkaloam™. To further test the impact of Alkaloam™ and P uptake over time, another treatment was imposed on the trial. This was achieved by applying P each year to the different treatments of P and Alkaloam™, thereby allowing a picture of how each treatment developed over time by comparing previous applications with freshly applied P. The Alkaloam™ was also compared with agricultural lime.

When 20 tonnes ha^{-1} of Alkaloam™ was applied to the plots, yields of dry matter were doubled when compared with the untreated controls. This was so in the year the Alkaloam™ was applied and in the year after application. As more P is applied to clover the yield increases to a maximum plateau. The Alkaloam™ increased the magnitude of this maximum plateau (see Figure 3). This effect occurred for freshly applied P and for P applied in previous years.

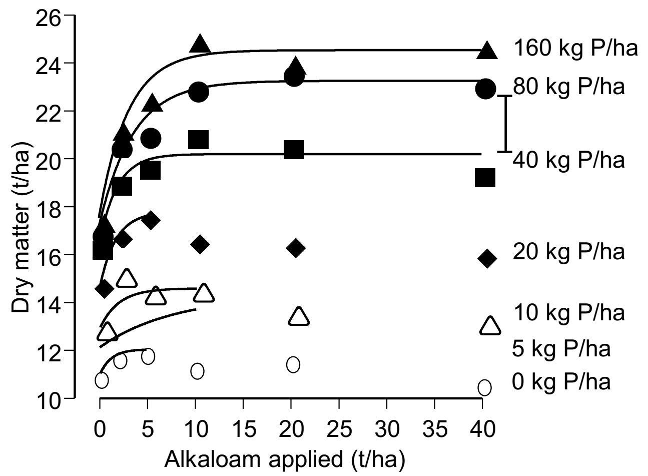

Figure 3. The effect of Alkaloam™ and P fertiliser on yield totalled for all four years of the trial. Not all of the fertiliser application rates could be adequately fitted to the growth curve (Mitserlich). The error bar shows the significant differences ($P > 0.05$) between the means (symbols) (from Summers *et al.*, 2001).

The efficiency of P fertilisers was initially reduced despite the yields being increased by the effect of Alkaloam™ increasing the pH. This increase in P requirement could be attributed to the increased P sorption or precipitation when the fertiliser was in close contact with the freshly applied alkaline Alkaloam™.

When Alkaloam™ had been applied for more than a year, the effectiveness of the P fertiliser was increased, i.e. less P fertiliser was needed to increase the yield on Alkaloam™ treated soil than on untreated soil. Again, overall yields were higher on the Alkaloam™ treated soil due to the increased pH of the soil. This improvement in P effectiveness relative to the first year was likely to be due to the reduction in sorption of P because the soil had neutralised the Alkaloam™ and some of the P already existing in the soil had reduced the capacity of the Alkaloam™ to adsorb freshly applied P.

The Alkaloam™ also had the effect of retaining more P in the soil in a form available for plant growth. These residues of P lasted several years after application. This effect could be seen in increases in plant yield, increases in plant P uptake and increases in plant available P in soil tests (Summers *et al.*, 2001).

METAL UPTAKE BY PLANTS

The uptake of metals by plants grown on Alkaloam™ has been investigated in both clover plants (Summers *et al.*, 1996a) and vegetables (Robertson *et al.*, 1994). Clover was grown in sandy soil treated with up to 80 tonnes ha^{-1} Alkaloam™ analysed for N, P, K, Ca, Cu, Zn, Mg, B, Fe, S, Mo, As, Cd, Hg, Pb, Th and U in the fresh clover pasture and in hay baled from the plots. The concentrations of contaminants in clover tissue were below the detectable limits for all of the rates of Alkaloam™ applied except one control plot without Alkaloam™ and one replicate of the 20 tonnes ha^{-1} Alkaloam™ which had As at 2 $\mu g\ g^{-1}$ (the detectable limit). The concentration of Cd was highest in the controls (0.5 to 1.5 $\mu g\ g^{-1}$) and declined in the clover tissue as the rate of Alkaloam™ increased.

The concentrations of Pb, Th, U, Hg and As in pasture plant tissue were all low and did not increase with increasing application of Alkaloam™. The presence of Cd in the control plots was probably due to the application of superphosphate and the decrease in Cd concentration with increasing Alkaloam™ was probably due to the increase in pH and sorption making the Cd less available. The Cu, Mn and Zn levels rose with the application of Alkaloam™, also likely to be due to the liming effect of the Alkaloam™ making these elements less available. This is similar to the effect of conventional agricultural lime and it is common practice to test pasture for deficiency or apply these nutrient metals when correcting soil pH with lime. Molybdenum increased with the application of Alkaloam™ although not to the point that it could cause Cu deficiency in animals grazing the pasture. Again this is monitored and corrected by applying Cu as is normally the practice with lime application.

The concentrations of contaminants were also investigated in lettuce, cabbage, carrots, onions, potatoes, cauliflower and Chinese cabbage when up to 256 tonnes ha^{-1} of Alkaloam™ (treated with 10% phosphogypsum) was applied There was no increase in the concentrations of any of the heavy metals Cd, Cr, Ni and Pb in carrot roots as the level of Alkaloam™ + gypsum (RMG) increased in the range to 250 tonnes ha^{-1} (Robertson *et al.,* 1994). Decreases in Pb and Cd in the roots and Ni in the leaves were attributed to increases in pH at increasing levels of RMG as well as the increase in iron and aluminium oxides. Similar results were found with Chinese cabbage and onions for the elements Cr, Co, Cu, As, Se, Mo, Cd, Sb, Ba and Pb where Ba, Cu and Ni concentrations decreased with increasing levels of RMG. When lettuce, cauliflower and potatoes were examined, an increase in the concentration of As, Se, Sb, Cr and Ba, was detected which is likely to be due to the increase in pH. However, even with the increase, these levels were always less than 4% of the legal limits.

The leaching of radionuclides (^{232}Th, ^{226}Ra, ^{228}Ra, ^{40}K) from soil amended with RMG at 9 rates (0, 2, 4, 6, 8, 16, 32, 64, 128 and 256 tonnes ha^{-1}) was measured using columns and intense leaching of 34 mm day^{-1} (McPharlin *et al.,* 1994). The increase in ^{232}Th specific activity in Joel sand amended with RMG was well below safety limits even at the highest rate. Neither ^{40}K nor ^{226}Ra were detectable in RMG amended sands up to 256 tonnes RMG ha^{-1}. There was no evidence of leaching of ^{226}Ra or ^{228}Ra at any rate of RMG, where both the treatment and control were less than 40 mBq L^{-1}. The uptake of radionuclides of U, Th, K, Ra, Pb and Cs by lettuce, cauliflower and potato crops is not significantly affected by the application of Alkaloam™ up to 480 tonnes ha^{-1}. Also there is evidence that ^{137}Cs in cabbage plants may be considerably reduced by the application of Alkaloam™. Radiation exposure from radionuclides in vegetable crops grown on soils amended with Alkaloam™ will not be significantly different from those incurred elsewhere (Cooper *et al.*, 1994).

The impact of Alkaloam™ on the background gamma radiation levels has also been studied at a number of field sites on the Swan Coastal Plain in Western Australia. To achieve an increase in the background dose of 1 mSv $year^{-1}$ would require the application of 1500 tonnes ha^{-1} of Alkaloam™ and continuous occupation on the site (O'Connor *et al.*, 1991; Summers *et al.*, 1993) The background radiation level of 0.5 mSv $year^{-1}$ on the Swan Coastal Plain is very low (Toussaint, 1985) and 1500 tonnes ha^{-1} would increase this to 1.5 mSv $year^{-1}$. As a comparison, the background levels of some suburbs on the Darling Scarp adjacent to the Swan Coastal Plain are between 2 and 3.5 mSv $year^{-1}$. Inside brick houses on the Swan Coastal Plain the background dose varies between 1 and 2 mSv $year^{-1}$ (Toussaint pers. comm.).

ENVIRONMENTAL APPROVALS AND MONITORING

As well as authorising the Department of Agriculture to undertake widespread application of Alkaloam™ within the boundaries of the Peel Harvey Catchment, the WA Environmental Protection Authority approval of the project also imposed a number of environmental requirements. These essentially focused on the development of appropriate research and monitoring programmes which should be designed to both prove the efficacy of Alkaloam™ in terms of P retention, and also to test the environmental safety of the material in other regards.

To meet these commitments, an extensive suite of ground and surface water monitoring points has been established throughout the Peel-Harvey region. These points represent an especially important resource in terms of regional water-metal monitoring points as no other agency routinely measures the metal levels in surface or groundwater resources at anything other than extremely long sampling periods. This resource has already been utilised by State and Federal environment agencies for State of the Environment reporting.

Water quality was measured at 22 sites throughout the catchment of the Peel Inlet and Harvey Estuary. Sampling occurred fortnightly during winter, and monthly during summer and has now been continuing for 8 years. The monitoring sites were grouped together to form four different water types: estuarine water bodies, fresh dams and rivers, agricultural drains and artificial water-bodies. The water was analysed for Ag, Al, As, Cu, Cr, F, Hg, P, Pb, N, Se, pH, turbidity, electrical conductivity, and colour.
All water quality information collected so far indicates little significant differences between the concentrations of contaminants in the Meredith Drain water (draining Alkaloam™ amended land) and the water in the other agricultural drains except for reduced P.

Additionally, extensive leachate analysis following the Toxicity Characteristic Leaching Procedure (TCLP) and Australian Standard Leaching Procedure (ASLP) have been undertaken on soil and Alkaloam™ samples. All results indicate that the amendment of catchment soils with Alkaloam™ poses no environmental risk in terms of contaminant export to regional ground and surface waters. TCLP results indicate that Alkaloam™ is stable enough to qualify for disposal in the least secure of municipal landfill sites. Regional vegetation, dust and animal health surveys have also been undertaken through the monitoring programmes. As with the other data sets, no negative environmental impacts have been detected.

CONCLUSIONS

The P retention of Alkaloam™ has been found to be very high and long-lasting when examined at the laboratory, sub-catchment and catchment scales. Alkaloam™ soil amendment has the potential to reduce P load by 25 to 50% at the large catchment scale and is one of the single most effective P reduction methods for diffuse sources of P. From the monitoring data to date, there does not appear to be any significant increase in the discharge of other contaminants from the application of Alkaloam™. The drainage from agricultural land, in general, was very low in heavy metal concentration.

Alkaloam™ increases pasture production when applied at rates between 5 and 80 tonnes ha^{-1}, with most benefit occurring at rates equivalent to traditional agricultural liming rates. Alkaloam™ also produces a liming effect when applied to the surface of the soil, without the need for incorporation into the soil as is the case with crushed limestone.

The development of safe, beneficial soil amendments and fertilisers from the re-use of industrial by-products produces clear benefits for the environment, the agricultural sector and the industries which need to manage these by-products. A win-win-win outcome.

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