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# Nutrient use efficiency and budgets explain why biochar and basalt effects depend on soil exchange capacity

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# Nutrient use efficiency and budgets explain why biochar and basalt effects depend on soil exchange capacity

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## Abstract

**Background and Aims Whether a soil amendment benefits crops depends not only on the nutrients it supplies but on whether the soil retains them. We built closed nutrient budgets and nutrient use efficiency (NUE) metrics for biochar and basalt across contrasting Ultisol textures, testing whether the exchange capacity governing leaching also governs nutrient fate and crop recovery.**

**Methods A greenhouse experiment crossed three Ultisol textures (clay, clay loam, sand) with eight amendments over a cereal rye (*Secale cereale* L.) and soybean (*Glycine max* (L.) Merr.) rotation. Mass balances for nine elements were built from soil, amendment, leachate, and tissue data, comparing Mehlich III with total elemental inputs, alongside agronomic, apparent recovery (ARE), and physiological efficiencies.**

**Results Residuals for Ca, Mg, K, and P were negative in all combinations, indicating a native supply Mehlich III did not capture. For basalt, the budget missed up to 92% of total Ca. ARE exceeded 100% in 33 of 84 cases and reached 112 to 8,100% for basalt, a soil conditioner signature rather than a fertilizer one. Oat hull biochar K recovery fell from 40.5% in clay to 7% in sand as exchange capacity declined, and the high-rate biochar-basalt combination shifted nutrients toward retention in finer soils but not in sand.**

**Conclusion Nutrient fate and recovery followed exchange capacity as a continuous gradient rather than a fixed threshold, retention failing where exchangeable Ca, Mg, and K fell below roughly 4 cmolc kg-1. Pairing closed budgets with NUE distinguishes sound amendment investments from poorly targeted inputs.**

**Keywords:** nutrient use efficiency; mass balance; biochar; basalt; apparent recovery efficiency; Ultisols

## Abbreviations

AE, agronomic efficiency; ARE, apparent recovery efficiency; CEC, cation exchange capacity; ECEC, effective cation exchange capacity; MIII, Mehlich III; NUE, nutrient use efficiency; PC, principal component; PCA, principal component analysis; PE, physiological efficiency

## Introduction

Nutrient leaching from agricultural soils presents both an economic loss to farmers and an environmental risk to water quality. In the southeastern United States, where Ultisols dominate the agricultural landscape, the combination of low effective cation exchange capacity and high rainfall (annual rainfall exceeds 1,100 mm) promotes rapid nutrient loss from the soil (Buol et al. 2011). Where these soils are acidic, exchangeable aluminum can also be high, but where they have been limed toward neutrality, as in the soils studied here, exchangeable Al is largely neutralized and the persistent constraint is the low exchange capacity itself (companion paper, Imoro et al., in review). Farmers using these soils face a fundamental inefficiency. Nutrients from fertilizer applications and from soil and organic matter mineralization are often lost through leaching before crops can use them. This inefficiency increases input costs, reduces yield potential, and exports nutrients and trace metals to surface and ground waters (Imoro et al., in review). Any amendment strategy for these soils must therefore be evaluated not only by whether it reduces leaching (the focus of the companion paper) but by whether it improves the proportion of applied nutrients that reach the plant, that is, whether it improves nutrient use efficiency (NUE).

Biochar has been used widely as a soil amendment capable of simultaneously improving nutrient retention and crop productivity. In a meta-analysis, Jeffery et al. (2017) reported that biochar can increase crop yields by 10 to 25% in tropical and subtropical regions (acidic and nutrient-poor soils), though yield responses in temperate, well-managed soils were negligible. The yield benefit in these highly weathered soils is attributed to biochar's capacity to increase CEC through surface oxidation (Liang et al. 2006), raise soil pH, and improve water retention (Bekchanova et al. 2024; Blanco-Canqui 2017). However, biochar is not a uniform product. Feedstock source and pyrolysis temperature control its nutrient content and availability. Herbaceous biochars produced below 500 C retain nutrients as water-soluble salts, while woody biochars produced above 600 C lock nutrients into recalcitrant aromatic structures (Bilias et al. 2023; Hassan et al. 2020; Tomczyk et al. 2020). A biochar that releases nutrients faster than the soil can retain may increase crop nutrient supply in high-CEC soils but simultaneously increase nutrient loss in low-CEC soils, representing a wasted input for the farmer and a pollution source for the environment. This duality, demonstrated for leachate chemistry in the companion paper, has not been quantified through closed nutrient mass balances that track where amendment-derived nutrients actually end up.

Crushed basalt rock dust offers a contrasting amendment strategy. Unlike biochar, basalt contributes minimal immediately available nutrients. For the basalt used in this experiment, only 7.8% of its total Ca and 3.6% of its total Mg were Mehlich III-extractable at application (Imoro et al., in review, Table 3), with the remainder locked in slowly dissolving plagioclase and pyroxene minerals (Edwards et al. 2017; Larkin et al. 2022). Although biochar can also raise pH and add negative charge, basalt differs in the durability and origin of that charge. Biochar's contribution is a finite, surface-bound charge that develops through oxidation of the added carbon, whereas basalt generates new mineral exchange capacity from within the soil matrix as silicate weathering proceeds, a supply that continues for years after a single application and is renewed as fresh

mineral surfaces are exposed (Anda et al. 2015; Gillman et al. 2002; Shamshuddin et al. 2011). Basalt's primary agronomic value therefore lies in buffering soil pH and generating new exchange capacity on variable-charge mineral surfaces by lowering the point of zero charge. This soil-conditioning function means that basalt may improve NUE not by supplying nutrients directly but by modifying the soil's chemical environment to enhance the availability and retention of native and applied nutrients. If this mechanism operates as proposed, apparent recovery efficiencies (ARE) for basalt-applied nutrients should substantially exceed 100%, because the plant captures more of a nutrient than the amendment supplied. This prediction has not been tested across contrasting soil textures.

A gap in the literature is the absence of studies that construct closed, multi-element nutrient budgets for biochar and basalt amendments across a soil-texture gradient. Most biochar NUE studies consider only nitrogen, monitor a single soil type, or rely on nutrient uptake data without accounting for leachate losses or changes in soil nutrient pools (Bekchanova et al. 2024; Liu et al. 2023). Without a complete mass balance, it is impossible to determine whether an amendment's apparent benefit to crop nutrition came at the expense of soil fertility depletion, or whether nutrients not taken up by the plant were retained in the soil for future crops rather than lost to leaching. Tracking the fate of applied nutrients across soil retention, plant uptake, and leachate loss provides the information farmers need to assess whether an amendment represents a sound investment.

Furthermore, the standard Mehlich III test is the most widely used nutrient-availability index in the southeastern US and provides only a snapshot of plant-available nutrients at a single point in time (Mehlich 1984). The extraction does not capture the slow, continuous dissolution of primary minerals that contributes to long-term nutrient supply, nor does it account for the mineral-locked fraction of basalt that becomes available over years of weathering. A nutrient budget that compares MIII-based residuals with total (acid-digest) residuals can reveal how much of an amendment's nutrient content is functionally invisible to standard soil testing.

This study, a companion to the leaching paper (Imoro et al., in review), used the same greenhouse experiment (3 Ultisol textures x 8 amendment treatments x 4 replicates, rye-soybean rotation) to construct complete nutrient mass balances and evaluate NUE. The objectives were to (1) construct closed mass balances for nine elements (Ca, Mg, K, P, Na, Al, Mn, Cu, Zn) by integrating initial and final soil MIII pools, amendment inputs, cumulative leachate losses, and plant tissue uptake; (2) compare MIII-based and total (acid-digest) residuals to quantify the fraction of amendment nutrients invisible to standard soil tests; (3) compute agronomic efficiency (AE), apparent recovery efficiency (ARE), and physiological efficiency (PE) for each treatment by soil by element combination to distinguish amendments functioning as nutrient suppliers from those functioning as soil conditioners; and (4) determine whether the exchange-capacity gradient identified in the companion paper for leaching also governs nutrient fate partitioning and crop recovery efficiency. We hypothesized that ARE would exceed 100% for basalt treatments, indicating mobilization of

native soil nutrients, and that ARE for high-availability biochars would collapse in low-exchange-capacity soils where nutrients leach before plants can take them up.

## Materials and Methods

### Experimental design

The experimental design, soil sources, amendment materials, and greenhouse conditions are described in detail in the companion paper (Imoro et al., in review). In brief, three surface Ultisol soils (0 to 10 cm) were collected: a Clay soil in the Lloyd series from the Piedmont Research Station, a Clay Loam in the Georgeville series from the Butner Beef Cattle Field Laboratory, and a Sand in the Candor series from the Sandhills Research Station. Soil textures were confirmed by hydrometer particle-size analysis (Imoro et al., in review, Table 2). These soils were combined with eight amendment treatments (control; basalt, 20 t $ha^{-1}$; oat hull biochar, 20 t $ha^{-1}$; oat hull biochar + basalt, 20 t $ha^{-1}$ each; hardwood biochar, 20 t $ha^{-1}$; softwood biochar, 20 t $ha^{-1}$; softwood biochar + basalt, 20 t $ha^{-1}$ each; and softwood biochar + basalt, 40 t $ha^{-1}$ each) in a completely randomized factorial design with four replicates per cell (n = 96 pots). Each pot contained 1.2 kg of air-dried, sieved (<2 mm) soil and was maintained under controlled greenhouse conditions (24 +/- 2 C day, 22 +/- 2 C night, 16-h photoperiod, irrigated every other day with Raleigh municipal water to 60 to 70% of field capacity by weight).

Powder X-ray diffraction confirmed that kaolinite was the main clay mineral in all three soils, consistent with their classification as kaolinitic Ultisols (Imoro et al., in review, Fig. 1). Full soil and amendment characterization, including all physical, chemical, and mineralogical properties and the soils' exchange capacity, is provided in the companion paper (Imoro et al., in review, Tables 2 and 3) and is not reproduced here. That characterization shows three low-CEC but not Al-toxic soils, with sums of exchangeable Ca, Mg, and K of 7.5, 5.7, and 1.7 cmolc $kg^{-1}$ for Clay, Clay Loam, and Sand and negligible exchangeable Al in all three. The basalt was primarily plagioclase feldspar (labradorite) with some pyroxene (augite), indicating that Ca and Mg would be the primary elements released during weathering.

### Crop rotation and biomass harvest

Cereal rye (*Secale cereale* L.) was sown on January 10, 2025 (five seeds per pot, thinned to three at the two-leaf stage) and grown for 120 days as a winter cover crop. Aboveground biomass was harvested on May 10, 2025. After a one-month fallow period, soybean (*Glycine max* (L.) Merr.) was sown on June 10, 2025 (four seeds per pot, thinned to two) and grown for 122 days until harvest on October 10, 2025. Some plant mortality was recorded. At rye harvest, 81 of 96 pots retained all three plants, while 15 had two. For soybean, mortality was more variable: 18 pots retained only one plant, 57 had two, 19 had three, and 2 had four (where thinning was missed). All aboveground biomass was oven-dried at 65 C to constant weight. Roots were left in the soil and were not included in the harvest or the nutrient budget.

## Plant tissue analysis and uptake calculation

Dried plant tissue from each pot was analyzed for elemental composition at the NCDA&CS Agronomic Division laboratory (Raleigh, NC). Total N and C were determined by combustion (Dumas method). Macronutrients (P, K, Ca, Mg, S, Na) and micronutrients and trace elements (Fe, Mn, Zn, Cu, B, Mo, Al, As, Cd, Cr, Ni, Pb, Se) were determined by nitric acid microwave digestion followed by inductively coupled plasma optical emission spectrometry (ICP-OES) (Donohue and Aho 1992; US EPA 2001). Macronutrient concentrations were reported as weight percent and micronutrient and trace-element concentrations as mg $kg^{-1}$. Elemental uptake per pot was calculated as macro uptake (mg) = (concentration / 100) x biomass (g) x 1000, and micro uptake (mg) = concentration (mg $kg^{-1}$) x biomass (g) / 1000.

Because the design intended a fixed number of plants per pot, but mortality reduced the surviving number in some pots, an exploratory normalized uptake was also computed on a common three-plant basis (normalized uptake = raw uptake / actual surviving plants x 3). All results reported in this paper, including the nutrient budget and the NUE metrics, use raw per-pot uptake and biomass. The budget must reflect the actual system from which leachate was measured, and because soybean pots largely compensated for missing plants through individual plant growth, normalizing to three plants inflated per-pot uptake and biomass. Raw values therefore provide the more realistic basis for recovery and efficiency calculations and keep the NUE metrics consistent with the budget.

## Soil sampling and Mehlich III analysis

Soil was sampled at three time points: pre-treatment (initial baseline; Imoro et al., in review, Section 2.2), May (post-rye harvest), and November (post-soybean harvest). Post-treatment soils were sampled from the upper 10 cm of each pot using a 5 cm diameter auger, air-dried, sieved (<2 mm), and extracted with Mehlich III solution (5 g soil in 50 mL extractant, a 1:10 ratio). Extracts were refrigerated and analyzed by ICP-OES within 48 h of extraction. Concentrations (mg $L^{-1}$) were converted to soil nutrient content (mg $kg^{-1}$ dry soil) using a multiplication factor of 10 (extract volume 0.05 L / soil mass 0.005 kg). Soil nutrient inventory per pot (mg) was calculated as soil concentration (mg $kg^{-1}$) x pot soil mass (1.2 kg). Soil pH was measured in 1:1 (w/v) soil-water suspensions at each sampling time.

Mehlich III was used here to define the initial and final plant-available soil pools for the nutrient budget, so that the two soil endpoints are measured on the same basis. Soil exchange capacity itself was characterized independently in the companion paper by summation of ammonium acetate exchangeable Ca, Mg, and K and 1 M KCl exchangeable Al (Imoro et al., in review, Table 2). The present paper uses those exchange-capacity values and does not compute exchange capacity from Mehlich III, because Mehlich III is an availability index rather than an exchange measurement.

## Amendment input quantification

The nutrient contribution of each amendment was determined from the Mehlich III characterization (Imoro et al., in review, Section 2.2 and Table 3). Extract concentrations were converted to mg of element per gram of material and multiplied by the mass of amendment applied

(51.04 g $pot^{-1}$ at 20 t $ha^{-1}$ or 102.09 g $pot^{-1}$ at 40 t $ha^{-1}$). For combination treatments, both material inputs were summed. This approach captures the plant-available fraction of each amendment, consistent with the Mehlich III framework used for soil measurements, though it underestimates total element content, particularly for basalt, where only 7.8% of total Ca and 3.6% of total Mg were MIII-extractable (Imoro et al., in review, Table 3).

Total elemental composition of all amendments was also determined by acid digestion (EPA Method 3050B/3051A; Imoro et al., in review, Section 2.2). The MIII extractability fraction was calculated for each element as (MIII-extractable content / total content) x 100. Full amendment composition and extractability data are reported in the companion paper (Imoro et al., in review, Table 3) and are not reproduced here.

**Nutrient mass balance**

A full mass balance was calculated for nine elements (Ca, Mg, K, P, Na, Al, Mn, Cu, and Zn) using soil, amendment, leachate, and tissue data. Cumulative leachate losses were calculated as described in the companion paper (concentration x volume, summed across all six monthly sampling events). Pot-level values were averaged across the four replicates within each Soil Texture by Treatment combination to produce group means for the budget. The budget equation was Residual = (Initial Inventory + MIII Amendment Input) - (Final Inventory + Leachate Loss + Plant Uptake).

Initial and final inventories were both derived from Mehlich III extraction to maintain methodological consistency within the soil terms, so that the two soil endpoints are measured on the same basis and their difference is not confounded by a change of method. The MIII pool is not static. It exchanges dynamically with the larger total pool through mineral dissolution and precipitation, and the dual-residual analysis reported in the Results was designed specifically to quantify that exchange rather than assume it away. A positive residual indicates unaccounted losses, for example precipitation into non-MIII-extractable mineral phases. A negative residual indicates unaccounted gains, for example mineralization of organic matter or dissolution of primary minerals not captured by MIII at the initial sampling. Because the target elements are non-volatile, gaseous loss is not a meaningful pathway for them.

To evaluate whether accounting for the total element content of amendments improved budget closure, a second residual was calculated by replacing the MIII input with the total elemental input (from acid digestion). The difference between the two residuals quantifies the contribution of non-MIII-extractable amendment content to the overall balance.

Two complementary sets of proportional metrics were derived from the budget. The first expressed each measured term relative to the total nutrient entering the system (Initial Inventory + Amendment Input): apparent retention, leaching fraction, and uptake fraction. Because measured outputs frequently exceeded this input baseline, owing to nutrient supply from native mineral dissolution and organic matter mineralization not captured by the initial MIII extraction, these input-relative fractions can exceed 100% and are reported as such where relevant in the Results.

The second set described the partitioning of nutrients among the three measured destinations. For this fate partitioning, final soil retention, plant uptake, and leachate loss were each expressed as a percentage of their sum, so that the three fates total 100% for each Soil Texture by Treatment by Element combination. This closing normalization was used for the fate-partitioning comparisons in the Results and for the stacked-bar visualization (Fig. 3).

**Net export of exchangeable Ca, Mg, and K**

To integrate cation losses through both measured pathways into a single budget term, net export of exchangeable Ca, Mg, and K was calculated for each pot as the sum of Ca, Mg, and K removed in leachate and in plant uptake, expressed in charge equivalents (meq). Concentrations were converted to charge equivalents using equivalent weights of 20.039, 12.153, and 39.098 mg meq-1 for Ca, Mg, and K, respectively. Leachate export was calculated as concentration (mg $L^{-1}$) x leachate volume (L) / equivalent weight, summed across all sampling events. Plant export was calculated as tissue concentration (% / 100) x biomass (g) x 1000 / equivalent weight, computed separately for rye and soybean and summed. Net export per pot was the sum of the leachate and plant terms and was analyzed with a two-way model (net export ~ Soil Texture x Treatment) using Type II sums of squares.

To distinguish whether differences in export between soils reflected drainage volume or drainage chemistry, a flow-weighted leachate cation concentration was calculated for each pot as the total leachate Ca + Mg + K (meq) divided by the total leachate volume (L) and analyzed with the same two-way model. A soil difference in net export accompanied by no soil difference in flow-weighted concentration indicates a volume-driven effect, whereas an elevated flow-weighted concentration indicates a concentration-driven effect.

**Nutrient use efficiency metrics**

Three standard NUE metrics were calculated for each non-control treatment by soil texture by element combination, using raw per-pot uptake and biomass values. Agronomic Efficiency (AE) = (Biomass treated - Biomass control) / Element Input (g $mg^{-1}$). Apparent Recovery Efficiency (ARE) = (Uptake treated - Uptake control) / Element Input x 100. Physiological Efficiency (PE) = (Biomass treated - Biomass control) / (Uptake treated - Uptake control) (g $mg^{-1}$). PE was undefined where treated uptake did not exceed Control. These metrics used the Control mean within each soil texture as the reference, ensuring that texture-inherent differences in productivity did not confound treatment effects.

ARE deserves particular comment, because its interpretation is central to this paper. An ARE above 100% does not signal a calculation error or a violation of mass conservation. It is the diagnostic signature of a soil-conditioner mechanism. The word apparent is doing deliberate work in the term. ARE measures recovery only against the nutrient the amendment itself supplied, so when an amendment supplies very little of an element but improves the soil conditions that release native reserves, the plant can take up far more of that element than the amendment contained and ARE rises well above 100%. Negative ARE indicates suppression of uptake relative to Control.

We therefore use ARE not as a recovery percentage in the conventional fertilizer sense but as an index that separates amendments acting as direct nutrient suppliers (ARE below 100%) from those acting as soil conditioners that mobilize native nutrients (ARE above 100%).

### Statistical analysis

All analyses were performed in R version 4.5.2 (R Core Team 2025) at alpha = 0.05. Biomass and per-element tissue uptake were each analyzed by two-way ANOVA (Soil Texture x Treatment) for each crop separately. For biomass, post-hoc comparisons used Sidak adjustment for the Treatment main effect and Tukey's HSD for simple effects within each soil texture (emmeans package; Lenth 2026). Principal component analysis (PCA) was performed on the nine Mehlich III soil nutrients from both sampling dates (n = 192), with variables standardized to zero mean and unit variance prior to analysis. To examine how the balance between nutrient recovery and loss separated across the texture gradient, plant uptake was plotted against cumulative leachate loss for each Soil Texture by Treatment group. All figures were generated using ggplot2 (Wickham 2016).

## Results

### Amendment nutrient availability differs by feedstock

The Mehlich III extractability of amendment nutrients, reported in full in the companion paper (Imoro et al., in review, Table 3), sets up the budget results that follow and is summarized here for the elements central to this paper. Oat hull biochar had by far the highest extractability for K (95.4%) and P (43.8%), reflecting the labile, water-soluble salts characteristic of low-temperature herbaceous biochars. Softwood and hardwood biochars were intermediate for K (68.9% and 64.5%), and basalt was lowest (17.4%). For Ca and Mg the ranking differed, with softwood biochar showing the highest extractability (Ca 59.9%, Mg 87.3%) and basalt the lowest (Ca 7.8%, Mg 3.6%). These differences translated into large contrasts in delivered nutrients. Oat hull biochar delivered 716 mg of MIII-extractable K per pot, roughly 20 times more than softwood biochar (35 mg) and 160 times more than basalt (4.4 mg). By contrast, basalt's total K content by acid digest (25.5 mg per pot) was within the same order of magnitude as softwood biochar (51.0 mg), yet about 83% of it was locked in the silicate matrix and unavailable to the standard soil test. This gap between total and extractable content is the central theme of the mass balance that follows, and it is largest for basalt.

### Budgets reveal hidden nutrients missed by standard tests

Closed mass balances for the nine elements exposed a systematic pattern. When the budget used Mehlich III inputs, residuals for the macronutrients were negative in every Soil Texture by Treatment combination (Table 1). A negative residual means that measured outputs (final soil pool, leachate loss, and plant uptake) exceeded measured inputs (initial soil pool and amendment).

Table 1. Nutrient mass balance for Ca and K (selected treatments), showing Mehlich III and total elemental inputs and the resulting Mehlich III residual (mg per pot, group means, n = 4). Negative

residuals indicate a nutrient supply not captured by the initial Mehlich III extraction. All values in mg pot$^{-1}$.

| Soil | Treatment | El | Initial | MIII in | Total in | Final | Leachate | Uptake | Resid |
|---|---|---|---|---|---|---|---|---|---|
| Clay | Control | Ca | 1148 | 0 | 0 | 925 | 1755 | 427 | -1959 |
| Clay | Basalt | Ca | 1148 | 120 | 1532 | 1113 | 1349 | 567 | -1760 |
| Clay | Oat hull | Ca | 1148 | 101 | 210 | 1011 | 1388 | 423 | -1572 |
| Clay | Hardwood | Ca | 1148 | 154 | 324 | 968 | 1360 | 613 | -1639 |
| Clay | Softwood | Ca | 1148 | 360 | 602 | 1122 | 1653 | 588 | -1855 |
| Clay | OB + Basalt | Ca | 1148 | 220 | 1742 | 1072 | 1231 | 551 | -1486 |
| Clay | SB + Basalt (20) | Ca | 1148 | 480 | 2134 | 1158 | 1740 | 364 | -1633 |
| Clay | SB + Basalt (40) | Ca | 1148 | 960 | 4267 | 1368 | 1043 | 419 | -722 |
| Clay | Control | K | 376 | 0 | 0 | 86 | 467 | 743 | -920 |
| Clay | Oat hull | K | 376 | 716 | 750 | 203 | 1511 | 1034 | -1655 |
| Clay | Softwood | K | 376 | 35 | 51 | 62 | 335 | 987 | -974 |
| Clay | SB + Basalt (40) | K | 376 | 79 | 153 | 74 | 188 | 750 | -556 |
| Clay Loam | Control | Ca | 829 | 0 | 0 | 834 | 1117 | 412 | -1534 |
| Clay Loam | SB + Basalt (40) | Ca | 829 | 960 | 4267 | 1214 | 557 | 396 | -377 |
| Clay Loam | Oat hull | K | 240 | 716 | 750 | 103 | 786 | 837 | -769 |
| Clay Loam | SB + Basalt (40) | K | 240 | 79 | 153 | 95 | 100 | 505 | -380 |
| Sand | Control | Ca | 289 | 0 | 0 | 250 | 1600 | 275 | -1835 |
| Sand | Oat hull | Ca | 289 | 101 | 210 | 259 | 1312 | 295 | -1475 |
| Sand | SB + Basalt (40) | Ca | 289 | 960 | 4267 | 507 | 3939 | 446 | -3643 |
| Sand | Control | K | 39 | 0 | 0 | 32 | 798 | 289 | -1079 |
| Sand | Oat hull | K | 39 | 716 | 750 | 33 | 3773 | 342 | -3393 |
| Sand | SB + Basalt (40) | K | 39 | 79 | 153 | 36 | 739 | 406 | -1063 |

El = element, MIII in = Mehlich III-extractable amendment input. Total in = total (acid-digest) amendment input. Resid, Mehlich III residual = (Initial + MIII in) - (Final + Leachate + Uptake). The dual-residual comparison uses Total in (see Fig. 1). Full nine-element budget in Online Resource 1.

The magnitude of these negative residuals was large. For Ca, Control residuals ranged from -1,534 mg (Clay Loam) to -1,959 mg (Clay), meaning that roughly 1,500 to 2,000 mg of Ca per pot appeared in the system beyond what the initial extraction detected. For K, Control residuals ranged from -648 mg (Clay Loam) to -1,079 mg (Sand). Irrigation with municipal water contributed a measured but minor part of this gap. Across the six leaching events the water added approximately 260 mg Ca, 99 mg Mg, 91 mg K, and 5 mg P per pot, accounting for roughly 6 to 17% of the negative macronutrient residuals. Sodium was the exception: irrigation added about 1,028 mg Na

per pot, and Control Na residuals were very large and negative (-4,751 mg in Clay Loam to -9,009 mg in Sand).

Aluminum behaved differently from the exchangeable cations. Its MIII residuals were small and mostly slightly negative (-422 to +177 mg per pot), with only the highest-rate biochar-basalt treatment in Clay giving a small positive value. These small residuals show no consistent directional change in MIII-extractable Al over the season.

**Dual-residual analysis reveals basalt's hidden minerals**

The negative MIII residuals raised a question the standard budget cannot answer: how much of the missing supply is amendment-derived mineral nutrient that the MIII test simply cannot see? To separate the amendment's invisible pool from native soil weathering, we recomputed each budget using the total (acid-digest) elemental input in place of the MIII input. The difference between the two residuals isolates the non-MIII-extractable amendment content (Table 1, Fig. 1).

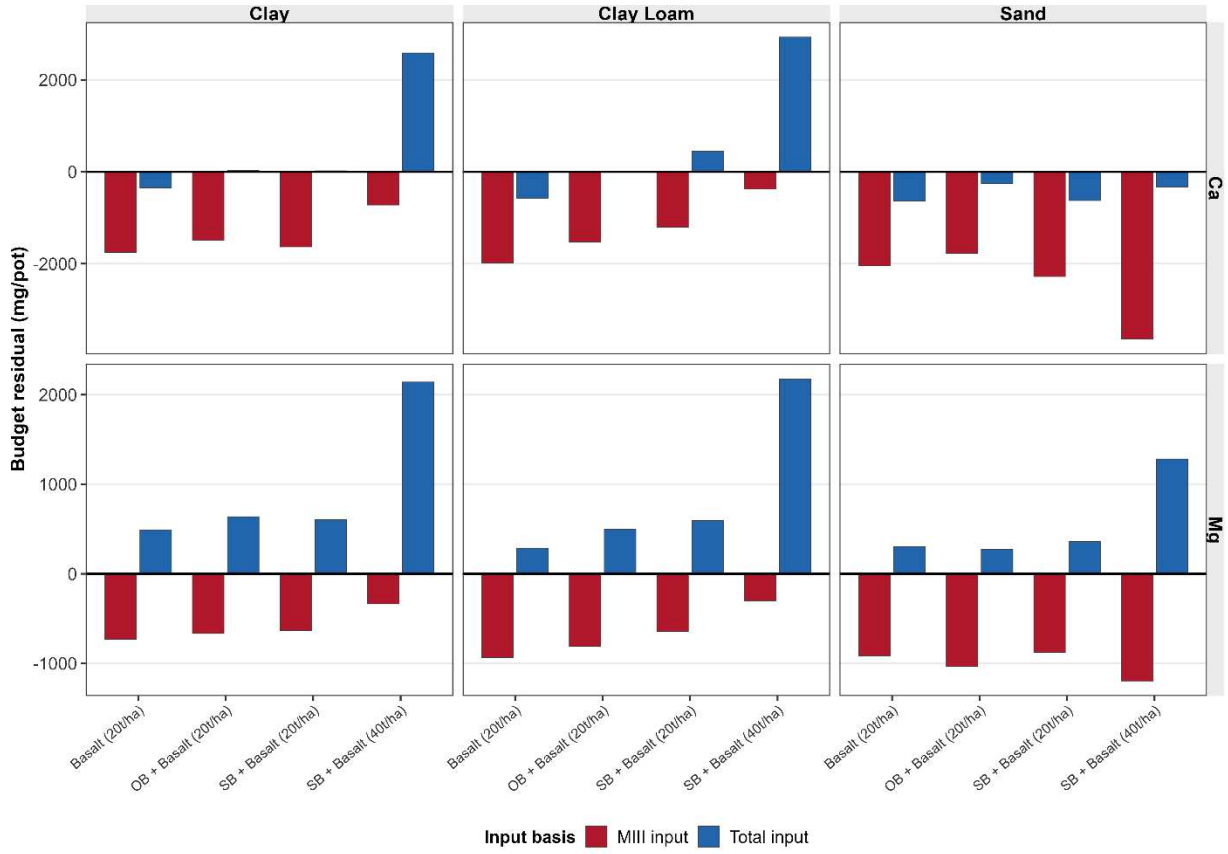


**Fig. 1** Nutrient budget residuals computed with Mehlich III (MIII) amendment input versus total (acid-digestible) input, by soil texture and treatment, for Ca and Mg. Red bars show MIII-based residuals and blue bars show total-input residuals (mg pot$^{-1}$). Positive residuals indicate more nutrient supplied than recovered in outputs. Negative residuals indicate unaccounted inputs, such as native mineral dissolution or organic matter mineralization

Basalt alone provides the clearest case. Its Ca extractability was only 7.8%, so the MIII input (120 mg per pot) captured a small fraction of the total Ca it carried (1,532 mg per pot). Switching to the total input moved the Clay Ca residual from -1,760 mg (a large apparent deficit under the MIII budget) to -348 mg, removing about 80% of the deficit while leaving it negative. In Clay Loam the same switch moved the Ca residual from -1,984 mg to -571 mg, and in Sand from -2,048 mg to -636 mg. The finer soils closed by roughly 70 to 80% once the mineral-locked Ca was counted, though none turned positive, and Sand retained the largest deficit, consistent with its combination of low retention and rapid drainage. Basalt Mg gave an even stronger signature and did change sign: MIII residuals of -730 to -916 mg became +286 to +491 mg once total Mg was counted. The high-rate combination made the Ca effect larger still. For SB + Basalt at 40 t $ha^{-1}$, the total-input Ca residual reached +2,586 mg in Clay and +2,930 mg in Clay Loam, a large pool of amendment Ca held in slowly weathering mineral form that no MIII-based budget would record.

**Plant uptake and apparent recovery efficiency**

Plant uptake responded to soil and amendment in a way that shifted between the two crops (Table 3). For rye, the winter cover crop, soil texture dominated uptake of every macronutrient ($F = 182$ to 248, all $P < 0.001$), while a significant treatment effect had emerged only for K and P and a significant soil by treatment interaction only for K. By soybean, the pattern had changed. Treatment significantly affected uptake of Ca, K, and Mg ($P < 0.01$), whereas the soil main effect had weakened, so that soybean Ca uptake no longer differed among the three textures. Interactions were nonsignificant for every macronutrient in soybean.

Apparent recovery efficiency (ARE) exceeded 100% in 33 of the 84 treatment by soil by element combinations (Table 2, Fig. 2). It was most common for the elements basalt supplies in only trace extractable amounts, appearing in 12 of 21 combinations for K and 9 of 21 for P, and less often for Ca and Mg (6 of 21 each).

Table 2. Nutrient use efficiency for selected treatment by soil by element combinations: agronomic efficiency (AE), apparent recovery efficiency (ARE), and physiological efficiency (PE), with Mehlich III input and plant uptake (mg per pot). AE and PE are in g biomass per mg input. ARE above 100% (bold) indicates a soil-conditioner response. PE is undefined (NA) where treated uptake did not exceed Control. The complete set for all 84 combinations is in Online Resource 2.

| Soil | Treatment | El | Input | Uptake | AE | ARE (%) | PE |
|---|---|---|---|---|---|---|---|
| Clay | Basalt | Ca | 119.6 | 567.0 | 0.078 | **117** | 0.067 |
| Clay | Basalt | Mg | 45.1 | 248.2 | 0.208 | **112** | 0.185 |
| Clay | Basalt | K | 4.4 | 860.5 | 2.112 | **2638** | 0.080 |
| Clay | Basalt | P | 0.26 | 121.3 | 35.447 | **6993** | 0.507 |
| Clay | Oat hull | K | 716.1 | 1033.6 | 0.004 | 40.5 | 0.009 |
| Clay | Oat hull | Ca | 100.5 | 422.5 | 0.027 | -5 | NA |
| Clay | Oat hull | Mg | 55.5 | 160.6 | 0.048 | -66 | NA |

| Soil | Treatment | El | Input | Uptake | AE | ARE (%) | PE |
|---|---|---|---|---|---|---|---|
| Clay | Hardwood | K | 29.6 | 863.7 | 0.400 | **406** | 0.098 |
| Clay | Softwood | K | 35.2 | 987.3 | 0.459 | **693** | 0.066 |
| Clay | SB + Basalt (40) | Ca | 960.0 | 418.8 | -0.002 | -1 | NA |
| Clay | SB + Basalt (40) | K | 79.3 | 750.0 | -0.030 | 8 | -0.362 |
| Clay Loam | Basalt | Ca | 119.6 | 583.4 | 0.081 | **143** | 0.057 |
| Clay Loam | Basalt | P | 0.26 | 111.9 | 36.639 | **8100** | 0.452 |
| Clay Loam | Oat hull | K | 716.1 | 836.6 | 0.0001 | 33 | 0.0002 |
| Clay Loam | Oat hull | Ca | 100.5 | 325.5 | 0.0004 | -86 | NA |
| Clay Loam | SB + Basalt (40) | K | 79.3 | 505.0 | -0.031 | -117 | NA |
| Sand | Basalt | Ca | 119.6 | 579.6 | 0.206 | **254** | 0.081 |
| Sand | Basalt | Mg | 45.1 | 259.3 | 0.548 | **281** | 0.195 |
| Sand | Basalt | P | 0.26 | 53.1 | 93.388 | **5519** | 1.692 |
| Sand | Oat hull | K | 716.1 | 341.8 | 0.019 | 7 | 0.250 |
| Sand | Softwood | Ca | 360.3 | 568.9 | 0.043 | 81 | 0.052 |
| Sand | SB + Basalt (40) | Ca | 960.0 | 446.1 | 0.018 | 18 | 0.101 |

El = element, Input = Mehlich III-extractable amendment input, AE = agronomic efficiency, ARE = apparent recovery efficiency (bold where above 100%, marking a soil-conditioner response; see Discussion), PE = physiological efficiency (NA where treated uptake did not exceed Control). Negative ARE indicates uptake suppression relative to Control.

Basalt produced the most extreme values. Its ARE ranged from 112% to 8,100% across soils and elements. For K and P, the two elements basalt barely supplies in extractable form, ARE reached 1,562 to 2,638% for K and 5,519 to 8,100% for P, because the plant took up substantial quantities of these nutrients while the extractable amendment input was near zero. Even for Ca and Mg, basalt ARE exceeded 100% in every soil (Ca 117 to 254%, Mg 112 to 281%).

Oat hull biochar showed the opposite pattern. Its K ARE stayed well below 100% and fell steeply as exchange capacity declined: 40.5% in Clay (sum of exchangeable Ca, Mg, and K 7.5 cmolc $kg^{-1}$), 33% in Clay Loam (5.7 cmolc $kg^{-1}$), and only 7% in Sand (1.7 cmolc $kg^{-1}$), a more-than-fivefold fall in recovery across the texture gradient for the same amendment and the same input.

Fourteen combinations produced negative ARE, indicating that the treatment suppressed uptake relative to Control, and all fourteen occurred in the finer soils (eight in Clay, six in Clay Loam).

These were concentrated in the high-input treatments. The most negative cases were K under SB + Basalt at 40 t ha$^{-1}$ in Clay Loam (-117%) and P under SB + Basalt at 20 t ha$^{-1}$ in Clay (-55%). Oat hull biochar also depressed Ca and Mg recovery in the finer soils (Ca -5% and Mg -66% in Clay, Ca -86% and Mg -84% in Clay Loam).

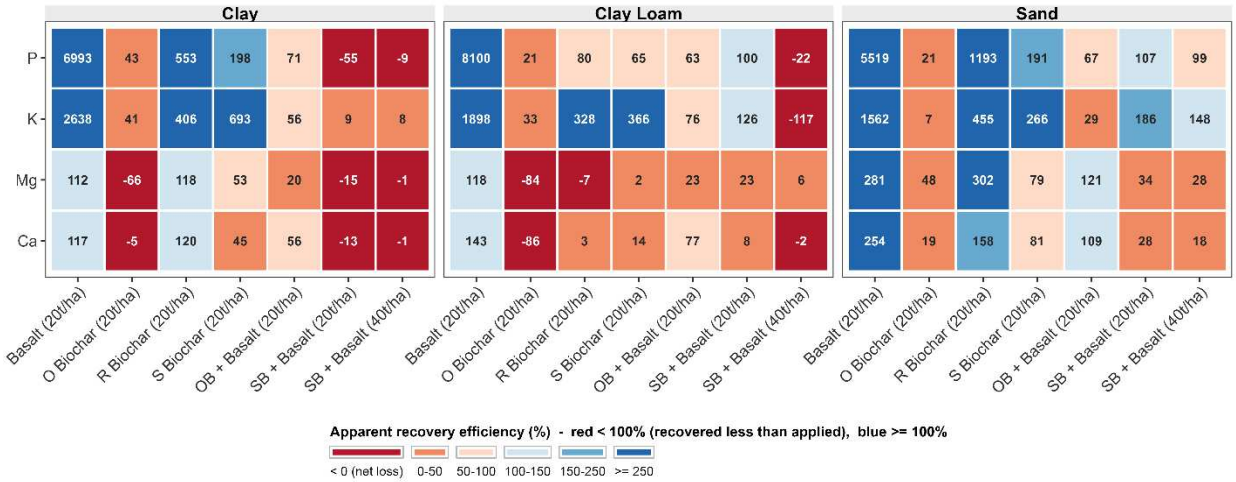


**Fig. 2** Apparent recovery efficiency (ARE, %) for each treatment x soil texture x element combination (Ca, Mg, K, P). Color bins ARE at the 100% recovery break-even: red shades mark ARE below 100% (the crop recovered less of the element than the amendment supplied), and blue shades mark ARE at or above 100% (recovery equaled or exceeded the amendment input, the signature of mobilized native soil reserves), deepening to the darkest blue for ARE >= 250%. The true percentage is printed in each cell

## Nutrient fate partitioning follows the texture gradient

Partitioning each nutrient among its three measured fates (soil retention, plant uptake, leachate loss), with the three expressed as a percentage of their sum, showed how texture reshaped nutrient destiny (Fig. 3). For Ca and Mg in Control pots, leaching was the dominant fate but its share rose sharply with coarseness. Leaching accounted for 47 to 60% of Ca and Mg output in Clay and Clay Loam but 75 to 79% in Sand, while soil retention was 21 to 35% in the finer soils but only 6 to 12% in Sand.

SB + Basalt at 40 t ha$^{-1}$ shifted this balance in the finer soils. In Clay the Ca leaching fraction dropped from 56% (Control) to 37% while soil retention rose from 30% to 48%, and in Clay Loam leaching dropped from 47% to 26% while retention rose from 35% to 56%. In Sand, however, the same treatment failed: the Ca leaching fraction stayed high at 81% (versus 75% for Control) and retention remained near 10%.

Potassium fate depended on feedstock as well as texture. In Control pots, plant uptake was the dominant K fate in Clay (57%) and Clay Loam (67%), with leaching taking 36% and 25%, but in Sand leaching dominated (71%) and uptake fell to 26%. SB + Basalt at 40 t ha$^{-1}$ and softwood biochar alone pushed K strongly toward uptake in the finer soils (uptake around 74% in Clay and

72 to 76% in Clay Loam, with leaching cut to 14 to 24%). Oat hull biochar reversed this. In Clay it raised the K leaching fraction from 36% to 55% and cut uptake from 57% to 38%, and in Sand it drove K leaching to 91% with only 8% uptake. Relative to the K present at the start plus the K applied, cumulative K leaching under oat hull biochar in Sand reached 500%.

Phosphorus fate differed from that of the cations. In Control pots, plant uptake was the dominant P fate in Clay and Clay Loam (about 65% in each), with leaching a minor 7 to 9%. In Sand, retention was the single largest P fate (retention 46%, leaching 26%, uptake 28%). Plotted against one another, cumulative leachate loss and plant uptake separate the three textures along the same gradient for all four macronutrients (Fig. 4). Oat hull biochar altered P fate most in Sand, where it raised the P leaching fraction from 26% (Control) to 59%, making P a leaching-dominated element. SB + Basalt at 40 t $ha^{-1}$ kept P uptake-dominated in the finer soils and reduced the Clay Loam P leaching fraction to about 3%, among the lowest of any treatment.

SB + Basalt at 40 t $ha^{-1}$ reduced the leaching fraction for Al, Mn, Cu, and Zn in all three soils, including Sand. In Sand the Cu leaching fraction fell from 46% (Control) to 16%, and the Zn leaching fraction from 19% to 4%.

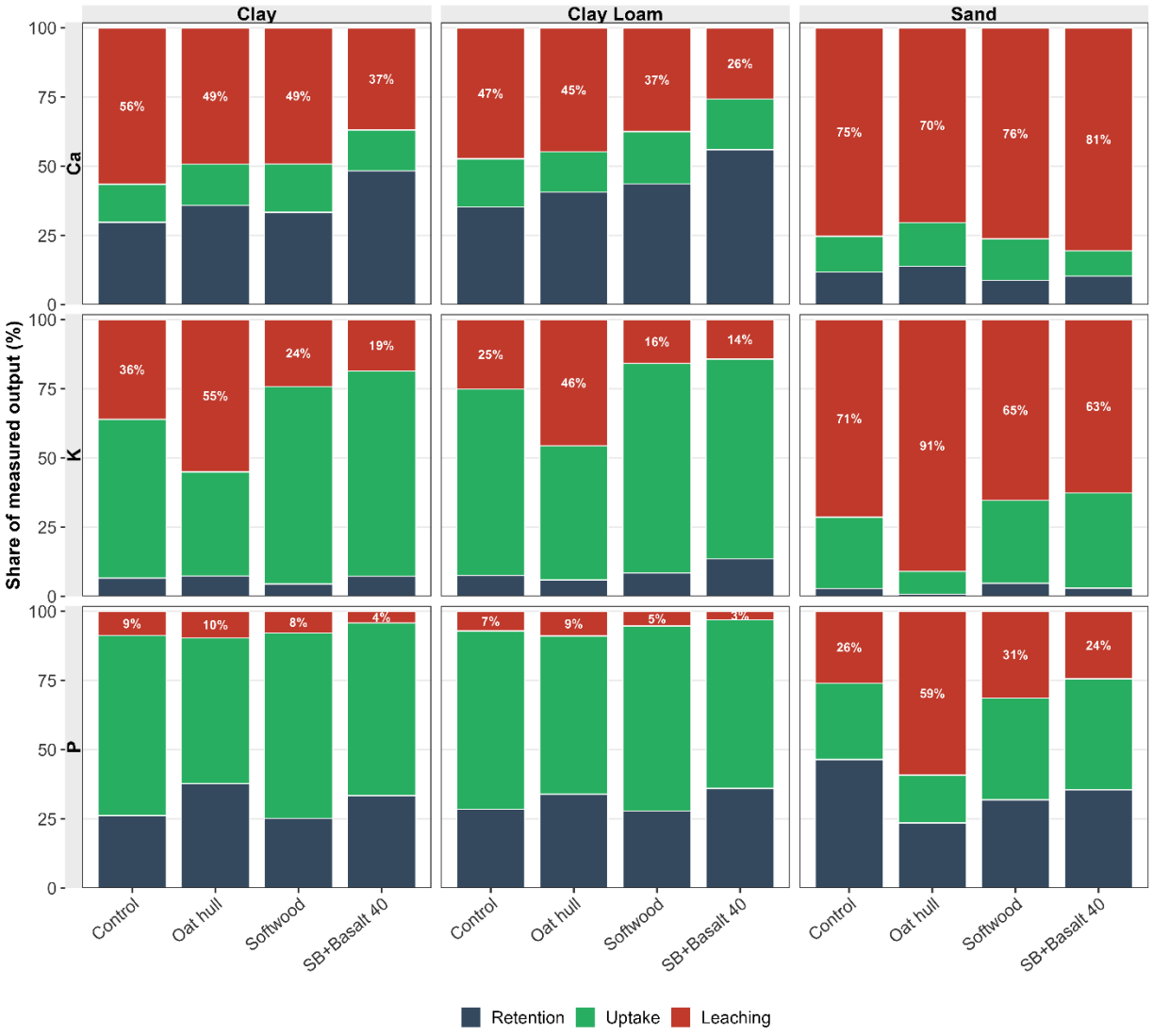


**Fig. 3** Partitioning of Ca, K, P among the three measured fates (soil retention, plant uptake, leaching) as a percentage of total measured output, by soil texture and treatment. SB+Basalt 40 = softwood biochar + basalt at 40 t $ha^{-1}$ each

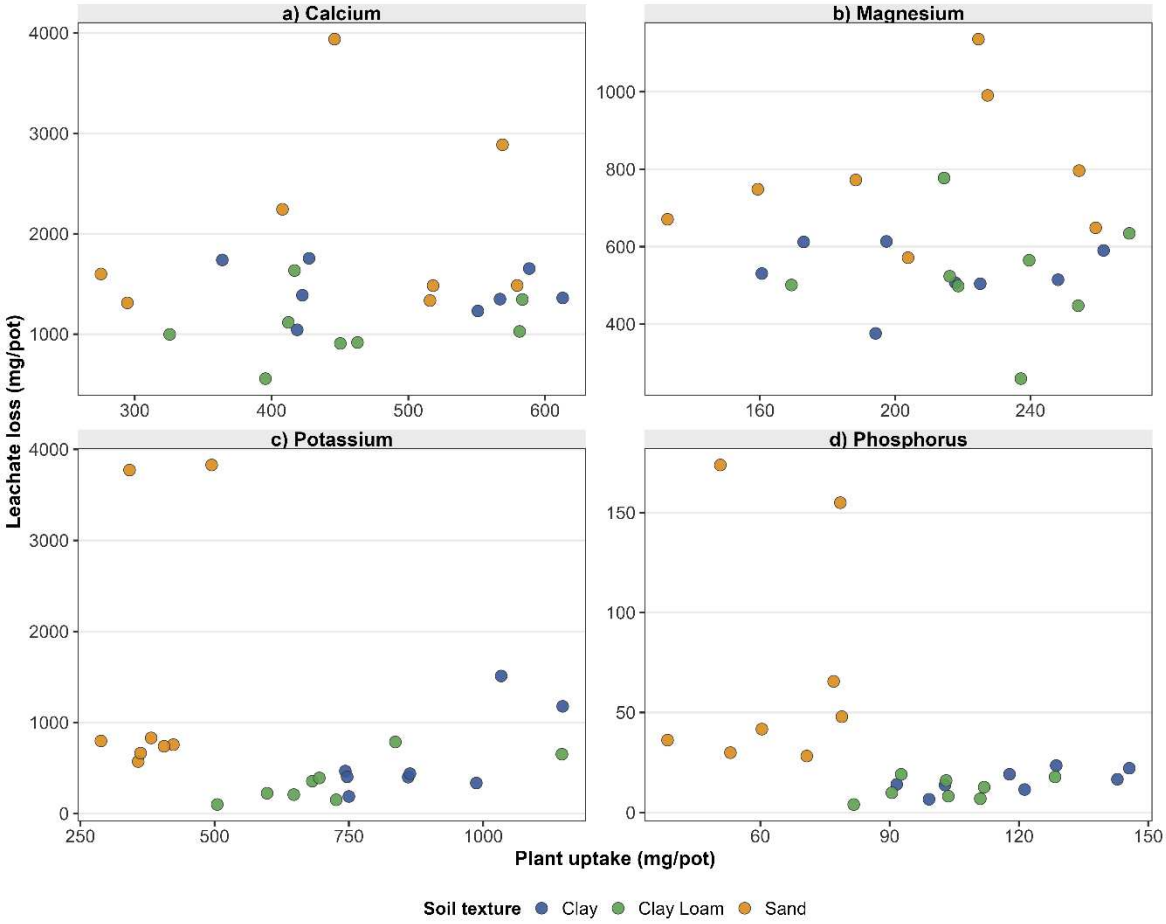


**Fig. 4** Cumulative leachate loss versus plant uptake for the four macronutrients (Ca, Mg, K, P), with points grouped by soil texture (Clay = blue, Clay Loam = green, Sand = orange). The spatial separation of textures illustrates the ECEC threshold: Clay and Clay Loam occupy a high-uptake, lower-leaching cluster, while Sand forms a distinct low-uptake, high-leaching band

Table 3. Two-way ANOVA F-values for macronutrient plant uptake (Soil Texture x Treatment), by crop. Numerator degrees of freedom: Soil Texture = 2, Treatment = 7, interaction = 14; residual df = 72. Uptake data are independent of the Mehlich III soil correction.

| Crop / Element | Soil Texture | Treatment | Soil x Treatment |
|---|---|---|---|
| Rye Ca | 189.7*** | 1.66 | 1.42 |
| Rye K | 247.8*** | 4.20*** | 2.33* |
| Rye Mg | 182.0*** | 1.41 | 1.05 |
| Rye P | 190.8*** | 5.07*** | 0.82 |
| Soybean Ca | 0.98 | 5.29*** | 0.85 |
| Soybean K | 7.69*** | 4.41*** | 1.22 |
| Soybean Mg | 3.61* | 3.47** | 0.86 |
| Soybean P | 4.68* | 1.87 | 1.07 |

* P < 0.05, ** P < 0.01, *** P < 0.001. Values without a flag are not significant. Full F- and P-values for all nine elements and both crops are in Online Resource 3.

**Multivariate structure of the soil nutrient response**

Principal component analysis of the nine Mehlich III soil nutrients (n = 192, May and November combined) provided an integrated view of how the soil nutrient status responded (Table 4a, Table 4b). The first component explained 48.7% of the total variance and the second 13.7% (cumulative 62.4%). This is a less strongly unidimensional structure than a single dominant axis would give, and the loadings explain why. PC1 was defined by Ca (-0.45), Mg (-0.44), Zn (-0.42), Mn (-0.40), and Al (-0.36), with Na loading moderately (-0.35). This is a coupled exchangeable-cation and oxide-metal axis, along which the elements retained on exchange and oxide surfaces rise and fall together. Notably, K and Cu did not load on this axis. They instead defined PC2 (K +0.67, Cu +0.61, opposed by Na -0.37), a separate dimension along which extractable K and Cu varied independently of the main nutrient-status gradient. Phosphorus was isolated on PC3 (-0.96) and loaded negligibly on the first two components.

Table 4a. Variance explained by the first five principal components of the nine Mehlich III soil nutrients (n = 192).

| Component | Std. dev. | Proportion (%) | Cumulative (%) |
|---|---|---|---|
| PC1 | 2.094 | 48.70 | 48.70 |
| PC2 | 1.110 | 13.70 | 62.40 |
| PC3 | 1.006 | 11.24 | 73.64 |
| PC4 | 0.912 | 9.23 | 82.87 |
| PC5 | 0.789 | 6.91 | 89.78 |

Table 4b. Loadings of the nine Mehlich III soil nutrients on the first three principal components. Loadings with absolute value >= 0.35 are in bold.

| Variable | PC1 | PC2 | PC3 |
|---|---|---|---|
| Ca | -0.45 | 0.02 | -0.01 |
| Mg | -0.44 | 0.03 | -0.03 |
| Zn | -0.42 | 0.01 | -0.14 |
| Mn | -0.40 | -0.03 | 0.04 |
| Al | -0.36 | 0.06 | -0.05 |
| Na | -0.35 | -0.37 | 0.03 |
| K | -0.06 | 0.67 | 0.05 |
| Cu | -0.10 | 0.61 | 0.24 |
| P | 0.05 | 0.17 | -0.96 |

PC1 (48.7% of variance): a coupled exchangeable-cation and oxide-metal axis (Ca, Mg, Zn, Mn, Al). PC2 (13.7%): a K and Cu axis. PC3 (11.2%): phosphorus.

Soil texture was the dominant axis of separation along PC1 (Fig. 5). The two finer-textured soils, Clay and Clay Loam, grouped together at the nutrient-rich (negative) end of the axis, while Sand

separated distinctly at the nutrient-poor (positive) end. Within the Clay and Clay Loam clusters, SB + Basalt at 40 t $ha^{-1}$ sat toward the nutrient-rich end. In Sand, all treatments clustered toward the nutrient-poor end.

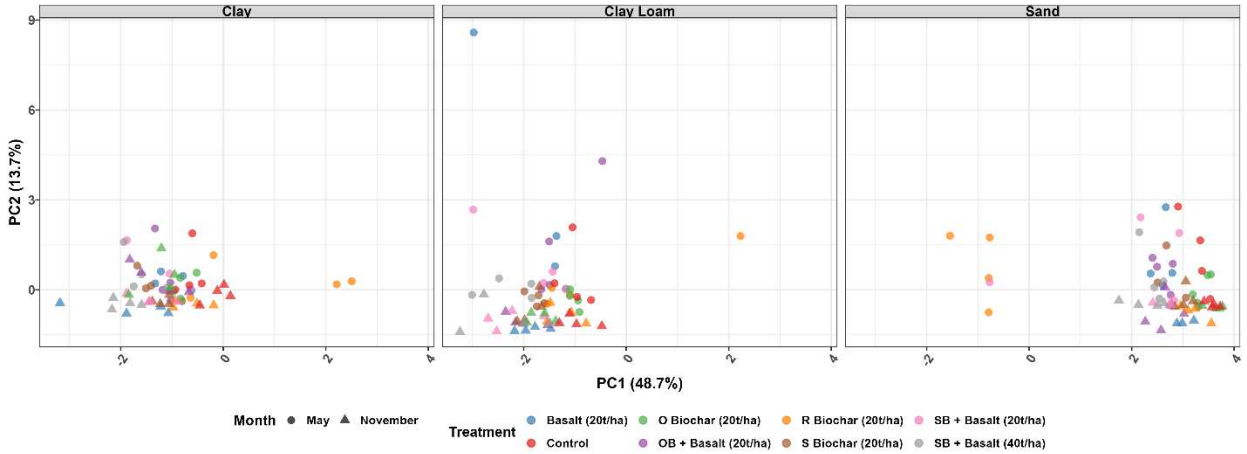


**Fig. 5** Principal component analysis of the nine Mehlich III soil nutrients (n = 192, May and November combined), faceted by soil texture. PC1 (48.7% of variance) represents an overall nutrient-status gradient. PC2 (13.7%) is driven mainly by K and Cu. Circles = May; triangles = November sampling

## Net export of exchangeable Ca, Mg, and K reverses direction across the texture gradient

Integrating leachate and plant losses into a single net export of exchangeable Ca, Mg, and K term (Ca + Mg + K in meq per pot) confirmed that the same amendment could conserve or deplete exchangeable cations depending on the soil (Fig. 6). The two-way model showed a highly significant Soil Texture by Treatment interaction ($F = 4.55$, $P < 0.0001$) and a strong soil main effect ($F = 31.3$, $P < 0.0001$), while the treatment main effect was not significant ($F = 1.37$, $P = 0.231$, $R2 = 0.654$). In other words, no amendment had a consistent effect on export of exchangeable Ca, Mg, and K across soils. Its effect depended entirely on the soil it was applied to.

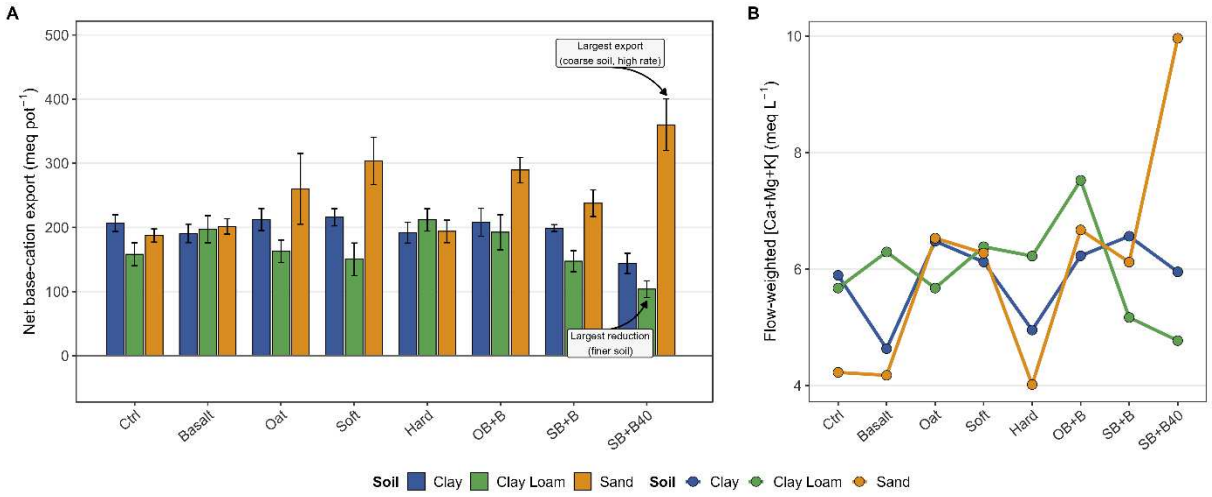


**Fig. 6** Net export of exchangeable Ca, Mg, and K (Ca + Mg + K in meq pot-1) by soil texture and treatment (panel A) and flow-weighted leachate cation concentration (meq $L^{-1}$, panel B). Compared with Control (Ctrl), SB + Basalt 40 t $ha^{-1}$ reduced net export by 30% in Clay and 34% in Clay Loam (CL) but raised it by 92% in Sand, illustrating the soil-dependent reversal governed by the ECEC threshold. Error bars = +/- 1 SE (n = 4)

The reversal was clearest for the most intensive treatment. Relative to Control, SB + Basalt at 40 t $ha^{-1}$ reduced net export of exchangeable Ca, Mg, and K by 30% in Clay and 34% in Clay Loam but raised it by 92% in Sand (360 versus 187 meq per pot). The treatment that best conserved exchangeable cations in the finer soils was the worst offender in the coarse soil. Indeed, net export in Sand exceeded the finer-soil mean for seven of the eight treatments, the single exception being hardwood biochar (Sand 194 versus a finer-soil mean of 202 meq $pot^{-1}$).

Flow-weighted leachate cation concentration did not differ significantly among soils (Sand 6.00, Clay 5.85, Clay Loam 5.96 meq $L^{-1}$, soil effect P = 0.868). Drainage volume, by contrast, did differ: Sand pots drained 34.2 L over the experiment versus 22.8 and 17.4 L for Clay and Clay Loam. SB + Basalt at 40 t $ha^{-1}$ raised the flow-weighted concentration in Sand to 9.96 meq $L^{-1}$, well above the 4.0 to 6.7 meq $L^{-1}$ range of the other Sand treatments, and this combination produced the highest export of any Soil Texture by Treatment combination.

## Discussion

### Standard soil tests miss mineral-locked nutrients

The macronutrient residuals were negative in every combination. Measured outputs therefore exceeded the inputs that Mehlich III could detect. Because these elements are non-volatile, gaseous loss cannot explain the gap. The missing source must be mineral dissolution and organic matter mineralization during the growing season. Irrigation water supplied only about 6 to 17% of the gap. Most of the unaccounted supply therefore came from the native soil. The very large negative

Na residuals point the same way. These soils received Na in irrigation water and also released Na through mineral weathering.

Aluminum is a different case. In the acid, fluoride-containing Mehlich III extractant, extractable Al reflects acid-soluble and mineral-associated Al. It does not isolate the exchangeable Al pool, which the companion paper showed to be negligible in these limed soils (Imoro et al., in review, Table 2). Exchangeable Al was therefore not a meaningful constraint here. We treat the Al residuals as a mineral-phase term and do not interpret them further.

The dual-residual analysis shows that part of this hidden supply came from the amendments themselves. For slow-release mineral amendments, a budget built on a standard extractable soil test can miss most of the nutrient actually applied. For basalt Ca, the MIII budget captured about 8% of what was added. This is not a failure of mass conservation. It is a failure of the availability index to represent a pool that dissolves over years rather than months. Reviews of silicate rock powders likewise describe them as slow-release amendments with medium- to long-term effects (Swoboda et al. 2022). And assessment of basalt that relies on MIII values alone will underestimate its nutrient contribution. It will also underestimate its contribution in a long-term nutrient supply.

**Recovery rates differentiate suppliers from conditioners**

Rye uptake was controlled mainly by soil, whereas soybean uptake responded to the amendments. This shift is consistent with amendments needing time to alter the plant-available pool. Interactions were nonsignificant for every macronutrient in soybean. Where treatment effects on uptake emerged, they were consistent across soils. This contrasts with the soil-dependent leaching responses reported in the companion paper. Raw uptake, however, cannot show how efficiently each amendment converted its nutrient load into crop uptake. The recovery metrics do this by normalizing uptake to the amendment input.

As noted in the Methods, ARE above 100% is not an artifact. It is the signature of a soil conditioner. Such an amendment supplies little of an element, yet the plant captures more of it than was applied because native reserves are released. Basalt's ARE values (112 to 8,100%) are exactly what this hypothesis predicts. Basalt supplied almost no immediately available nutrient. Yet it improved the plant's access to native and mineral-locked pools in all three textures. The effect was strongest in Sand, where the relative improvement over a nutrient-poor baseline was largest. This agrees with earlier work in which finely ground basalt raised pH and exchange capacity in highly weathered soils (Anda et al. 2015; Gillman et al. 2002). Kelland et al. (2020) likewise found that basalt raised sorghum yield by about 21% without P or K fertilizer. In that study, the released base cations accumulated mainly in exchangeable pools.

Oat hull biochar showed the opposite, fertilizer-like pattern. It supplies K in large, immediately available amounts, so its K ARE stayed well below 100%. Biochars made from herbaceous feedstocks at low temperature hold much of their K in water-soluble forms (Bilias et al. 2023). Oat hull biochar's 40.5% K recovery in Clay is close to the roughly 40% efficiency commonly cited for K fertilizers (Baligar et al. 2001). In the coarse soil, however, most of the K leached before the

plant could recover it. Recovery fell more than fivefold across the texture gradient, for the same amendment and the same input. This is the clearest single expression of how exchange capacity governs the fate of an applied nutrient.

Negative ARE values were concentrated in the high-input treatments in the finer soils. A large soluble load appears to have shifted the balance of competing cations. It may also have promoted co-mobilization rather than uptake. Under oat hull biochar, the lower Ca and Mg recovery is consistent with its large K load displacing these cations from exchange and uptake. Potassium is known to suppress Mg uptake more strongly than Mg suppresses K uptake (Xie et al. 2021). Negative ARE therefore shows an input that is not merely inefficient. It is actively counterproductive for the element in question.

**Exchange capacity influences nutrient fate and net export**

The fate partitioning showed that Sand had almost no capacity to hold exchangeable cations against drainage. SB + Basalt at 40 t $ha^{-1}$ redirected Ca from leaching toward retention only where the soil could hold it. Potassium showed that feedstock can override texture. Under oat hull biochar in Sand, cumulative K leaching reached 500% of the K present at the start plus the K applied. The biochar therefore mobilized native soil K as well as leaching its own large input. Phosphorus fate reflected its strong retention chemistry in the finer soils, where leaching stayed minor. In Sand, oat hull biochar overwhelmed a limited P sorption capacity, as it did for K.

These results qualify the view that biochar reliably benefits sandy soils. A recent systematic review reported that biochar improves nutrient cycling and crop yield in sandy-textured soils (Bekchanova et al. 2024). Our data show that this benefit is not guaranteed. It fails when a biochar carries a large soluble nutrient load and the soil has very little exchange capacity to hold it.

The trace metals told a consistent story of pH-mediated retention. SB + Basalt at 40 t $ha^{-1}$ lowered the leaching fractions of Al, Mn, Cu, and Zn. This suggests that the pH increase shifted these metals from solution onto soil surfaces. Biochar is also known to lower contaminant mobility through sorption on its surfaces (Beesley et al. 2011). This result is the fate-partitioning counterpart of the strong pH-metal correlations in the companion paper. Even in Sand, where exchangeable-cation retention failed, the amendment still curbed trace-metal loss through its effect on pH.

The principal component analysis showed that the soil fertility response was only partly unidimensional. About half of the total variance followed a single exchangeable-cation and oxide-metal axis. Potassium, Cu, and P each varied along their own dimensions. This matches the element-specific fate patterns described in the Results. Potassium responded to amendment loading in a way the exchangeable cations did not. Phosphorus, held by sorption in the finer soils, behaved differently again. The multivariate analysis and the mass balance thus agree that no single mechanism governs these elements.

In the finer soils, SB + Basalt at 40 t $ha^{-1}$ sat toward the nutrient-rich end of PC1. This fits its role as the most effective treatment for maintaining exchangeable cation status there. All Sand

treatments clustered at the nutrient-poor end. In that soil, limited exchange capacity prevented any amendment from sustaining soil nutrient levels. This separation mirrors the exchange-capacity gradient that governed nutrient fate and recovery.

The flow-weighted analysis identified the mechanism behind the net-export reversal. Drainage water from the three soils carried a similar cation concentration. Sand's greater export of exchangeable Ca, Mg, and K was therefore volume-driven. It reflected rapid drainage through a soil that could not hold water, not a more concentrated leachate. This differs from a field study on a Colombian savanna Oxisol. There, biochar increased Ca, Mg, and K leaching in the upper profile through higher solution concentrations, not greater water flow (Major et al. 2012). Where our amendment did concentrate the leachate, it made matters worse in Sand. A more concentrated leachate then combined with a large drainage volume.

Net export of exchangeable Ca, Mg, and K therefore behaved as a soil-dependent property governed by exchange capacity. In Clay and Clay Loam, the sum of exchangeable Ca, Mg, and K was high enough to hold released cations. There, the softwood biochar plus basalt combination retained exchangeable cations and reduced export. In Sand, the sum was very low (1.7 cmolc $kg^{-1}$, below roughly 4 cmolc $kg^{-1}$). There, the same combination accelerated the loss of exchangeable Ca, Mg, and K. This single net-export term captures the amendment-soil matching problem that runs through the whole budget.

**Implications for amendment-soil matching**

Read together, the budget, the recovery metrics, and the net-export analysis point to one practical conclusion. Amendment value cannot be judged from the amendment alone. A standard MIII budget can miss up to 92% of a slow-release amendment's total nutrient content. Routine soil testing therefore understates basalt's contribution. The same physical input can also act as a fertilizer in one soil and a pollutant source in another. Oat hull biochar returned 40% of its K to the crop in Clay but only 7% in Sand. Basalt's extreme ARE values (112 to 8,100%) mark it as a soil conditioner. Its benefit is mediated through the soil rather than delivered directly.

The governing variable is the soil's exchange capacity. It operates as a continuous gradient rather than a single fixed cutoff. This is in line with meta-analytic evidence that biochar yield responses depend strongly on soil conditions (Jeffery et al. 2017). With only three soils, we cannot locate a precise threshold. The direction, however, is consistent across every metric in this paper and the companion paper. As the sum of exchangeable Ca, Mg, and K fell from 7.5 to 5.7 to 1.7 cmolc $kg^{-1}$, recovery fell, leaching fractions rose, and net export increased. The qualitative break fell somewhere below roughly 4 cmolc $kg^{-1}$. Above this range, amendments that raise pH and add exchange capacity shift nutrients from leaching toward retention and uptake. In such soils, the biochar-basalt combination is a sound investment. Near or below this range, as in our Sand, the same amendments can accelerate nutrient loss. A high-availability biochar in particular should not be applied without weighing its nutrient load against the soil's retention capacity. Amendment

type and rate should therefore be matched to the soil's exchange capacity. That decision, rather than the merits of the amendment alone, determines whether the input is recovered or lost.

## Conclusions

This companion study constructed closed, multi-element nutrient budgets and nutrient use efficiency metrics for biochar and basalt amendments across three Ultisol textures. Seven conclusions follow.

First, Mehlich III systematically underestimates the nutrient supply of these soils and their amendments. Macronutrient residuals were negative in every combination, showing a large native supply from mineral dissolution and organic matter mineralization that the standard test does not capture. For a slow-release mineral amendment such as basalt, switching from the MIII input to the total elemental input moved the Clay Ca residual from -1,760 mg to -348 mg per pot. The residual stayed negative, but the shift recovered most of the apparent deficit, and the 7.8% extractability shows the MIII budget saw only about 8% of the Ca actually applied.

Second, apparent recovery efficiency cleanly separates the two amendment strategies. ARE exceeded 100% in 33 of 84 combinations and reached 112 to 8,100% for basalt, the diagnostic signature of a soil conditioner that mobilizes native nutrients rather than supplying its own (only 7.8% of basalt Ca and 3.6% of basalt Mg were extractable at application).

Third, the soil exchange-capacity gradient governs nutrient recovery. Oat hull biochar K recovery fell from 40.5% in Clay (sum of exchangeable Ca, Mg, and K 7.5 cmolc $kg^{-1}$) to 33% in Clay Loam (5.7) to 7% in Sand (1.7), a more-than-fivefold decline for the same amendment and input, driven entirely by the soil's declining ability to retain K against leaching.

Fourth, nutrient fate partitioning followed the same gradient. SB + Basalt at 40 t $ha^{-1}$ shifted Ca from leaching toward retention in the finer soils (Ca leaching fraction dropped from 56% to 37% in Clay and from 47% to 26% in Clay Loam) but failed in Sand, where leaching remained at 81%. Amendments that raise exchange capacity redirect nutrients only where the soil has enough exchange capacity to hold them, that is, where the sum of exchangeable Ca, Mg, and K is above roughly 4 cmolc $kg^{-1}$.

Fifth, the same amendments curbed trace-metal loss even where they failed to retain exchangeable cations. SB + Basalt at 40 t $ha^{-1}$ reduced the leaching fraction of Al, Mn, Cu, and Zn in all three soils, cutting the Sand Cu leaching fraction from 46% to 16% and Zn from 19% to 4% through its effect on pH.

Sixth, net export of exchangeable Ca, Mg, and K reversed direction across the texture gradient. The Soil Texture by Treatment interaction was highly significant while the treatment main effect was not ($P = 0.231$), so no amendment had a consistent effect across soils. SB + Basalt at 40 t $ha^{-1}$ reduced export by 30% in Clay and 34% in Clay Loam but raised it by 92% in Sand. The Sand effect was volume-driven, and where the amendment also concentrated the leachate (flow-weighted 9.96 versus 4.0 to 6.7 meq $L^{-1}$), export was highest of all.

Seventh, pairing closed nutrient budgets with NUE metrics provides a diagnostic framework that neither approach gives alone. The budget reveals hidden mineral pools and native supply, while the recovery metrics reveal whether applied nutrients reach the crop. Together they show that amendment value is a property of the amendment-soil combination, not of the amendment alone, and they give farmers and land managers a basis for matching amendment type and rate to soil exchange capacity.

## Statements and Declarations

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**Competing interests.** The authors declare no competing interests.

**Author contributions.** R.I. conceived and conducted the experiment, performed the analyses, and wrote the manuscript. A.W. supervised the work and edited the manuscript. W.S. and H.L. contributed to methodology and manuscript revision and editing. All authors read and approved the final manuscript.

**Data availability.** The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

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