Growth and Elemental Accumulation by Canola on Soil Amended with Coal Fly ash

I. A. M. Yunusa[1,*], V. Manoharan[1], D. L DeSilva[1], D. Eamus[1], B. R. Murray[1] and S. P. Nissanka[2]

[1]*Institute for Water and Environmental Resource Management, and Department of Environmental Sciences, University of Technology, Sydney, PO Box 123, Broadway 2007, Australia*

[2]*Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya, Sri Lanka*

* Corresponding author: isa.yunusa@uts.edu.au; tel: (61) (2) 9514 4086; fax: (61) (2) 9514 4201

Published in Journal of Environmental Quality 37, 1263 – 1270.

Abstract

To explore the agronomic potential of an Australian coal fly ash, we conducted two glasshouse experiments in which we measured chlorophyll fluorescence, CO_2 assimilation (*A*), transpiration, stomatal conductance, biomass accumulation, seed yield and elemental uptake for canola (*Brassica napus*) grown on soil amended with an alkaline fly ash. In Experiment 1, application of up to 25 Mg/ha of fly ash increased *A* and plant weight early in the season, before flowering commenced, and seed yield by up to 21%; but these variables including leaf area and chlorophyll concentration were all reduced at ash rate of 625 Mg/ha. Increases in early vigour and seed yield were associated with enhanced uptake of phosphorus (P) by the plants treated with fly ash. Fly ash application did not influence accumulation of B, Cu, Mo or Zn in the stems at any stage of plant growth or in the seed at harvest, except Mo concentration that was elevated in the seed. Accumulation of these elements was mostly in the leaves, where concentrations of Cu and Mo increased with any amount of ash applied while that of B occurred only with ash applied at 625 Mg/ha. In Experiment 2, fly ash applied at 500 Mg/ha and mixed into the whole 30 cm soil core was detrimental to growth and yield of canola, compared with restricting mixing to 5 or 15 cm depth; whereas at 250 Mg/ha increasing depth of mixing increased *A* and seed yield. We concluded that fly ash applied and mixed into top 15 cm of soil is sufficient to obtain agronomic benefits.

Keywords: boron accumulation, chlorophyll fluorescence, gas exchange, heavy metals, fly ash, seed yield

1.0 Introduction

There is a renewed interest in Australia for developing opportunities for the beneficial use of coal fly ash for agricultural soil management. Australia produces more than 13 million metric tonnes of coal fly ash annually of which less than 40% is effectively utilised, while the balance is emplaced in landfill at substantial cost (Heidrich, 2003). This absence of fly ash application is partly due to concerns over risk of elemental toxicity, but this would appear to be a misplaced fear since Australian coals are noted to have low concentrations of metals that are of concern to the environment and public health (ACRL, 1996). Much of the recent and past efforts in Australia have concentrated on using fly ash to improve water availability to plants on coastal sands. Pathan et al. (2001), for example, obtained a doubling of root mass in turf (*Cynodon dactylon*) grown on ash-amended soil. Yunusa et al. (2006) recently argued, however, that fly ash could be used to ameliorate a range of structural and chemical constraints to crop performance on many of the major agricultural soils in Australia. These could include management of problems such as soil acidity and soil-water dynamics.

Coal fly ash could be a potential source of essential nutrients for plants. For instance, Kuchanwar and Matte (1997) observed yield increases for peanuts (*Arachis hypogaea*) treated with ash at up to 10 Mg/ha, which were at par with yields obtained from NPK (19:38:0 kg/ha) fertiliser. Wallace and Wallace (1989) explained that a 43% increase in the yield for wheat was due to improvements in soil nutrition and concluded that large quantities of fly ash could be disposed on farmlands with little or no risk to the environment. Nutrients commonly associated with yield benefits in crops grown on media amended with fly ash include S (Elseewi et al., 1978), P (Pathan et al., 2002; Matsi et al., 1999), Zn, Mn, Fe and

several trace elements (Khandkar et al., 1996). Other studies, however, have shown that plants grown on ash-amended media suffer from deficiency of several nutrients including N, P, K, Cu, Mn and Zn (Adriano et al., 1978), possibly because they are tied up in the ash (Carlson and Adriano, 1993).

A major impediment to routine agronomic use of fly ash is potential elemental toxicity to crops. The element commonly associated with poor plant growth in soils amended with fly ash is B (Plank et al. 1975; Adriano et al., 1978; Aitken and Bell, 1985; Taylor and Schuman, 1988), although other elements such as Mo, As, Be, Se and Ba have also been mentioned (Adriano et al., 2002). Aitken and Bell (1985) reported that B toxicity reduced growth in beans (*Phaseolus vulgaris*) and Rhodes grass (*Chloris gayana*) grown on sandy soil amended by weight with between 15 and 100% of fly ash by weight of soil. Seed yields for both species were reduced by as much 25% with 15% ash, falling further to 48% in both plants as fly ash was increased to 70%. Also, accumulation of B in the shoot of the beans increased by 2.5- to 6.0-fold, when grown on ash-treated soil, from 88 mg/kg in the absence of fly ash; for the grass the increase was 2.5- to 4.5-fold over the 33 mg/kg in the control. A later study by Aitken and Mccallum (1988) found that once concentration of B rose above 1.9 mg/L in soil solution, sunflower (*Helianthus annuus*) suffered significant growth reductions. The foregoing demonstrates that species differ in their tolerance to B toxicity and possibly to other elemental stresses as well.

Changes in plant growth as a consequence of fly ash treatment could manifest in physiological processes, such as stomatal conductance, transpiration, photosynthetic pigments, and CO_2 assimilation (Srivastava et al., 1995; Gupta et al 2002; Siddiqui and Singh, 2005). Improvements in major nutrient and trace element availability would be

expected to enhance CO_2 assimilation or photosynthesis (Enriquez et al., 2004), whereas elemental toxicity could impair this process through reduced concentration of chlorophyll directly or by substituting Mg into the pigment, which reduces the efficiency of photosystem II (Küpper et al., 1998). In this study, we report how physiological processes, elemental uptake, and seed yield in canola responded to fly ash applied at variable rates and depths into a loamy and a sandy soil. Our main aim was to explore whether application of fly ash is beneficial to this crop and if the ash can be routinely used for soil management.

2. Materials and methods

The study was undertaken in 2004 in a glasshouse equipped to monitor internal temperature and humidity that were logged twice daily at 0900 and 1500 hrs. Soil cores were collected in PVC cylinders of 150 mm internal diameter and 300 mm length. The cylinders were bevelled at one end to ease being pushed into the soil. This study involved two experiments detailed below.

2.1 Experiment 1

In this experiment we compared effects of application of different rates and grades of fly ash on canola grown on loamy or sandy soil types from the teaching farms at University of Western Sydney, Richmond (37^{o} 33’ 35”S, 150^{o} 42’ 00”E), Australia. The loamy soil had 7% more clay, but 12% less sand than the sandy soil. The basic textural and chemical characteristics for these soils are presented in Table 1. The loamy soil had been under various seasonal vegetable crops in the preceding 10 years, while sandy soil had been under various *Acacia* spp in the past six years. The soils were collected with PVC tubes of 150 mm

ID and 300 mm length. Soil was collected into the PVC tubes either by pushing the tubes into the soil and carefully digging them up (Intact cores) or by shovelling soil into the PVC cylinders (Disturbed cores). All cores were sealed at both ends with plastic bags held in place with elastic rubber bands and were carefully transported to the glasshouse where the plastic bags were removed. The core were than transferred onto trays and arranged on benches. An alkaline fly ash was obtained from a power station north of Sydney, Australia. This ash consisted mostly of particle-size in the sandy category (Table 1). Except for B, Cu, Cr, S, Se, Mo and Zn that were higher, concentrations of other cations were either similar to or less, in the ash than in either of the two soils. Extractable B was determined based on hot water extraction (Aitken et al., 1987).

Treatments consisted of four factors involving soil type (loamy or sandy), core type (intact or disturbed), ash grade (fine or unsorted) and rates of ash (0, 5, 25, 125 and 625 Mg/ha), corresponding to 0, 8.84, 44.2, 222 and 1105 g per core. These made a total of 40 treatments that were replicated three times making a total of 120 cores. The ash was mixed thoroughly into top 50 mm of soil cores. The pots were randomly assigned to pre-numbered positions on the benches and later re-randomised around three times during the course of the experiment. The cores were watered twice daily at a rate of 40 ml/min for 3 mins for the first four weeks. After this time, watering regime was maintained to supply enough water to avoid stressing the plants, while avoiding drainage from beneath the pots. The pre-installed fans were switched on for extended periods during flowering to facilitate pollination.

2.1.1 Plant material

Canola variety Surpass 603CL (Pacific seeds, Toowoomba) was used in this study. Ten seeds were sown per pot at 10–20 mm depth on 26th March 2004 and the pots gently watered. Three weeks later on 14th April 2004 each pot was given 200 ml of "Thrive" liquid fertiliser (8:3:8, NPK) (Yates Garden Supples, Australia), and then once every four weeks until flowering in late July. The plants were closely monitored for fungal and pest attacks, and were treated with insecticide (Tau-fluvalinate and myclobutanil) against aphids and with fungicide (polysulphide sulphur) to control damping off and other fungal infection. Weeds were manually removed from the cores.

2.1.2 Plant sampling for growth

Emergence of seedlings occurred within 5 days on all cores and number of seedlings was counted at 20 days after sowing (DAS) to calculate percentage germination. The plants on each were progressively thinned to 4 at 27 DAS, then to 3 plants at 47 DAS and finally to 2 at 83 DAS when plants were at early flowering stage. At each thinning exercise, the plants removed were collected in paper bags, dried in oven at 45 ^{o}C for 7 days and then weighed to estimate biomass or dry matter (DM) accumulation.

2.1.3 Chlorophyll fluorescence

We used a Mini PAM (Walz GmbH, Germany) to measure effective quantum yield on 24 May (60 DAS) and 20 July (117 DAS), expressed as the ratio of photon absorbed to photons emitted through fluorescence $\Delta F/F'$m, in which ΔF is the difference between instantaneous fluorescence and the maximum fluorescence in a light-adapted state (F'm). F'm is obtained by applying a saturating flash of irradiance (8000 mmol m^{-2} s^{-1} for 1 s) to the leaf to fully

reduce electron receptors of photosystem II. Instantaneous fluorescence (F) is obtained from application of constant illumination to activate carbon fixation and onset of photochemical and heat dissipation processes. The ΔF is taken as F'm - F as a measure of efficiency of photosystem II, and hence the general capacity to fix CO_2 (Küpper et al., 1998) and to accumulate biomass. Details of the technique and the underlying principles have been reported (Van Kooten & Snell 1990, Macinnis-Ng and Ralph, 2003). Measurements were made between 1030 and1100 hrs AEST, under natural light conditions.

2.1.4 Photosynthesis, transpiration & stomatal conductance

Photosynthesis was assessed by determining the rate of CO_2 assimilation (*A*) and was measured along with transpiration and stomatal conductance on tagged youngest fully expanded leaves on 10 and 26 May, 9 and 30 June and 14 July corresponding to 46, 62, 76, 97 and 111 DAS, respectively. We monitored *A* with a portable photosynthesis system (Walz Portable Photosynthesis System, HCM-1000, Heinz Walz GmbH, Germany) with all measurements made under constant artificial illumination (350 μmol m^{-2} s^{-1} at leaf level) from a metal halide lamp 400 W (Lowbay Luminaire, Blackwoods, Smithfield, Australia). The equipment also monitored stomatal conductance (g_s) and transpiration simultaneously with *A*.

2.1.5 Seed yield and quality

At final harvest on 22 October (211 DAS), flower stalks and pods were counted on each plant. The pods were then removed into bags and then threshed by hand to recover the seeds, which were dried in an oven at 40 ^{o}C for 48 hours before being weighed to determine seed

yields. The total number of seeds produced per plant was counted, and 100 seeds were counted and weighed from each core to estimate mean grain weight (MGW).

2.1.6 Chemical analysis of plants

This analysis was performed on leaves and stems of plants sampled on 83 DAS (16 July) at start of flowering, and on stems and seeds taken at final harvest. The samples were ground in a stainless steel ball mill, acid digested using analytical grade (AR) concentrated HNO_3 and 20% H_2O_2 and then analysed using Inductively Coupled Plasma-Optical Emission Spectrometer (ICPOES) or Inductively Coupled Plasma-Mass Spectrometer (ICPMS).

2.2 Experiment 2

We evaluated how depths of mixing ash into the soil influenced canola physiology, growth and seed yield in this experiment, and used the same ash and similar size of cores to those used in Experiment 1. The cores contained intact loamy soil that were taken as was done in Experiment 1, and the coarse ash applied at three rates equivalent to 0, 250 and 500 Mg ha^{-1}. The ash was then mixed with the soil to depths of 50, 150 or 300 mm. The soil and ash were mixed as required and 15 seeds were sown in each core on 17 May. The cores were watered regularly to ensure that neither water-stress nor drainage from the cores occurred throughout the experiment. Each core received 200 ml of liquid fertiliser Thrive® (12.4 N: 3.0 P: 6.2 K, and some trace elements) four times during growth, while weeds, diseases and other pests were controlled as described in Experiment 1.

We recorded number of days to seedling emergence. Plant numbers were thinned to 4 plants per core at 45 DAS and finally to 2 plants/core at flowering at 86 DAS. We used portable photosynthesis system to measure net assimilation rate and quantum yield during flowering at 90 DAS following the same procedures as used in Experiment 1. The 2 plants left in each core were harvested at 159 DAS (22 October), and we determined final plant height, seed yield and seed size.

2.3 Statistical analysis

All the data were analysed using general linear models (SPSS version 12, SPSS Inc., USA). We used Turkey *post hoc* tests to determine significant differences between treatment groups. Log transformation of the data was made before analyses as there were indications that the variances were not normally distributed. If the transformation failed to normalise the variance, the ANOVA was undertaken on the form of data that produced the highest *P* for homogeneity, and the results interpreted cautiously. Treatment means were compared for statistical differences at 95% level of probability ($p \leq 0.05$).

3. Results

3.1 Conditions inside the glasshouse

The weather inside the glasshouse was generally warm and humid. Monthly averages for minimum and maximum temperature were 11 ^{o}C and 27 ^{o}C, respectively. Temperatures remained largely stable for much of the study period, showing small falls during the winter months (June –August), when these averages fell to 10.5 and 24 ^{o}C respectively. The relative

243 humidity fluctuated within 80 – 95% range during the study, mostly due to frequent irrigate
244 of other experiments going on at the time. To facilitate comparison with field based studies,
245 the time intervals are given in growing degree days (GDD) taking 0 ^{o}C as base temperature.
246
247 *3.2 Experiment 1*
248
249 Germination was observed within one week in all pots and by 800 GDD within three weeks
250 after sowing, at least 80% of seeds had germinated and the seedlings well established.
251 Germination and establishment were not significantly affected by treatments. The plants
252 started flowering around 1722 GDD and attained 50% flowering at 2260 GDD on 16 July.
253 Maturity was recorded at 3520 GDD on 22 September (181 DAS).
254
255 *3.2.1 Plant physiology, yield and yield components*
256
257 Treatment with ash did not have a significant effect on quantum yield (QY) in the mid-
258 season (Table 2), indicating stability in chlorophyll function in canola. At the start of
259 flowering (1722 GDD), concentration of chlorophyll in the leaf was, however, reduced in
260 plants treated with 125 Mg/ha or more of ash, but by start of flowering this was reduced only
261 in plants supplied with 625 Mg/ha. This reduction was as high as 16% during mid-season,
262 but was only 6% at start of flowering. Treatment with fly ash increased gas exchange and
263 stomatal conductance early in the season (Fig. 1). At 1330 GDD, *A* was almost 29% larger
264 for plants supplied with 5 Mg/ha compared to those that did not receive ash. Response in the
265 rate of g_s was generally similar to that in *A*, increasing with ash rates early in the season
266 before onset of flowering. There was no significant influence of fly ash on transpiration,
267 which was similar for all plants during the study.

Application of fly ash at 625 Mg/ha reduced leaf area at 1290 GDD (60 DAS) by at least 22% (Table 2), but dry weight for plants measured at the same sampling time was increased by 52% with 5 Mg/ha of fly ash (Fig. 2). There was a gradual decline in plant weight with increasing ash rate beyond 25 Mg/ha such that plant weight at 625 Mg/ha of fly ash was only 60% that for control and 40% that for 5 Mg/ha. Plant weight at flowering was also reduced significantly with fly ash of 625 Mg/ha compared control and either 5 or 25 Mg/ha.

Fly ash applied at either 5 or 25 Mg/ha increased number of flowers and of pods produced, while rates of 125 or 625 Mg/ha either produced no benefit or reduced these variables (Table 3). These differences in flowers and pods were not reflected in the amount of seeds produced. There was considerable shattering of pods at final harvest that resulted in loss of seeds. However application of fly ash of up to 25 Mg/ha increased seed yield by at least 21% compared to control, but yield fell by 10% with fly ash at 625 Mg/ha. The weight of individual seeds was not affected by application of fly ash.

3.2.2 Elemental uptake by canola

Application of fly ash increased concentrations of B, Cu and Mo in the leaves at flowering, while accumulation of other elements was not affected by treatment (Fig. 3). There was a significant concentration of B in leaves only at 625 Mg/ha, while both Cu and Mo both increased at all rates of ash, compared to control treatment. B in leaves at 625 Mg/ha was 80% more than we found in control. Application of fly ash did not affect concentrations of any of the elements in the stems, except for Mo that had greater concentration in stems of plants grown on ash-treated soil compared to those in control. There was a general decline in

293 the concentrations of elements in stems between flowering and maturity, except B that
294 remained steady while P increased, in all treatments. Seeds accumulated substantial amounts
295 of Mo, P and Zn, to at least the same concentration as found in the leaves earlier at
296 flowering. It is noteworthy that application of fly ash promoted accumulation of Mo only in
297 the grains; this increased at least 3-fold with application of fly ash compared to the control
298 (Fig. 3e).
299
300 Of all the elements we analysed only P showed any correlation with any of the plant
301 variables we measured. Plant dry weight at start of flowering (1039 GDD) was correlated
302 with total (leaf and stem) P content measured at the same time (Fig. 4). This relationship
303 indicates that P in fly ash enhanced early growth in canola.
304
305 *3.3 Experiment 2*
306
307 Germination was observed within one week in all cores, and by 380 GDD (three weeks after
308 sowing), at least 80% of seeds had germinated and the seedlings well established.
309 Germination and establishment were not significantly affected by treatments. The plants
310 attained flowering at 1465 GDD (6 August) and maturity at 2736 GDD (9 Oct), or 82 and
311 146 DAS respectively. There were significant interactions between rate and depth of
312 application of fly ash on variables of canola growth that we measured (Table 4). When the
313 ash was applied at 500 Mg/ha by mixing it into the whole 30 cm depth soil column growth
314 and yield variables were reduced, compared with restricting the addition to either 5.0 or 15
315 cm depths. Whereas applying fly ash at 250 Mg/ha mixed into the whole 30 cm core
316 increased both *A* and seed yield, compared with treating only the shallower depths of 5.0 or
317 15 cm. On the whole, there was no difference between the mean effects of rates of ash

addition, but applying ash to the whole 30 cm profile of the soil decreased *A*, shoot weight at flowering and plant height at maturity.

4.0 Discussion

Application of coal fly ash at moderate rates enhanced early vigour increasing plant weight by as much as 20% in canola treated with 5 Mg/ha of ash. This increase in early growth was associated with P accumulation in the shoot (stems and leaves) with which dry weight was correlated at flowering (Fig. 4). An earlier study by Pathan et al. (2001) found that unweathered fly ash contained as much as 410 mg/kg of extractable P, and when applied to a sandy soil increased extractable P by at least a factor of two, from 19 mg/kg to more than 43 mg/kg. They however found no difference in the concentration of P the tissue of turf (*Cynodon dactylon*) due to sufficient supply of this nutrient from the applied fertiliser. Several other studies have associated improvements in growth and/or yield with enhanced P uptake from media amended with fly ash for species such as corn (Sims et al., 1995) and ryegrass (Matsi et al., 1999). Although our soils had high total P (Table 1), most of it must have been in non-extractable forms, but addition of fly ash would have promoted solubilisation. An increase of just 20% in solubilisation of total P in the ash-soil mixture would have provided additional 35 mg of P for the plants supplied with 5 Mg/ha.

Fly ash became particularly detrimental to canola growth only when rate of application exceeded 25 Mg/ha (Fig. 2). The initial poor growth for plants supplied with 25 and 125 Mg/ha was overcome with the plants producing dry weights similar to those in the control and in the 5 Mg/ha treatment at maturity, when only plants treated with 625 Mg/ha of ash suffered reductions in weight. This suggests that any detrimental effect on canola from

application of moderate rates of fly ash was transitional so that from mid-season onwards there was similarity in the physiological processes for the plants irrespective of amount of ash additions (Fig. 1). Declines in these physiological processes in all treatments from mid-season onwards could not be due to environmental stress such as high vapour pressure deficit or limited water supply (Nissanka et al., 1997; Yunusa et al., 2005), but most likely to age and ontogeny. Lewis et al. (2002) found that narrowing the gap between capacities of source and sink, as a determinate plant grows older, often leads to declines in photosynthesis.

Phytotoxicity caused by B is widely associated with reduced plant growth on media amended with fly ash (Plank et al., 1975; Aitken and Bell, 1985; Matsi and Keramidis, 2001). Results presented show that either ash additions of up to 125 Mg/ha was not high enough to cause phytotoxicity, or that canola was tolerant of moderate levels of B, or both. These results were contrary to those reported by Aitken and Bell (1985) who applied fly ash at between 15 and 100% by weight of soil, which was equivalent to between 180 and 1200 Mg/ha if applied to the top 10 cm of a field soil having a bulk density of 1.2; these rates were well beyond what would be appropriate for routine agronomic use. Furthermore, they grew the plants in only 2 kg of soil thereby confining the root systems to a substrate that was highly fortified with B (and salt) throughout the growing period. Excessively large amounts of fly ash (216 or 288 Mg/ha) used by Plank et al. (1975) could also be the major cause of phytotoxicity suffered by corn (*Zea mays*). Another feature of our current study is the use of fine textured soil, which had high capacity to adsorb B and so limits its availability to the plant, unlike the coarse soil used by Aitken and Bell (1985) that generally have low capacity for elemental adsorption (Matsi and Keramidas, 2001). This phenomenon was demonstrated by Plank et al (1975) who reported that B concentration in leaf increased by between 9 and 21% on a silt loam soil, by up to 78% on loamy sand, compared with control plants that had

6.8 mg/kg on the silty soil and just 4.7 mg/kg on sandy soil. The study of Aitken and Bell (1985) also showed differences amongst species in their accumulation of B, which was 33 mg/kg in the grass compared with 88 mg/kg in the beans, due to possible differences between the species in their rate and partitioning of this element (Wimmer et al., 2005).

Reductions in plant biomass at high rates of fly ash were consistent with declines in *A* early in the season (Fig. 1). These reductions did not seem to have resulted from impaired efficiency of the photosynthetic mechanism since QY was unaffected. Küpper et al. (1998) discussed how photosynthetic efficiency could be impaired by substitution of Mg in chloroplast with any other elements such as Cu, Hg, Ni, Pb and Zn when they accumulate in large amounts in the leaf. Of all the metals we analysed, only Cu accumulation was elevated in the leaf of plants treated with fly ash (Fig. 3), but we found no significant correlation between any of the growth variables with accumulation of any of the metals. Reductions in biomass and *A* at high rates of fly ash could in part be associated with declines in the concentrations of chlorophyll (Table 2). Furthermore, improvements in early growth and in number of flowers produced in Experiment 1 (Table 3) were not significantly correlated with seed yield, most probably because of pod shattering mentioned earlier.

It is also possible that poor growth and yield of canola at high rates of fly ash were simply due to salinity resulting from relatively large amounts of soluble salts in the ash (data not presented). Although canola is often regarded as a tolerant of high salinities, varieties differ widely in this regard (Francois, 1994). An assessment of canola on saline scotched land found a linear decline yield when salinity exceeded 0.5 dS/m (McCallum et al., 2001). We found no significant correlation ($p \leq 0.05$) between any growth variable and accumulation of

any of the metals analysed, but the combined effects of salinity and metal accumulation could have restrained growth and yield of canola when fly ash was applied at 625 Mg/ha.

Responses in physiological and other growth and yield variables in Experiment 2 could be associated with benefits of P and detrimental effects of salinity resulting from treatment with fly ash. At relatively low rate of 250 Mg/ha, mixing fly ash into the whole of the soil profile ensured access to P by all the roots, while diluting salinity level, throughout the soil profile resulting in increased yield (Table 4). Applying fly ash at 500 Mg/ha to shallow layers, however, meant large portions of the soil remained relatively favourable for root growth and function. The deep roots that experienced minimal impediment are able to function close to normality, while the shallow roots in ash-treated layer were able to access nutrients, especially P, from the ash. Whereas applying large amounts of ash to most or whole of the soil profile meant that majority or all of the roots were exposed to soil of high salinity and elevated metal concentrations.

Concluding remarks

Results presented in this study show that fly ash at low to moderate rates of up to 25 Mg/ha enhanced growth and yield variables in canola. At these low rates, ash can be applied to soil at depths similar to those used for soil amendments such as lime and gypsum, because toxicity due to salinity will be negligible at these low rates of fly ash. At these low rates, there was no evidence of excessive bioaccumulation of any element that we assessed; even the elevated accumulation of Mo in the seed was well below regulatory limit to be of any concern. It was only on soil supplied with 625 Mg/ha that plant physiological processes were adversely affected with subsequent penalty on growth and yield, even though canola

established successfully. The adverse effects of high rates of fly ash was most probably due to salinity and/or B toxicity, none of which was manifested at 125 Mg/ha or less of fly ash. We concluded that that this fly ash applied at rates of not more than 25 Mg/ha and mixed into top 15 cm of soil is sufficient to provide some yield benefits to the crop. Future studies with Australian fly ashes should involve field evaluation of interactions between different ashes and a range of soils and crop types.

Acknowledgement

We acknowledge the many discussions we had with Professor Margaret Burchett during this study, and appreciate with thanks the assistance from Narelle Richardson, Gemma Armstrong and Bill Briggs. We thank Dustin Hobbs, Aining Mao and Aisha Yunusa for assistance with sample collection and analysis, and also Professor Jan Conroy, Dr Philip Groom and Mr Steve Clark for providing access to the research farm at the University of Western Sydney. Canola seeds were kindly supplied by Pacific Seeds, Australia. We acknowledge Dr Cate Macinnis-Ng and Associate Professor Peter Ralph for their advice on techniques for chlorophyll fluorescence and gas exchange. We thank the two anonymous referees for their comments on the manuscript. This study was supported by the Ash Development Association of Australia, which along with Australian Research Council co-funded this project, and we apreciate the support of Mr Craig Heidrich.

References

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

442 countries. Australian Coal Research Limited; Project 3096.
443 http://www.acarp.com.au/Newsletters/traceelements.html. (Accessed: 23 April 2006).
444 Adriano, D.C., J.Weber, N.S. Bolan, S. Paramasivam, B-J. Koo, and K.S. Sajwan. 2002.
445 Effects of high rates of coal fly ash on soil, turfgrass, and groundwater quality. Water,
446 Air Soil Pollut. 139: 365 –385.
447 Adriano, D.C., T.A.Woodford, and T.G. Ciravolo. 1978. Growth and elemental composition
448 of corn and bean seedlings as influenced by soil application of coal ash. J. Environ.
449 Qual. 7: 416–421.
450 Aitken, R.L. and L.C. Bell. 1985. Plant uptake and phytotoxicity to boron in Australian fly
451 ashes. Plant Soil, 84: 245-257.
452 Aitken, R. L., A.J. Jeffrey, and B. L. Compton. 1987. Evaluation of Selected Extractants for
453 Boron in Some Queensland Soils. Aust. J. Soil Res. 25: 263-273.
454 Aitken, R.L. and L.E. Mccallum. 1988. Boron toxicity in soil solution. Aust. J. Soil Res. 26:
455 605 – 610.
456 Carlson, C. L. and D. C. Adriano. 1993. Environmental impacts of coal combustion residues.
457 J. Environ. Qual. 22: 227-247.
458 Elseewi, A.A., F.T. Binghum and A.L. Page. 1978. Availability of sulphur in fly ash to
459 plants. J. Environ. Qual. 7: 416 – 421.
460 Enriquez, S., N. Marba, J. Cebrian, and C.M.Duarte. 2004. Annual variation in leaf
461 photosynthesis and leaf nutrient content of four Mediterranean seagrasses. Bot. Marina
462 47: 295 –306.
463 Francois, L.E. 1994. Growth, seed yield, and oil content of canola grown under saline
464 conditions. Agron. J. 82: 233 – 237.
465 Gupta, D.K., U.N. Rai, R.D. Tripathi, M. Inouhe. 2002. Impacts of fly ash on soil and plant
466 responses. J. Plant Res. 115: 401-409.

467 Heidrich, C. 2003. Ash (CCP's) Utilisation - An Australian Perspective. Proc. International
468 Ash Utilization Symposium. April 11-15, CAER, University of Kentucky, Lexington,
469 Kentucky, USA.
470 Khandkar, U.R, M.S. Gangwar, P.C. Srivastava, and M. Sigh. 1996. Effect of coal fly ash
471 application on the elemental composition and yields of some crops and on the
472 properties of calcareous soil. Acta Agron. Hung. 44: 141 –151.
473 Kuchanwar, O.D. and D.B. Matte. 1997. Study of graded doses of flyash and fertilisers on
474 growth and yield of groundnut *Arachis hypogaea* L. J. Soils Crops 7: 36 – 38.
475 Küpper, H., F. Küpper, and M. Spiller. 1998. *In situ* substitution of heavymetal substituted
476 chlorophylls in water plants. Photosyn. Res. 58: 123 –133.
477 Lewis, J.D., X.Z. Wang, K.L. Griffin, and D.T., Tissue. 2002. Effects of age and ontogeny
478 on photosynthetic responses of a determinate annual plant to elevated CO2
479 concentrations. Plant Cell Environ. 25: 359 –368.
480 McCallum, M.H., J.S. Salmon, and J.F. Angus. 2001. A case study to reduce dryland salinity
481 on a Temora farm. Proc. 10th Australian Agron Conf., Hobart.
482 http://www.regional.org.au/au/asa/2001/3/b/mcallum.htm (Accessed: 18 April 2006).
483 Macinnis-Ng, C.M.O. and P.J. Ralph. 2003. In situ impact of petrochemicals on the
484 photosynthesis of the seagrass *Zostera capriconi*. Marine Pollut. Bull. 46: 1395 –1407.
485 Matsi, T. and V.Z. Keramidas. 1999. Fly ash application on two acid soils and its effect on
486 soil salinity, pH, B, P and on ryegrass growth and composition. Environ. Pollut. 104,
487 107 –112.
488 Matsi, T. and V.Z. Keramidas. 2001. Alkaline fly ash effects on boron sorption and
489 desroption in soil. Soil Sci. Soc. Am. J. 65, 1101 – 1108.
490 Nissanka, S.P., M.A Dixon, and M.Tollenaar. 1997. Canopy gas exchange response to
491 moisture stress in old and new maize hybrid. Crop Sci. 37: 172–181.

492 Pathan, S.M., L.A.G. Aylmore, and T.D. Colmer. 2002. Reduced leaching of nitrate,
493 ammonium, and phosphorus in a sandy soil by fly ash amendment. Aust. J. Soil Res.
494 40: 1201 –1211.

495 Pathan, S.M., L.A.G. Aylmore, T. D. Colmer. 2003. Soil properties and turf growth on a
496 sandy soil amended with fly ash. Plant Soil 256: 103-114

497 Plank, C.O, D.C. Martens, and D.L Hallock. 1975. Effect of soil application of fly ash on
498 chemical composition and yield of corn (*Zea mays* L.) and on chemical composition of
499 displaced soil solutions. Plant Soil, 42: 465 – 476.

500 Sims, J.T., B.L. Vasilas and M. Ghodrati. 1995. Evaluation of fly-ash as a soil
501 amendment for the Atlantic Coastal-Plain .2. Soil chemical-properties and crop
502 growth. Water Air Soil Pollut. 81, 363 – 372.

503 Srivastava, K., A. Farooqui, K. Kulshreshtha, and K.J. Ahmad. 1995. Effect of fly ash
504 amended soil on growth of *lactuca-sativa* L. J. Environ. Biol. 16: 93-96.

505 Taylor Jr., E.M. and G.E. Schuman. 1988. Fly ash and lime amendment of acid coal spoil to
506 aid revegetation. J. Environ. Qual. 17: 120 – 124.

507 Wallace, A. and G.A. Wallace. 1986. Enhancement of the effects of coal fly ash by a
508 polyacryamide soil conditioner on growth of wheat. Soil Sci. 141: 387–389.

509 Wimmer, M.A., E.A. Bassil, P.H. Brown, and A. Läuchli. 2005. Boron response in wheat is
510 genotype-dependent and related to boron uptake, translocation, allocation, plant
511 phenological development and growth rate. Functional Plant Biol. 32: 507–515.

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

515 Yunusa, I.A.M., S.E. Thomson, K.P. Pollock, L. Youwei, and D.J. Mead. 2005. Water
516 potential and gas exchange did not reflect performance of *Pinus radiata* D. Don in an

agroforestry system under conditions of soil-water deficit in a temperate environment. Plant Soil, 275: 195–206.

520 Table 1. Selected chemical properties for fly ash and soils used in the study.

521

Property	Fly ash	Loamy soil	Sandy soil
Proportions (%) of particles in the various size-classes (μm)			
≤2 (clay)	0	10.9	3.3
2–20 (silt)	0	17.4	13.1
20–200 (sand)	100	71.7	83.6
pH	10.2	6.57	6.38
EC (dS/m)	0.66	0.41	0.35
CEC (cmol/kg)	0.9	4.90	5.95
Elemental concentrations (mg/kg)			
B	66	18.0	5.0
B (extractable)	6.7	0.48	0.44
Na	210	85	20
Ca	2100	2000	1400
Mg	500	430	280
P	200	1000	700
K	1300	2500	800
Cu	18.0	13.0	7.6
Cr	42.0	10.0	3.5
Pb	9.4	15.0	8.7
S	200	74	73
Se	3.7	0.2	0.1
Mo	6.1	0.5	<0.3
Zn	56	29.0	16.0

522

523

Table 2. Growth characteristics for canola measured at two growing degree days (GDD) on ash-amended soil during Experiment 1: mean leaf area per plant, quantum yield (QY) and chlorophyll content of leaves.

Ash rate (Mg/ha)	Leaf area (cm^2) at 1290 GDD	QY		Chlorophyll conc. (µg/g)	
		1290 GDD	1722 GDD	1290 GDD	1722 GDD
0	334a	0.77	0.74	49.0a	49.8a
5	316a	0.74	0.74	50.4a	52.6a
25	322a	0.77	0.75	48.0a	51.2a
125	314a	0.75	0.76	45.6b	49.4a
625	244b	0.75	0.76	41.4c	46.8b
SED	20.0	0.034	0.058	3.10	4.32

GDD of 1290 and 1722 correspond with 60 and 83 days after sowing, the latter was early flowering phase. Means within each variable followed by the same letter(s) are similar at $p \leq 0.05$

533 Table 3. Yield characteristics for canola grown on ash-amended soil during

534 Experiment 1.

535

Ash rate (Mg/ha)	Number of flowers/plant	Number of pods/plant	Seed yield (g/plant)	Mean seed weight (mg)
0	145b	59c	2.17b	3.95a
5	174a	75a	2.64a	3.97a
25	156ab	65b	2.65a	4.02a
125	148b	60bc	2.42ab	3.53b
625	125c	54c	1.96b	3.49b
SED	21.3	5.39	0.364	0.215

536 Flower numbers were determined from flower stalks soon after flowering. Means within each

537 variable followed by the same letter(s) are similar at $p \leq 0.05$

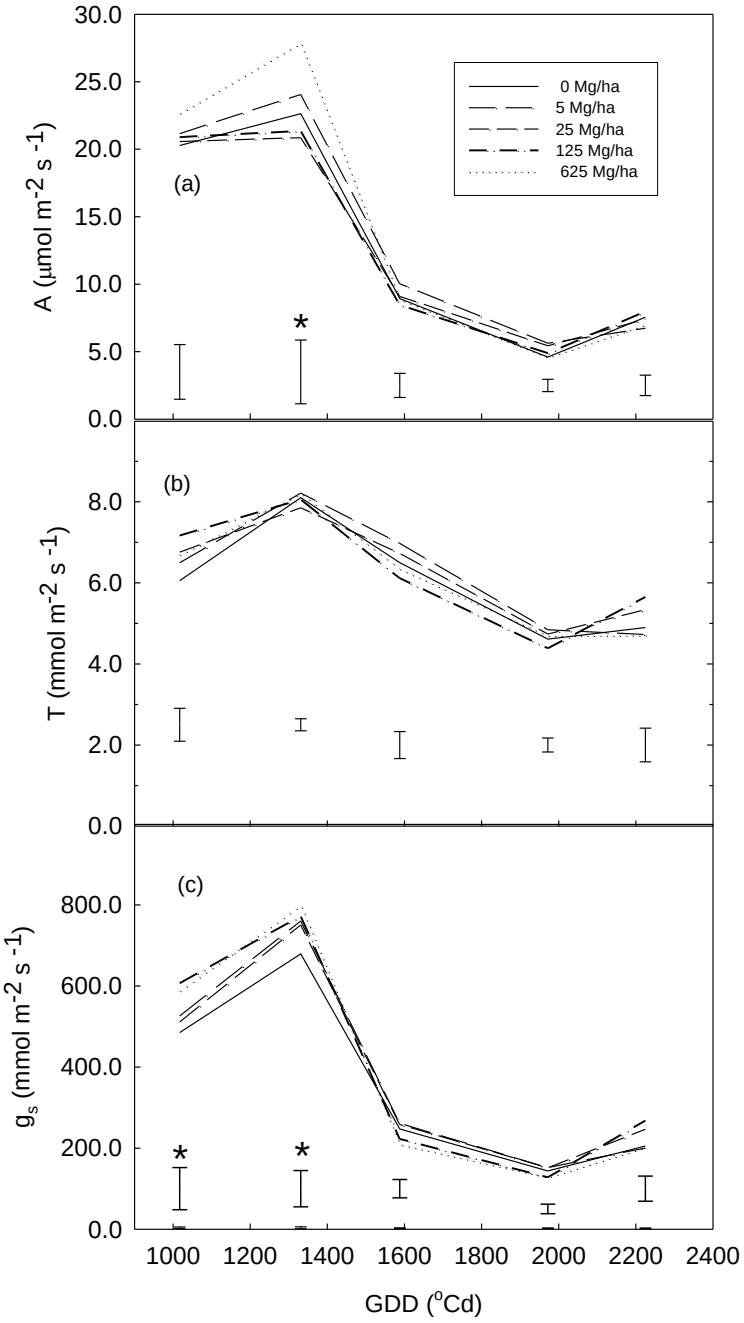
538

Table 4. Selected plant variables for canola grown with different rates of fly ash that was mixed into soil at different depths during Experiment 2.

Depth of application (cm)	Ash rate (Mg/ha) 250	500	Mean
Leaf area per plant (cm^2) at flowering			
5	292b	434a	363A
15	286b	369ab	327A
30	357ab	98c	227A
Mean	311A	300A	
A ($\mu mol\ m^{-2}\ s^{-1}$) at flowering			
5	8.13a	6.56ab	7.34A
15	8.68a	8.68a	8.68A
30	5.80b	5.43b	5.61B
Mean	7.53A	6.88A	
Shoot dry weight (g/plant) at flowering			
5	8.3a	11.7a	10.0A
15	8.9a	11.3a	10.1A
30	10.8a	2.6b	5.6B
Mean	9.3A	8.5A	
Plant height at maturity (cm)			
5	115b	142a	129A
15	105b	126ab	115A
30	115b	61c	88B
Mean	112A	110A	
Seed yield (g/plant)			
5	3.03b	4.93a	3.98A
15	3.70b	3.83b	3.77A
30	4.60a	1.94c	3.27A
Mean	3.77A	3.57A	
Mean seed weight (mg/seed)			
5	3.44a	3.36a	3.40A
15	3.17a	3.85a	3.51A
30	3.35a	3.16a	3.25A
Mean	3.32A	3.46A	

Within each variable, means followed by the same letter(s) are similar at $p \leq 0.05$; small letters compare depth x rate interactions, and capital letters main effects of either depth (column) or ash rate (row)

544



545

546

547 **Fig. 1. Response in physiological variables of canola to soil amended with fly ash during**

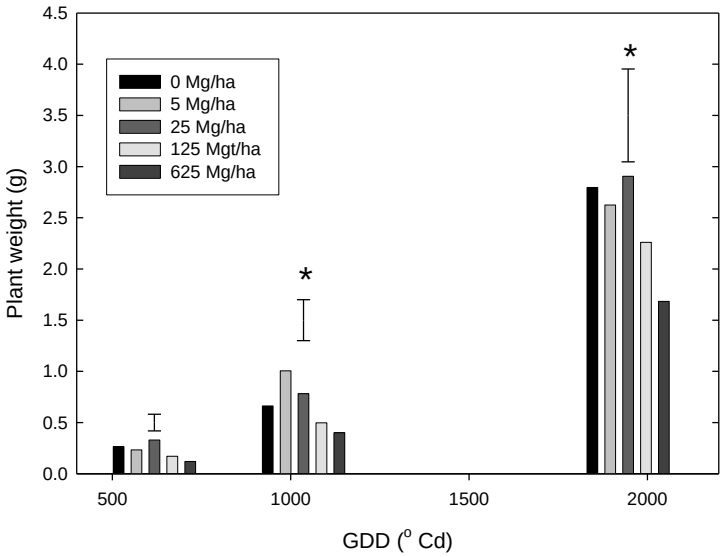
548 **experiment 1: (a) rate of gas exchange, (b) transpiration and (c) stomatal conductance.**

549 **Bars are standard errors of difference (SED) and * indicate that means are**

550 **significantly different at $p \leq 0.05$.**

551

552



553

554

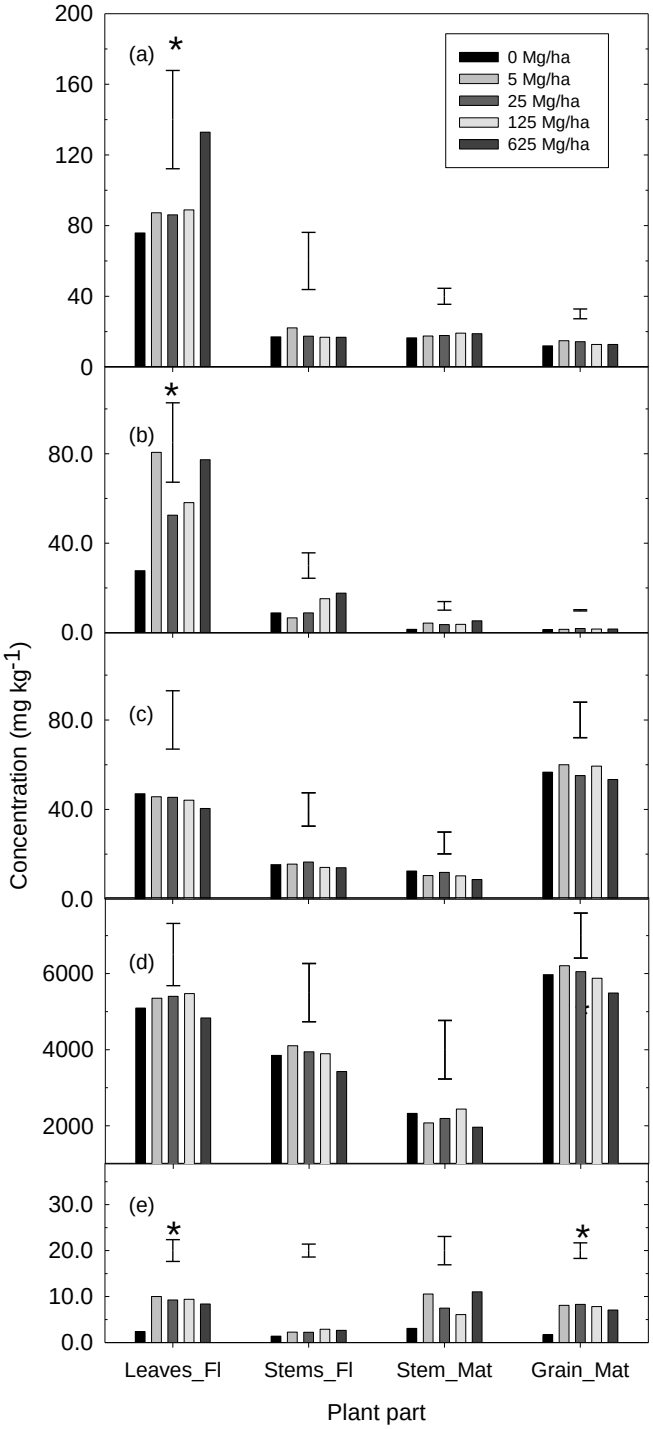
555

556

557 Fig. 2. Mean dry weight per plant for canola grown on ash-amended soil at 618, 1036
558 and 1946 growing-degree days (GDD) during experiments 1. The three periods
559 coincided with 27, 47 and 96 days after sowing (DAS); the plants were in early
560 flowering at 96 DAS. Bars are standard errors of difference (SED) and * indicate that
561 means are significantly different at $p \leq 0.05$.

562

563



564

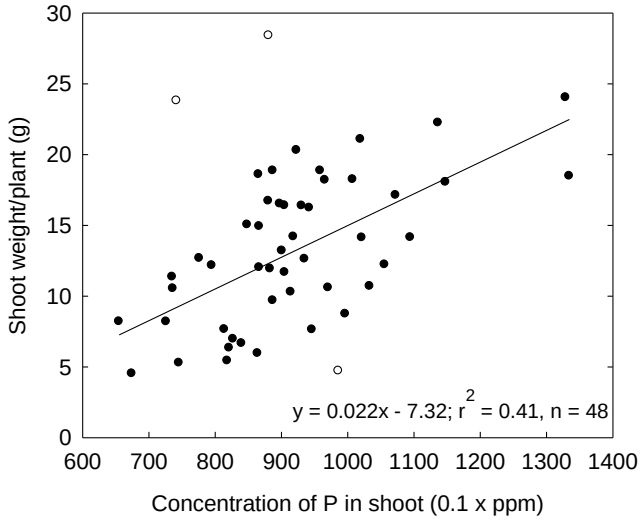
565

566 **Fig. 3. Elemental concentrations in canola partitioned into the leaves, stems or grain at**

567 **either early flowering (Fl) or maturity (Mat): (a) B, (b) Cu, (c) Zn, (d) P, and (e) Mo.**

568 **Bars are standard errors of difference (SED) and * indicate that means are**

569 **significantly different at $p \leq 0.05$.**



570

571

572 **Fig. 4. Relationship observed between shoot dry matter and concentration of**

573 **phosphorus in shoot of canola early flowering (1946 GDD or 96 DAS). The open**

574 **symbols are outliers that were excluded from regression.**

575