Economic and environmental advantages of using fly ash as a soil amendment in agronomy

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Abstract: In this paper we highlight the findings of our ongoing studies on the agronomic use of Australian coal fly ashes in the light of pre-existing concerns that the ashes could cause phytotoxicity and, hence, reduced growth and yield of crops. We tested canola on soil treated with an alkaline fly ash added at up to 625 t/ha, and obtained increases in seed yields with fly-ash rates of not more than 36 t/ha, beyond which there was no further response in yields. Concentration of B was elevated in the leaves with ash addition of 625 t/ha, while that Mo elevated in the leaves and grains with addition of fly ash at all rates, but that of Zn was not affected by addition of fly ash. There was a correlation between plant dry weight and tissue concentration of P at flowering, suggesting that addition of fly ash might have enhanced P nutrition. We found in another experiment that both acidic and alkaline fly ashes applied at not more than 12 t/ha significantly increased the pH of acidic soil by up to a unit of 0.4 within 6 months of soil treatment. Much of the benefits of fly ash in terms of amelioration of acidity and other nutritional benefits could be achieved with fly ash applied at not more than 10 t/ha without any detrimental effects on the environment. Salinity (EC < 4.0 dS/m) and B concentration (<60 mg/kg hot water soluble) are the main criteria for selecting Australian fly ashes for soil amelioration. Developing a sustainable application for fly ash in agriculture should reduce the need for its disposal in landfill, while saving farmers at least 30% the cost associated with treating the soil using lime.

Key-words: agronomy, soil acidity, plant nutrients, phytotoxicity, plant growth

1. Introduction

Soil health as determined by its structural and nutritional characteristics, is a key to viability of agricultural enterprises. Soils in Australia are very old, highly weathered and poor in essential plant nutrients. They have topsoils that are generally low in nutrients while the bottom soils are often dense and poorly permeable to water and plant root. These soils therefore need significant input of nutrients through fertilisation, correction of pH with lime, and structural amelioration through application of gypsum. Furthermore, almost half of the 100 million ha of the agricultural land has pH levels of less than 5.5, with 11 million ha considered extremely acidic (pH < 4.5) [1]. Soil acidification is continuing due to excessive use of fertilizers, increasing inclusion of legumes in farming systems and product removal from the farms. Acidity adversely affects availability of some of the major plant nutrients and structural properties of soil. Fertilisers, agricultural lime and gypsum are therefore common inputs in Australian farming systems.

Coal fly-ash may have significant benefits in the management of these agricultural soils by ameliorating structural and/or chemical constraints to attaining high productivity of horticultural and field crop and of pastures. This is because the ash has unique properties that can ameliorate many of the chemical and structural deficiencies, which cause poor soil health and constraint crop productivity. Results from previous studies were inconsistence on the plant responses to treatment of growth media with coal fly ash [2, 3, 4, 5]. These inconsistent results could be mostly associated with different experimental setup and context (e.g. greenhouse versus field), and differences amongst the ashes, soils and crops used. Developing modalities for sustainable use of fly ash in soil management will benefit the environment by reducing the substantial amounts of the ash that is disposed in landfill, while providing a significant input for the agricultural sector. For instance, more than half of the 13 million tonnes of fly ash produced annually in Australian is disposed in landfill [6]. Meanwhile, production cost for amendments commonly suit to treat soil could be prohibitive. This cost for lime production, for instance, accounts for between 20 and 50% the total cost of using this material to treating soil acidity [1].

Earlier studies in Western Australia have shown that ash application increased productivity of clovers (*Trifolium subterraneum*) [7] and turf (*Cynadon dactylon*) [8, 9] on coastal sands. These studies showed that fly-ash could double the productivity of turf sown on sandy soils, primarily by increasing the water holding capacity and phosphorus availability in the soil.

There is however, a greater potential for fly-ash in the mainstream horticultural and agricultural sector, where high amounts of plant nutrients, including Ca, K, Mg, P and Mo, are removed from the soil and ash application will be of great benefit to supplement these elements. We have been engaged in a series of glasshouse and field studies testing a range of fly ashes on selected crop species in the past few years in Australia. Our ultimate objective is to develop protocols for routine use of fly-ash in soil management. In this paper we briefly highlight progress of this project and the significance of our findings in the light of information available in literature.

2.0 Potential for coal fly ash in Australian Agriculture

Although fly-ash has many of the beneficial characteristics of agricultural lime and gypsum, to-date there has been no studies that systematically examine all the facets of how fly-ash can be employed in soil amendment for field and horticultural crops in Australia. Our overall objective was to explore the potential for a sustainable use of fly ash in managing agricultural soils in terms of:

1. Identifying desirable characteristics of fly-ashes for agronomic applications
2. Potential benefits of fly ash for ameliorate soil acidity
3. Crop yield benefits due to fly-ash
4. Uptake and phytotoxicity of key elements by plants grown with fly ash

2.1 Desirable ash properties for agronomic application

Fly ashes are highly variable in their chemical and physical properties depending on the parent coal and operating conditions of the power plant. As such, we don't expect all fly ashes to be equally effective in ameliorating problems of the soil and/or increasing crop productivity. Although there is considerable homogeneity in the physical properties of ash, for example, most are in the fine sand category, there is a wide range in terms of their chemical properties (Table 1). Well-defined criteria for the selection of fly ash in crop and pasture production is rare in literature. Concentrations of trace metals, dioxins, salinity and pH are key properties that would determine suitability of fly ash for agronomic use. Fly ashes from Australian coals, however, have generally low concentration of trace elements (Table 1) compared with coals from other parts of the world [10]. Hence, concentration of these elements in Australian fly ashes are low and well below the threshold limits set by the US-EPA according to Pathan et al. [9].

Table 1. Concentrations of selected total elements (mg/kg) for Australian and international coal fly ashes

Elements	Australian ashes[1]		International ashes[2]	
	Acidic ash	**Alkaline ash**	**Acidic ash**	**Alkaline ash**
Al (x10^3)	106–134	21.1–60.4	93.9–110.1	*na*
As	7.4–25	0.36–9.8	23–139	322–366
B	7.4–25	11–123	10.2–59.8	7.5–534
B (hot water extractable)	2.5 –9.1	5.4 –13.7	*na*	*na*
Ba	13–4310	61–605	599–1020	311 –3134
Be	13.0–24.0	5.4–8.6		*na*
Cd	0.38–1.34	0.01–0.19	0.4–0.5	1.0–52.4
Co	11.0–100	6.0–44	33–48.5	*na*
Cr	49.6 –130	2.9–34	125–167	23.4–281
Cu	51.6–94	1.8–20	147–395	5.0–47.7
Fe (x10^3)	7.1–86	7.62–343	68.7–86.6	*na*
Pb	59.0–81	1.1–22	14.5	16.1–1075
Mn	88–488	5–157	109–272	*na*
Mo	8.1–21	0.21–4.2	2.9–24.4	3.0–47.7
Hg	0.1–0.08	0.03–0.19	0.3–1.3	0.01–1.4
Ni	41.2–242	1.5–2.1	6.6	13.0–377
Se	1.09–5.15	0.15–5.0	5.1–16.8	2.4–36
Zn	108–283	5.1–305	11.8–233	20–924
	Other constituents (ng/kg)[3]			
Dioxins	<100	<100	*na*	*na*
Furans	<100	<100	*na*	*na*

[1]from Killingly et al. [10] and Yunusa et al. [11]; [2] from literature [12, 13, 14, 15, 16, 17]; [3] from Anon. [18] (2004); *na*, data not available;

Table 2. Responses in the mean pH (± standard errors of means) for soils treated with Australian fly ashes

Soil type	Type of fly ash	Rate of ash applied (t/ha)	Resulting pH
Clay loam (pH = 5.41)	Alkaline (pH = 10.77)	0	4.9 ± 0.03
		12	5.3 ± 0.05
		36	5.1 ± 0.11
		108	5.1 ± 0.10
	Acidic (pH = 3.28)	0	4.9 ± 0.03
		12	5.1 ± 0.08
		36	5.1 ± 0.17
		108	5.0 ± 0.13
Sandy loam (pH = 4.45)		0	4.0 ± 0.07
	Acidic (pH = 3.28)	4	4.1 ± 0.08
	Alkaline (pH = 10.78)	4	4.1 ± 0.08

2.2 Potential benefits of fly ash for ameliorate soil acidity

Fly ashes tend to possess high amount of calcium oxides and related basic components, which would nominally be expected to neutralise soil acidity. They therefore have significant agronomic and economic potential in Australia where about 50 million hectares of land are affected by acidity [1] and costing yield losses of more than $1.5 billion dollars annually [19]. This is however often hampered by the poor pH buffering capacity and liming value of the ash [3], and more so for the Class F than for Class C ashes. Class C ashes are derived from low-rank coals, such as lignites, and are high in CaO (> 10%), alkali and crystalline compounds, but low in silica, while Class F are derived from higher-rank coals, e.g. bituminous coals, and contain only modest concentrations of CaO (< 10%) [20]. We have found, however, that Class F fly ashes, such as those produced in Australia, can provide some neutralisation of soil acidity in some soils. Both fine textured clay loam soil and the coarse textured sandy loam showed increases in pH eight months following treatment with variable amounts of either acidic or alkaline fly ash (Table 2). These increases in pH were achieved at much lower rate (12 t/ha) of ash application than would be expected from short-term titration assessment of liming value of fly ash in the laboratory, which predicted that up to 60 – 80 t/ha of ash would need to obtain liming value equivalent of 1 t/ha of pure lime [21]. Treatment with fly ash also produced increases in the pH of leachate collected during the 5-month growth of canola (*Brassica napus*) in large intact cores of acidic soil [22]

Table 3. Yield characteristics for canola grown on ash-amended soil in the glasshouse.

Ash rate (Mg/ha)	Number of pods/plant	Seed yield (g/plant)	Mean seed weight (mg)
0	59c	2.17b	3.95a
5	75a	2.64a	3.97a
25	65b	2.65a	4.02a
125	60bc	2.42ab	3.53b
625	54c	1.96b	3.49b
SED	5.39	0.364	0.215

Flower numbers were determined from flower stalks soon after flowering. Means within each variable followed by the same letter(s) are similar at $p \leq 0.05$.

2.3 Crop yield benefits due to land application of fly-ash

Growth and yield responses by plant to media treated with fly ash have been highly variable. Where positive responses were reported they were often associated with amelioration of either physical [5], chemical [23] and/or nutritional [8, 7]. Adverse yield outcomes are generally ascribed to phytotoxicity caused by excessive uptake and accumulation of trace elements by the plant [3]. From these previous studies it could be deduced that the crop response depends on the types of soil, fly ash and crop type, but perhaps more significantly the type and rate of fly ash used. When we tested an alkaline fly ash at rates equivalent to 0, 5, 25, 125 and 650 t/ha on canola in a laboratory study, we found a 23% increase in yield with 5 or 25 t/ha of fly ash (Table 3). Other yield attributes were either increased by, or remained benign to, ash applied at up to 125 t/ha, and any reductions in the magnitudes of any of the response variables occurred only when ash rate was raised to 625 t/ha. It is noteworthy that seed yield was not reduced even with ash rate of 625 t/ha. It seemed in this case that fly ash enhanced P nutrition for canola given that we found a significant correlation between plant weights with tissue P at flowering:

$$\text{Shoot weight (g)} = 0.022x - 7.32, \quad r^2 = 0.41, \ n = 48 \qquad (1)$$

where x is P concentration in plant tissue (mg/kg). It had been reported earlier that fly ash enhanced availability and uptake of this P and growth by turf [8].

A later field study in which we applied either an acidic or alkaline fly ash to wheat also showed either benign or increased yield. Taken overall, we observed decreases in plants growth that were supplied with fly ash at rates greater than36 t/ha most probably due to high salinity rather than any particular trace element. This is considered further in the next section below.

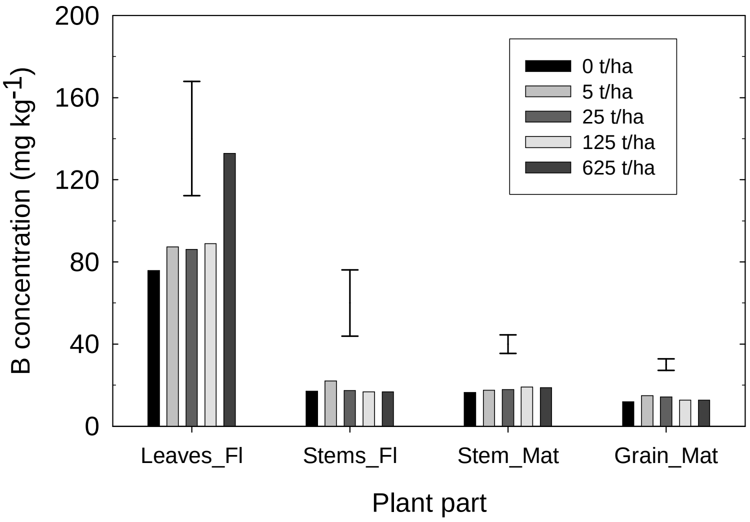

Fig. 1. Accumulation of B in the plant part at flowering (Fl) and at maturity (Mat) for canola supplied with coal fly-ash at rates between 0 and 625 t/ha.

2.4 Uptake and phytotoxicity from elemental content of fly ash

One of the major impediments to routine of fly ash in agricultural soil management is the concern over risk posed by the high levels of trace elements in the fly, which have been classified as being of either major (As, B, Cd, Hg, Mo, Pb and Se) or moderate (Cr, Cu, Ni, V, Zn and F) concern in terms of environmental considerations [24], which is highly relevant to agricultural applications of fly ash. Fly ashes derived from Australian coals generally have low concentrations of these and other trace elements falling well below the threshold limits set by the US-EPA [9]. While dioxins and furans, along with other organic toxins, in these ashes are usually found to be so low as to be reported as “not detected” with most measuring less than the regulatory limit of 100 ng/kg [18]. Earlier studies with Australia fly ashes identified B as the major cause of phytotoxicity in plants [3], and it was the main reason that had precluded utilisation of fly ash as a soil ameliorant, particularly in New South Wales, which is the largest state and producer of fly ash in Australia. Detrimental effect of excessive B on plants is well established [25, 26], but majority of these earlier studies applied excessively large amounts of ash (equivalent to 180 – 1200 t/ha) and also often to limited volume of soil in containers without leaching. In laboratory studies where fly ash was mixed with substrate even at seemingly low rate of just 10% by weight could translate to 180 t/ha in the field. In our study, introduced above, in which canola was grown in six litres of soil, we found no significant elevation in the uptake of B by canola grown with fly ash applied at up to 125 t/ha (Fig. 1). Amongst the other trace elements only Mo showed elevated concentration in the leaves and in the seeds (data not presented), but the latter was below regulatory limit. A follow-up study using large one meter long cores later also showed that B uptake was significantly elevated only when canola was supplied with 108 t/ha of a particular alkaline fly ash, which was noted for having high amounts of hot water extractable B [22]. Similarly field studies where the roots are not confined, plants grown on fly ash treated soil did not suffer B toxicity [4].

Given the generally low contents of trace elements in Australian fly ashes, individual trace elements may pose minimal risk of phytotoxicity if fly ash is applied at agronomically realistic rates. It is most likely that the rather than phytotoxicity caused by a single element, the salinity of ash, which sums the magnitude of total soluble will be of greater concern. Salinity of the ash may be more practical surrogate for assessing trace elemental concentration for fly ashes and suitability for agronomic application.

3.0 Basic protocols in using fly-ash for soil management

Protocols for routine use of fly ash for soil treatment involve several steps, principally:

a. selection of fly ash
b. rate of ash to apply
c. mode of, and precaution in, application Each of these is discussed briefly further.

a. *Selection of ash:* The first step in developing protocols for use of fly ash in land management, especially in an agricultural context, is the choice of ash. It is imperative that application does not exacerbate any pre-existing physical and/or chemical conditions of the soil. The aim in agricultural use of fly ash then is to maintain the soil as near to optimum conditions for plant growth as possible. It is impossible to prescribe detailed guidelines for use of fly ash tailored for the myriad of individual ashes, soils, crops and pastures, and their various combinations. A productive topsoil should have low salinity with its electrical conductivity (EC) of < 1.5.0 dS/m, sodicity measured as sodium absorption ratio (SAR) of < 4.0 and a pH range 6.5–7.5 (http://wwwrrualbertaca/courses/RenR495/course_materialasp). On this basis, a vast majority of Australian fly ashes would be suitable for soil treatment, because they have low salinity and sodicity, along with low concentrations of trace elements as presented in Table 1. The pH of ash is of minor consideration because of the poor buffering capacity of the ash, and selection of the ash for agronomic use can be based on the following criteria:

i. Salinity – this gives a measure of the amounts of soluble salts in the ash, which, if high, may cause soil salinity with prolonged application of ash. Ashes should have electrical conductivity (EC) below 4.0 dS/m, but preferably below 2.0 dS/m.

ii. Boron content – boron is possibly the only element found in considerable amounts in many fly ashes that could be injurious to plants on certain soils. An upper limit of hot water extractable B of 60 mg/kg ash has been set in New South Wales.

iii. Nutrient content – high concentrations of cations (especially calcium, magnesium and potassium) and phosphorus are beneficial to the plant

iv. pH – this may be important in determining the leaching potential of the constituent elements within the ash

b. *Rate of ash to apply*: It is desirable from environmental and economic considerations that rates of fly ash do not exceed that commonly used for other soil amendments such lime and gypsum. From our studies for which some results are presented here (Table 2), the rates should not exceed 10 t/ha, and in most cased less than 5 t/ha.

c. *Mode of, and precaution in, application*: Equipment such as those used applying fine soil amendment such as agricultural lime should be effective in incorporating the ash into the soil. a typical example is the spreader equipped with belt-fed spinner and horizontal discs with radial ribs. Attachment of shrouds to the spreader and/or moistening the ash with about 4% by weight of ash is effective in minimising spray drift. It is important, too, that the ash be incorporated into the top 5–10 cm of the soil.

4. Conclusion

Our studies have shown that the uncertainty over the agronomic potential of Australian fly ashes is largely unfounded and need to be reconsidered. Being mainly Class F and containing low soluble calcium ions, these ashes can still be effective ameliorants of soil acidity. These ashes could also be a significant source of P amongst others for plants. Development and implementation of uniform protocols applicable across all states will establish fly ash to complement, and in some cases substitute, the non-renewable amendments commonly used, such as gypsum and lime. Although our studies showed potential benefits of fly ash in agricultural applications, there are several questions to be addressed. These include uncertainties over the longevity of the benefits of fly ash, loading of trace elements in the soil, bioaccumulation, and offsite effects, under sustained used of fly ash for soil amelioration.

References:

[1] Dolling, P.J., Moody, P., Noble, A., Helyar, K., Hughes, B., Reuter, D., Sparrow, L., 2002. Soil acidity and acidification. National Land and Water Audit. http://nlwra.gov.au/.

[2] Adriano, D.C., T.A.Woodford, and T.G. Ciravolo. 1978. Growth and elemental composition of corn and bean seedlings as influenced by soil application of coal ash. J. Environ. Qual. 7: 416–421.

[3] Aitken, RL and Bell, LC 1985, Plant uptake and phytotoxicity of boron in Australian fly ashes, Plants and Soil, 84, 245–257.

[4] Cline, JA, Bijl, M & Torrenueva, A 2000, Coal fly ash as a soil conditioner for field crops in southern Ontario, Journal of Environmental Quality, 29, 1982–1989

[5] Mishra, M, Sahu, RK & Padhy, RN 2007, Growth, yield and elemental status of rice (Oryza sativa) grown in fly ash-amended soil, Ecotoxicology, 16, 271–278.

[6] Heidrich C., 2003. Ash (CCP's) Utilisation - An Australian Perspective. Proc. International Ash Utilization Symposium, University of Kentucky, Lexington, Kentucky, USA, . April 11-15, CAER. http://www.flyash.info/2003/.

[7] Summers, R, Clarke, M, Pope, T & O'Dea, T 1998, Western Australian fly ash on sandy soils for clover production, Communications in Soil Science and Plant Analysis, 29, 2757–2767.

[8] Pathan, S.M., Aylmore, A.G., Colmer, T.D., 2001. Fly ash amendment of sandy soil to improve water and nutrient use efficiency in turf culture. International Turfgrass Soc. 9, 33-39.

[9] Pathan, SM, Aylmore, LAG & Colmer, TD 2003, Properties of several fly ash materials in relation to use as soil amendments, Journal of Environmental Quality, 32, 687–693.

[10] Killingley J., McEvoy S., Dokumcu C., Stauber J., and Dale L., 2000. Trace element leaching from fly ash from Australian Power Stations. End of Grant Report, Australian Coal Association Research Program, Project C8051, CSIRO Division of Energy Technology.

[11] Yunusa, I.A.M., Eamus, D., DeSilva, D.L, Murray, B.R., Burchett, M.D., Skilbeck, G.C. and Heidrich, C., 2006. Fly-ash: an exploitable resource for management of Australian agricultural soils. Fuel, 85, 2337–2344.

[12] El-Mogazi, D, Lisk, DJ & Weinstein, LH 1988, A review of physical, chemical and biological properties of fly-ash and effects on agricultural ecosystems, Science of the Total Environment, 74, 1–37.

[13] Gupta, DK, Rai, UN, Tripathi, RD & Inouhe, M 2002, Impacts of fly ash on soil and plant responses, Journal of Plant Research, 115, 401–409.

[14] Moreno, N, Querol, X, Andres, JM, Stanton, K, Towler, M, Nugteren, H, Janssen-Jurkovicova, M & Jones, R 2005, Physico-chemical characteristics of European pulverized coal combustion fly ashes, Fuel, 84, 1351–1363.

[15] Schumann, AW & Sumner, ME 2000, Chemical evaluation of nutrient supply from fly ash–biosolids mixtures, Soil Science Society of America Journal, 64, 419–426.

[16] Furr, AK, Kelly, WC, Bache, CA, Gutenmann, WH & Lisk, DJ 1976, Multi-element uptake by vegetables and millet grown in pots on fly ash-amended soil, Journal of Agricultural and Food Chemistry, 24, 885–888.
[17] Furr, AK, Parkinson, TF, Gutenmann, WH, Pakkala, IS & Lisk, DJ 1978, Elemental content of vegetables, grains and forages field-grown on fly ash-amended soil, Journal of Agricultural and Food Chemistry, 26, 357–359.
[18] Anon. 2004, Coal combustion product (CCP) environmental testing programme 2003–2004, Ash Development Association of Australia Inc., Wollongong, NSW, 27 pp.
[19] Hajkowicz, S & Young, M 2005, Costing yield loss from acidity, sodicity and dryland salinity to Australian agriculture, Land Degradation and Development, 16, 417–433.
[20] American Coal Ash Association (ACAA) 1995, Fly ash facts for highway engineers, Report FHWA-SA-94-081, American Coal Ash Association and Federal Highway Administration, National Technical Information Services, Springfield, USA.
[21] Bell, LC & Aitken, RL 1984. The potential for edaphic utilisation of fly ash from Australian power stations. In: Proceedings of Australian Mining Industry Council, Environment Workshop, Kalgoolie, Australia, p 1 -12. 2 -5 October.
[22] Manoharan, V, Yunusa, IAM, Lawrie, R, Skilbeck, GC & Eamus, D 200-, Changes in soil chemical properties and distribution of boron, molybdenum and selenium in soil and plant following application of coal fly ashes to two acidic soils, Fuel, (under review).
[23] Clark, RB, Zeto, SK, Ritchey, KD & Baligar, VC 1999, Boron accumulation by maize grown in acidic soil amended with coal combustion products, Fuel, 78, 179–185.
[24] ACRL, 1996. Trace Elements in Coals: Australian thermal coals generally have low levels of toxic trace elements in comparison to internationally traded thermal coals from other countries. Australian Coal Research Limited; Project 3096. http://www.acarp.com.au/Newsletters/traceelements.html.
[25] Kukier, U & Sumner, ME 1996, Boron availability to plants from coal combustion by-products, Water, Air and Soil Pollution, 87, 93–110.
[26] Matsi T, Keramidas VZ (1999) Fly ash application on two acid soils and its effect on soil salinity, pH, B, P and on ryegrass growth and composition. Environmental Pollution 104, 107-112.