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Effects of fly ash application on plant biomass and element accumulations: a meta-analysis☆

Chih-Li Yu [a], Qi Deng [a, b], Siyang Jian [c], Jianwei Li [c], E. Kudjo Dzantor [c], Dafeng Hui [a, *]

[a] Department of Biological Sciences, Tennessee State University, Nashville, TN, USA
[b] Key laboratory of Vegetation Restoration and Management, South China Botanical Garden, The Chinese Academy of Sciences, Guangzhou, 510650, China
[c] Department of Agricultural and Environmental Sciences, Tennessee State University, Nashville, TN, USA

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Fly ash generated from coal-fired power plants is a source of potential pollutants, but can be used as a soil ameliorant to increase plant biomass and yield in agriculture. However, the effects of fly ash soil application on plant biomass and the accumulation of both nutrient and toxic elements in plants remain unclear. Based on 85 articles, we conducted a comprehensive meta-analysis to evaluate changes in plant biomass and concentrations of 21 elements in plants in response to fly ash application. These elements included macro-nutrients (N, P, K, Ca, and S), micro-nutrients (B, Co, Cu, Fe, Mn, Mo, Ni, and Zn), and metal(loid)s (Al, As, Cd, Cr, Pb, and Se). Overall, fly ash application decreased plant biomass by 15.2%. However, plant biomass was enhanced by fly ash application by 11.6–29.2% at lower application rates (i.e. <25% of soil mass), and decreased by 45.8% at higher application rates (i.e. 50–100%). Belowground biomass was significantly reduced while yield was enhanced by fly ash application. Most of the element concentrations in plants were enhanced by fly ash application, and followed a descending order with metal(loid)s > micro-nutrients > macro-nutrients. Concentrations of elements tended to increase with an increase in fly ash application rate. Our syntheses indicated that fly ash should be applied at less than 25% in order to enhance plant biomass and yield but avoid high accumulations of metal(loid)s.
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1. Introduction

Coal fly ash is one of the by-products of combustion in thermal power plants (Ukwattage et al., 2013; Dzantor et al., 2015). The annual production of coal fly ash is more than 700 million tons and will continue to increase in the near future (Shaheen et al., 2014). Fly ash consists of fine and powdery particles that can be a source of water pollution but it also contains plant macro-nutrients (N, P, K, Ca, Mg and S) and micro-nutrients (B, Co, Cu, Fe, Mn, Mo, Ni and Zn) essential for plant growth (Plank and Martens, 1973; Sharma and Kalra, 2006). However, fly ash also contains metal(loid)s such as Al, Cr, Pb, Hg, Ni and As which are toxic to plants and animals (Sharma and Kalra, 2006; Dzantor et al., 2015). How fly ash application to soil would influence plant growth and element accumulations in plants remains unclear.

Fly ash has been used as a soil ameliorant in agricultural fields for several decades (Adriano et al., 1978; Gupta et al., 2002; Nayak et al., 2015). Fly ash application often enhances soil nutrients and plant nutrient uptake, and increases the biomass of crops and crop yields (Ram et al., 2006; Ram et al., 2007; Aggarwal et al., 2009; Thind et al., 2012; Ukwattage et al., 2013). For example, Nayak et al. (2015) demonstrated that the rice grain and straw yield in the greenhouse are significantly increased by applying up to 20% of fly ash. A 3-year field experiment showed the grain yields of sunflower and maize are increased with about 49% (40 t ha^{-1}) fly ash application (Yeledhalli et al., 2008). However, some studies reported that fly ash application does not change or even suppresses plant growth, as fly ash contains toxic metal(loid)s that inhibit plant growth (Jala and Goyal, 2006; Sharma and Kalra, 2006). Metal(loid)s accumulation could impair biochemical and physiological functions in plants and influence crop productivity (Shahid et al., 2015). Rautaray et al. (2003) applied 10 t ha^{-1} fly ash to a rice field and found no significant difference of the rice grain yields. Biomass of maize grown in a greenhouse is reduced by 5–40% due to the application of fly ash (Sims et al., 1995). Whether fly ash could be used as a value-added soil ameliorant to increase plant biomass should be carefully assessed (Basu et al., 2009; Shaheen et al., 2014).

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* Corresponding author.
E-mail address: dhui@tnstate.edu (D. Hui).

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Even though fly ash application increases plant nutrient uptakes, it may lead to metal(loid)s accumulations in plants (Gupta et al., 2002). The presences of relatively high concentrations of trace elements, such as As, B, Cd, Cr, Ni, Mo and Se, are mostly observed with fly ash application to soil (Sharma and Kalra, 2006; Manoharan et al., 2007). For example, Lee et al. (2006) reported high B concentration of 55 $mg\ kg^{-1}$ in rice under the 120 $t\ ha^{-1}$ fly ash application, but no B toxicity in rice was observed. The concentrations of Co, Cu, Mn, Ni, Zn, Cr, Cd and Pb in rice grain increase progressively with an increase in fly ash application rate (5–100 $t\ ha^{-1}$) (Padhy et al., 2016). In a greenhouse study, toxic metal(loid)s concentrations (i.e. As, Cd and Mo) in the crop yield under fly ash application (5%–20% of soil weight) are significantly higher than that under no fly ash application (Jensen et al., 2004). On the other hand, Nayak et al. (2015) showed there is no significant changes in the Cu, Mn, Pb, Cd and Cr concentrations of rice grain with fly ash application up to 40% of soil mass in the greenhouse. Studies of the changes in trace element concentrations in plants under fly ash application are inconsistent. Therefore, it is important to quantify the element concentrations in plants with fly ash application.

In this study, we compiled a database from 85 articles on plant biomass, soil pH, and 21 elements (N, P, K, Al, As, B, Ca, Cd, Co, Cr, Cu, Fe, Mg, Hg, Mn, Mo, Ni, Pb, S, Se and Zn) in plants grown with and without fly ash application in the greenhouse and field conditions, and evaluated the effects of fly ash application using meta-analysis. The three specific objectives of this study were: 1) to quantify the effects of fly ash application on plant biomass, soil pH, and element accumulations in plants; 2) to determine the effects of fly ash application on the accumulations of macro-nutrients, micro-nutrients, and metal(loid)s in plants; 3) to assess the influences of fly ash application rate and soil pH on plant biomass and element accumulations. We hypothesized that: 1) Fly ash application at a low rate would increase plant biomass but heavy fly ash application would decrease plant biomass; 2) Fly ash application would enhance plant nutrients and metal(loid)s accumulation in plants; and 3) Plant responses to fly ash application could vary with experimental settings such as application rate or soil pH. Plant element concentration would increase with increasing application rate. Information in this study would be useful for farmers and policy makers to make decisions on fly ash application and management in agriculture.

2. Materials and methods

2.1. Literature search

We searched literature in Web of Science and Google Scholar databases using the keywords ‘fly ash’, ‘coal’, ‘crop’, ‘metal’, ‘uptake’, ‘biomass’, ‘productivity’, and ‘accumulation’, with no restriction on publication year. As fly ash has been used for the remediation of contaminated soil, we excluded these experiments conducted in contaminated soils to avoid the confounding effects with pollutants. We focused on plant biomass, soil pH, and 21 element accumulations in plants. The elements included N, P, K, Al, As, B, Ca, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Mo, Ni, Pb, S, Se and Zn. The data were collected from tables or extracted from figures using the GetData Graph Digitizer (version 2.24, Russian Federation). We included data with sample size, mean and standard deviation or standard error for both no fly ash application and with fly ash application treatments. In total, more than 1000 observations from 85 peer-review publications were collected for this meta-analysis (Table S1).

To assess the influences of experimental setting (field versus greenhouse), fly ash application rate, duration of experiment, and plant tissue, we collected all necessary experimental setup information from the papers. The unit of fly ash application was converted from mass per area to percentage by volume if needed using soil bulk density. If no soil bulk density was provided, we assumed it to be 1.5 $g\ cm^{-3}$. We grouped all data into five categories for fly ash applications including 0–5%, 5–10%, 10–25%, 25–50%, and 50–100% of soil weight. All high concentrations of fly ash application (>25%) were pot studies. Soil pH was assigned alkaline ($pH > 8$), acidic ($pH < 6$), or neutral pH ($6 \le pH \le 8$) based on the pH at the control site. For plant tissues, both plant biomass and element concentrations in different plant tissues (aboveground, belowground, yield, and whole plant) were considered. The data from leaf, stem and silage were combined into the “aboveground” part. The “belowground” part only included root. The fruit, grain, haulm and tuber were included in the “yield” part. The whole plant included all three plant tissues. Experimental duration had seven groups: ≤30, 30–60, 60–90, 90–180, 180–365, 365–730, 730–1095 days.

2.2. Meta-analysis

We quantified the effects of fly ash application on plant biomass and the element concentrations in plants by calculating the response ratio (RR), a metric commonly used in meta-analyses (Hedges and Olkin, 1985; Luo et al., 2006; Deng et al., 2015):

$$RR = \ln(X_t/X_c) = \ln(X_t) - \ln(X_c) \tag{1}$$

Where RR is the natural-log of the ratio of the mean value of the chosen variable in the fly-ash treatment group (X_t) to that in the control group (X_c), an index of the effect of the experimental treatment on the target variable. A weighted RR was computed from individual RR by giving greater weight to studies whose estimates have greater precision (lower variance):

$$RR_{++} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij} RR_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}} \tag{2}$$

The standard error of RR_{++} was calculated by:

$$s(RR_{++}) = \sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}}} \tag{3}$$

The w in equations (2) and (3) was defined as weighting factor, the inverse of the pooled variance ($w_{ij} = 1/v$). m was the number of compared groups, and k was the number of comparisons in the corresponding groups.

95% confidence intervals (95% CI) for the RR_{++} were derived using following equation:

$$95\%\ CI = RR_{++} \pm 1.96 \times s(RR_{++}) \tag{4}$$

The treatment effect of the number of replicates was considered to be significant if the 95% confidence interval (CI) of RR did not overlap with zero (Luo et al., 2006; Deng et al., 2015). A transformation from average response ratio to percentage change was conducted in order to evaluate the effect directly using the equation below:

$$[\exp(RR_{++}) - 1] \times 100\% \tag{5}$$

The significance among groups was detected by comparing the overlap of 95% CI between adjacent groups. If the 95% CI of one group did not overlap with another, we assumed significant difference between these two groups. We presented the results as percent change for ease of visualization, but statistical analyses were performed using the response ratio. All data analyses were performed in SAS (Version 9.3, SAS Inc. Cary, NC, USA; Hui and Jiang, 1996).

3. Results

3.1. Effect of fly ash on plant biomass: overall, under different fly ash application rates, and under experimental settings

Fly ash application decreased plant biomass by an average of 15.2% (Fig. 1a), with varied responses under different application rates. However, plant biomass was enhanced by 11.6, 22.1, and 29.2% when rate of fly ash application was 0–5%, 5–10%, and 10–25% respectively, compared to no fly ash application (Fig. 1b). Large rate of fly ash application (50–100%) significantly reduced plant biomass by 45.8%. Medium rate of fly ash application (25–50%) did not have a significant effect to plant biomass (Fig. 1b).

Fly ash application increased plant yield by 11.9% on average, but decreased aboveground and belowground biomass by 5.7% and 18.6%, respectively (Fig. 1c). Fly ash application in pot experiments in the greenhouses showed a significantly negative effect ($P < 0.01$), while no significant effect of fly ash application on plant biomass was found in field experiments (Fig. 1d).

The effects of fly ash application significantly differed between soil acidity. In alkaline soils ($pH > 8$), fly ash application significantly increased plant biomass by 21.8% compared to no fly ash application. However, in neutral ($6 \leq pH \leq 8$) and acidic ($pH < 6$) soils, fly ash application significantly decreased plant biomass by 17.6 and 22.3%, respectively (Fig. 1e).

3.2. Effect of fly ash on plant biomass: fly ash application rates

Large rate of fly ash application (50–100%) lead to a significantly negative effect on different plant tissues and the whole plant (Fig. 2a). The plant yield and aboveground biomass were increased by 27.6% and 22.0%, respectively, with less than 10% fly ash application, but no significantly effect was shown when more than 10% of fly ash was applied. For the belowground biomass, 10–25% of fly ash application significantly increased it by 32.9%, whereas 25–50% and over 50% of fly ash application decreased it by 10.5% and 46.8%, respectively. For the whole plant, 0–5% fly ash application increased plant biomass by 28.0%.

Aboveground biomass was enhanced by 4.9% under 0–5% application rate and 27.1% by 5–10%, but reduced by 40.0% by 50–100% application rate (Fig. 2a). Belowground biomass was only

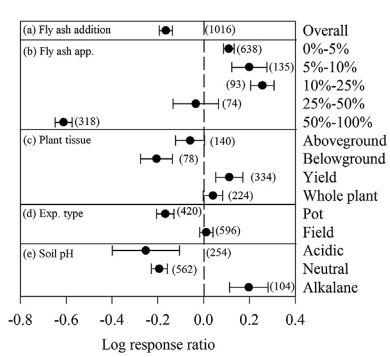

Fig. 1. Responses of plant biomass to fly ash application (a), different rates of fly ash application (b), among plant tissues (c), and experimental type (d) or soil pH (d).

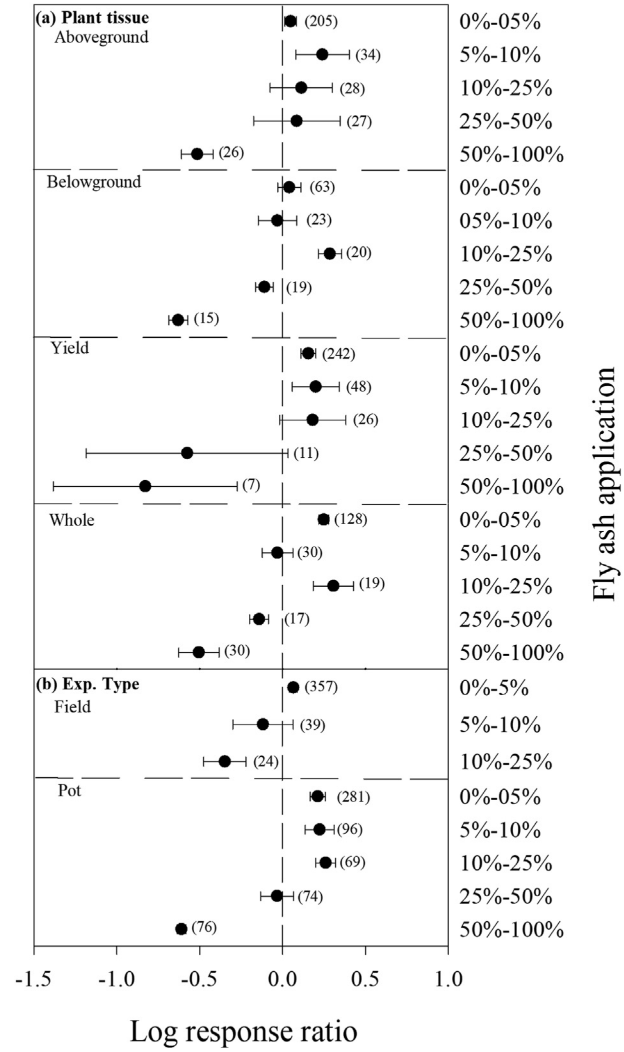

Fig. 2. Response of plant biomass of different plant tissues (a) and under different experimental types (b) to different fly ash application rates.

enhanced (32.9%) by fly ash application with 10–25% application rate, and reduced when application rate was higher than 25%. 50–100% application rate significantly reduced belowground biomass by 46.8%. Yield biomass was enhanced under low fly ash application, and reduced when application rate was 50–100%. For whole plant biomass, 0–5% and 10–25% application rate enhanced biomass, and biomass was reduced when fly ash application rate was higher than 25%.

Since different fly ash application rates were often used in field studies and pot experiments, we further separated field and pot studies. We did not find data collected from above a fly ash application rate of 25% in the field experiments. In both field and pot experiments, the smallest rate of fly ash application (0–5%) significantly increased plant biomass (by 6.3% and 4.5%, respectively, Fig. 2b). In the field experiments, 5–10% application rate did not significantly influence biomass in the field studies, but biomass was reduced when application rate was 10–25%. For pot experiments, 5–10% and 10–25% application rates also increased biomass, 25–50% application rate did not influence biomass, but 50–100% application rate significantly reduced biomass. The best rate of fly ash application in the field experiments (0–5%) was smaller than that in the pot experiments (10–25%).

3.3. Effect of fly ash on plant biomass: time after application

Of the total 437 observations, about 90% of data were collected from studies lasted for less than one year (Fig. 3). Only five studies were conducted for more than 2 years. Fly ash applications reduced plant biomass in the short term (30–180 days), but increased in long term studies (2 years and longer) (Fig. 3).

3.4. Effects of fly ash application on plant biomass: soil pH and concentrations of various elements

Soil pH increased by 7.4% (Fig. 4). Most of the element concentrations of plants were significantly increased by fly ash application except that Co and Mg concentrations were unchanged and Zn concentration declined. Nitrogen concentration in plant was increased by 67.9% which was higher than P (7.7%), K (6.7%), Ca (6.6%) and S (24.8%). Among micro-nutrients, fly ash application increased B by 154.1%, Cu by 14.4%, Fe by 21.9%, Mn by 43.7%, Ni by 435.3% and Zn by 12.9%. All metal(loid)s in plants were significantly increased: Al (39.4%), As (537.9%), Cd (120.4%), Cr (109.1%), Pb (231.9%) and Se (352.0%). These increases could pose a health threat to plants.

Fly ash application significantly increased N, P, K, Ca, B, Cu, Fe, Mo, Ni, Al, As, Cd, Cr, Pb, and Se concentrations of grains, but reduced Zn concentration ($P < 0.01$) (Fig. 5). The concentrations of macro-nutrients such as N, P, K, Ca were slightly enhanced. The concentrations of several micro-nutrients such as Ni and B were increased. The largest increases of metal(loid)s such as Se, As, Cd, Cr, and Pb were found by fly ash application. The concentration of Se in grains was enhanced by 565.1%.

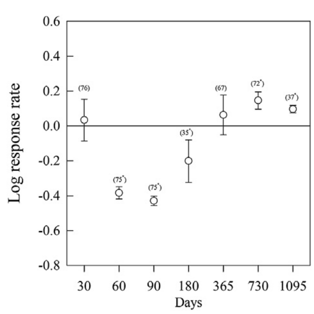

Fig. 3. Response of plant biomass under experimental duration to fly ash addition to soil.

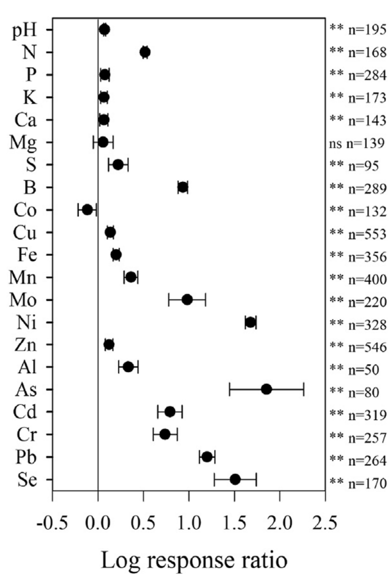

Fig. 4. Response of soil pH and 21 elements in plants to fly ash application to soil. Error bars represent 95% bootstrap confidence intervals. Right side labels show category means (number of observations). Stars indicate the significance (** = $p < 0.01$).

3.5. Effect of fly ash on element concentrations in plants: different fly ash application rates

The 0–5% fly ash application rate lead to a significantly positive effect on the N, P, K, Ca, Mg, S, B, Mn, Mo, Ni, Zn, Al, As, Cd, Cr and Se concentrations in plant and the negative effect on the Fe concentrations in plant ($P < 0.01$) (Fig. 6). There was no significant effect on the Co, Cu and Pb concentrations in plant at the 0–5% fly ash application rate. The response ratios of P, K, Co, Ni, Zn, As, Cd and Cr concentrations in plant were lower at the 5–10% fly ash application than at the 0–5% fly ash application. The response ratio of B and Se concentrations in plant increased with fly ash application rate.

4. Discussion

Application of fly ash to soil may influence plant biomass, soil pH and elements concentrations of plants (Gupta et al., 2002; Basu et al., 2009; Singh et al., 2010; Nayak et al., 2015). This meta-analysis showed the fly ash application overall decreased plant productivities, but increased soil pH and most elements concentrations of plants. The decrease of biomass by 15.2% under fly ash application was different from previous reviews (e.g., Singh et al., 2010) that found positive effects of fly ash application. The different results could be that this synthesis included more studies with high rates of fly ash application. Actually, when application rate was considered, we found that plant biomass was enhanced when the application rate was below 25%. High application rates of fly ash reduced plant biomass. The increase in element concentrations of plants after fly ash application was similar to several previous studies (Singh et al., 2010; Nayak et al., 2015; Padhy et al., 2016). For example, Pandy et al. (2016) found that accumulations of K, P, Fe, Mn, Ni, Co, Zn, Cu, Pb, Cr, and Cd increased in plants due to fly ash application. Interestingly, we found that toxic metal(loid) concentrations were increased more with fly ash application than

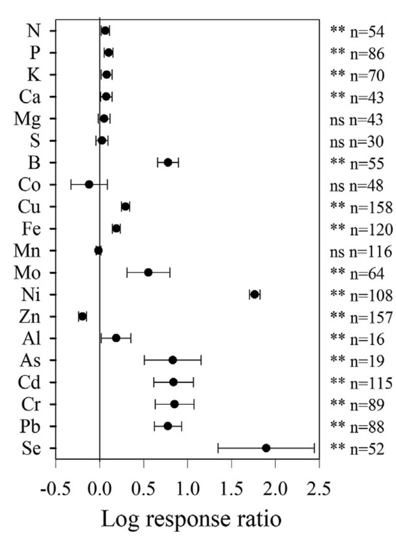

Fig. 5. Response of macro-nutrients (N, P, K, Ca, Mg and S) and Micro-nutrients (B, Co, Cu. Fe, Mn, Mo, Ni and Zn) and metal(loid)s (Al, As, Cd, Cr, Pb and Se) in plant yield only to fly ash application to soil.

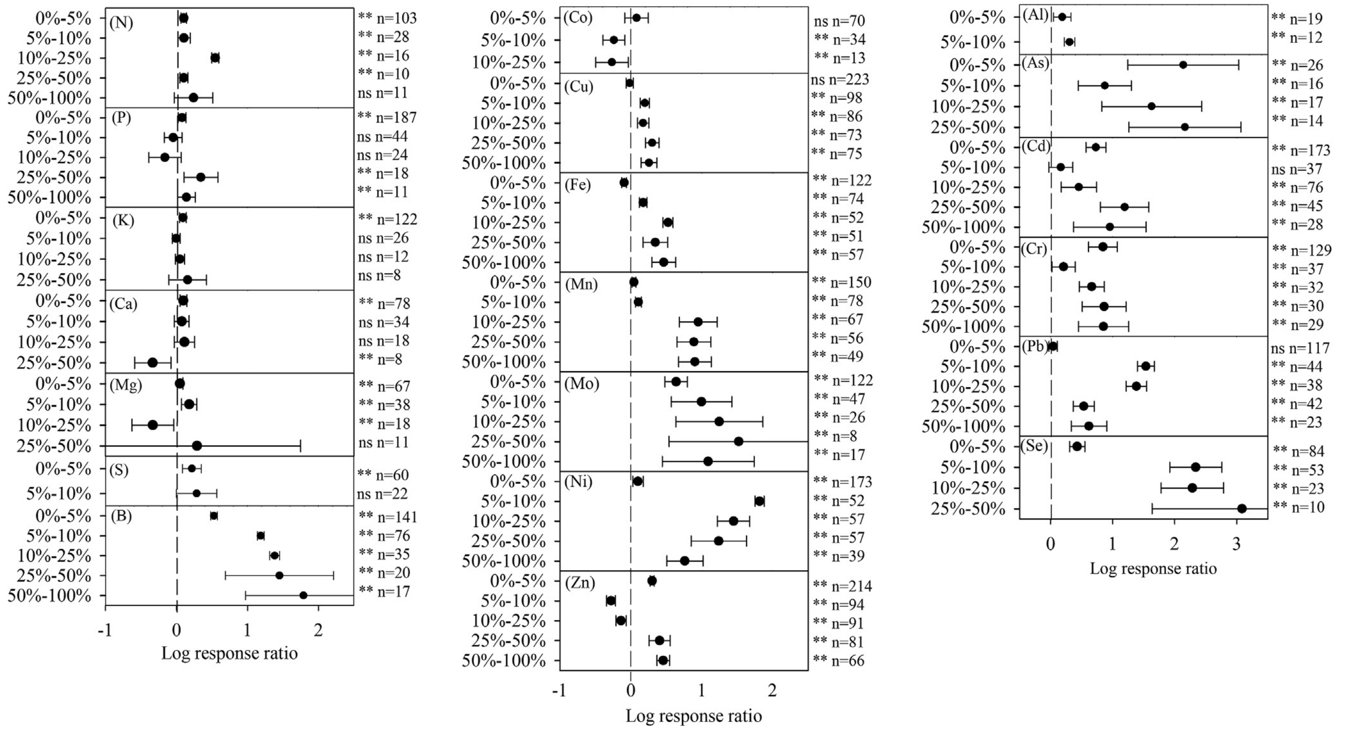

Fig. 6. Response of macro-nutrients (N, P, K, Ca, Mg and S) and Micro-nutrients (B, Co, Cu. Fe, Mn, Mo, Ni and Zn) and metal(loid)s (Al, As, Cd, Cr, Pb and Se) in plants to different fly ash application rates.

micronutrients and macronutrients. Low rates of fly ash application seem to stimulate plant growth through increased availability of macro- and micro-nutrients but, at higher application rates, this stimulation is undone by the stress from increased toxic metal(loid)s concentrations. The findings from this synthesis suggest that fly ash can be used as a soil ameliorant when at the application rate is 25% or lower in order to improve plant biomass and avoid large increases in toxic element accumulations.

The response of plant biomass varies with different rates of fly ash application (Gupta et al., 2002; Sharma and Kalra, 2006). The adequate application of fly ash has been shown to promote plant biomass and grain yield through altering soil pH and supporting sufficient nutrients (Singh et al., 2010). In this analysis, application of fly ash at a rate of less than 10% increased whole plant biomass, aboveground biomass and yield (Fig. 2), but all of plant parts were decreased in higher fly ash application rates (50–100%). Similar results were reported in the previous studies (Gupta et al., 2002; Basu et al., 2009). For example, Dwivedi et al. (2007) showed the rice growth and yield in pot experiments are increased by the fly ash application (10% and 25%) but decreased by higher fly ash application (50%, 75% and 100%). A field study showed 10% fly ash to soil significantly increased the plant biomass and grain yield of mung bean (Singh and Agrawal, 2010). For the belowground part, the root growth could be impeded by the cementing effects of fly ash creating hard areas near the soil-fly ash interface (Sharma and Kalra, 2006).

The enhanced plant biomass with lower rate of fly ash application was probably due to the improvement of soil pH as a result of the liming effect of fly ash, and the enhancements of soil macro- and micro-nutrients (Sharma et al., 2002). It is worth mentioning that lower rate of fly ash application rate was all applied in the field study (<10%) than in the pot study (<25%, Fig. 2b). Application of fly ash to the field with perennial plants may be a better choice, as its positive effects only occur after one year (Fig. 3). However, if fly ash is applied at higher levels to soil, some elements accumulated in plants and soil might inhibit plant growth (Adriano et al., 1978; Nayak et al., 2015).

Similar to previous reviews, our study showed that not only the uptake of micro-nutrients and macro-nutrients were increased by fly ash application to soil but also more metal(loid)s were accumulated in plants (Shaheen et al., 2014; Singh et al., 2010). The accumulations of some fly ash-derived elements by plants seem to depend on the rate of fly ash application (Basu et al., 2009; Ukwattage et al., 2013; Shaheen et al., 2014). At the 0–5% fly ash application rate, Pb, Cu and Ni concentrations in plant were lower compared to high application rates (Harter, 1983; Shaheen et al., 2014). Some research showed that the higher fly ash application decreases the Zn concentration in plant, possibly due to increased soil pH which decreased Zn solubility (Gupta et al., 2002; Tripathi et al., 2004; Dwivedi et al., 2007). In fly ash amended soil, the uptakes of As, Cd and Cr by the plants are significantly elevated (Tripathi et al., 2004; Chaudhary et al., 2011; Kumar and Patra, 2013).

5. Conclusions

To the best of our knowledge, this is the first comprehensive evaluation of changes in plant biomass and 21 elements of plants after fly ash application to soil. Our meta-analysis showed the fly ash application at less than 25% of soil weight could improve the plant biomass while maintaining relative lower metal(loid) concentrations in plants. Fly ash applications at a lower rate could have a positive effect on agriculture due to increasing yields. High rates of fly ash application could reduce plant biomass, and increase element concentrations especially metal(loid) concentrations in plants. It is worth noting that while more metal(loid)s were accumulated under fly ash application, the uptakes of metal(loid)s by plants were within the safe limits for plant growth (Table S2). However, responses of yield and concentrations of elements to fly ash application may vary with different plant species and soil conditions, further studies should be conducted considering more plant species and soil.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.04.013.

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