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Basalt Rock Dust Amendment on Soil Health Properties and Inorganic Nutrients—Laboratory and Field Study at Two Organic Farm Soils in New England, USA

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Abstract: Basalt rock dust (RD) is a rock quarry byproduct that may improve soil health in organic farming systems. RD was applied at two contrasting organic farms (the no-till VT-Farm in Thetford, Vermont, and the tilled MA-Farm in Barre, Massachusetts) and in soil batch reactors to investigate the impacts of basalt RD applications (6.7 tons ha^{-1}) on physical and chemical soil health properties. Triplicate soil pits at two fields (RD and no RD) at each farm were sampled down between 80 to 110 cm depths in 2020. Median coarse (>2 mm) and very coarse aggregates (>50 mm) increased by 15% to 25%, and soil organic carbon concentrations increased by 69% to 135% for RD added, compared to no RD, in the top 20 cm of the soil profile at both farms. Plant-available Ca, Mg, and K increased between 62% and 252% in the top 30 cm for both farms. Plant-available micronutrients (B, Mn, Cu, and Zn) showed limited increases from the RD addition at the two farms. The laboratory batch reactor results confirm the increased Ca and Mg release rates tested across soils, but K, P, and the micronutrient batch reactor results did not increase from the RD addition. One contrary finding was (−41% at the VT-Farm) the lower plant-available P and soluble P (−5 to −29%) under the RD addition, suggesting that further studies on the interactions with Fe and pH from the RD addition are warranted.

Keywords: soil nutrients; rock dust; rock powder; macroaggregates

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1. Introduction

Organic farming is an increasingly important agricultural, economic, and sociocultural system across New England and other states, with over 1400 certified organic farms in 2021 across Connecticut, Maine, Massachusetts, Rhode Island, New Hampshire, and Vermont [1]. These farms produce staple grains, vegetables, fruits, beef, eggs, chicken, and many more regional and specialty products, such as hemp and maple syrup, with sales over $250 million USD in 2021 [1]. Organic farming suffers from similar issues as conventional agricultural systems in maintaining soil health parameters, specifically physical and chemical health properties through amendments [2]. Unlike conventional agricultural systems, organic farms must follow core principles to maintain their USDA certified status and cannot use synthetic chemicals or petrochemical fertilizers to supplement nutrient losses. Thus, the development of organic-certified, non-petrochemical soil amendments is needed to maintain or improve soil health criteria, which is essential for organic farms across New England, and other states across the USA.

Rock dust (RD) is a soil amendment comprising rock quarry byproducts, from gravel to clay-sized particles, and may improve soil health. RD can be composed of materials with varying particle size distributions and lithologies, ranging from igneous rocks (e.g., granites, dunites, and feldspathoids) to metamorphic rocks (e.g., serpentine, gneiss, and metabasalts) [3,4]. In particular, the application of basalt RD is increasingly popular for enhanced rock weathering (ERW), which consumes atmospheric CO_2 through aluminosilicate dissolution, carbonic acid to bicarbonate conversion, and base cation release [5,6]. Field experiments and modeling estimates suggest that CO_2 sequestration from ERW can sequester 0.2 to 0.4 tons of CO_2 per ton of basalt RD added [5,6], with experimental application rates of basalt RD of 1.6 up to 400 tons of ha^{-1} [4,5]. The effects of basalt RD on physical and chemical soil health properties via field and greenhouse studies remain poorly constrained due to the heterogeneity in basalt lithology, particle size composition of the RD, agricultural methods applied to soils, and the response from strongly contrasting soil properties.

Beyond CO_2 sequestration, other physical and chemical properties and changes to the soil are important understudied dimensions of RD impacts on soil health and agricultural systems. Basalt RD releases inorganic macronutrients (P, K, Ca, and Mg) and micronutrients (Mn, B, Cu, and Zn), which are essential for crops due to their roles in chemical signaling, protein structures, cellular structures, enzyme co-factors and many other roles in plants and humans [7]. Inorganic macronutrients and micronutrients are sourced from the dissolution of minerals present in basalt RD, specifically olivine, augite, diopside, apatite, and anorthosite [5,8]. These minerals contain important inorganic macro and micronutrients as major structural components, or they are isomorphically substituted within the minerals at trace concentrations [4,7]. Lastly, elements, such as B, may be present within additional trace accessory minerals [7]. Field trials and greenhouse studies have shown mixed effects on agricultural soils. In sorghum (*Sorghum bicolor*) field trials, Kelland et al. [5] found basalt RD addition had significantly higher soil Si and Mg but not Ca or soil pH. In a greenhouse study conducted by Vienne et al. [8], soil and soil leachate, Ca, Mg, and K significantly increased with the addition of basalt RD, but soil pH was not affected. The weathering of basalt RD can also promote the precipitation of secondary Al and Fe oxyhydroxide minerals that may immobilize nutrients, particularly phosphate [9,10]. Furthermore, these neo-formed secondary Al and Fe oxyhydroxides can help promote and protect soil organic carbon (SOC). All of these coinciding processes altering SOC, pH, inorganic nutrients, micronutrients, aggregation, and other soil health properties from RD can affect soils and crop production and have been understudied in temperate organic farming systems. Before RD can be applied at scale, field trials in organic farms in temperate regions are needed to evaluate if RD does have the intended effects.

The overall objective of this study was to leverage existing fields at two contrasting organic farms and laboratory experiments to investigate the impacts of basalt RD applications on physical and chemical soil health properties as well as inorganic nutrient availability for plants. These two farms are contrasting in soil textures commonly found in the New England region: sandy loam in glacial till areas and silt loams found in major river floodplains. Furthermore, these two farms contrast in the application of tillage, with no-till applied to rocky, sandy loam soil and conventional tillage applied to silt loam. Lastly, these two farms had RD applied two years before sampling. In the first hypothesis, it was expected that basalt RD treatments would increase in soil health properties, specifically macroaggregation, %C, and soil pH from the addition of fine particles and the weathering of the RD. In the second hypothesis, it was expected that RD weathering would increase plant-available nutrient (both macro and micronutrient) concentrations and pools compared to a control field without treatments. In the third hypothesis, laboratory batch reactor experiments were conducted to confirm if enhanced nutrient release rates from RD would yield higher nutrient releases and if the type of RD added would impact the nutrient release rates. This information is needed to quantify if ERW can provide co-benefits of soil health parameters (C storage, aggregation, and nutrient pools) in organic farming systems, particularly the understudied aspects of inorganic nutrients and aggregation.

2. Materials and Methods

2.1. Study Farms and Soil Sampling

Both farms studied are located in the New England region of the United States (Figure 1A; Table 1). The Cedar Circle Farm and Education Center (hence referred to as the VT-Farm) is an organic farm located in Thetford, Vermont, along the floodplain in the Connecticut River Valley (Figure 1B). Using the Köppen climate classification, the climate is Dfa, with humid, continental mild to hot summers with no dry season. The 30-year average mean annual temperature is 5.4 °C and receives 1067 mm of precipitation [11]. The coldest month has an average temperature below −11 °C, and the warmest month averages a daily high of 28 °C. The VT-Farm is in USDA Plant Hardiness Zone 4, and the outdoor growing seasons are approximately 5 months per year. Soils at the VT-Farm are silt loams Entisols derived from recent reworkings of glaciofluvial deposits and glacial outwash (Figure 1C,D; Table 1). The plots studied at the VT-Farm undergo conventional tillage (10″ disk plows) twice per year prior to cover cropping and planting. The VT-Farm produces diversified organic vegetables: Cucurbitaceae, Apiaceae, Brassicaceae, Amaryllidaceae, and Fragaria (strawberries). Cover crops at the VT-Farm were either unseeded fallow or mixes of Sudangrass (Sorghum drummondii), Winter Rye (*Secale cereale*), Hairy Vetch (*Vicia villosa*), and White Clover (*Trifolium repens*). Soils in both fields are limed every four to five years (pelletized calcium lime), and manure and compost applications are limited to every four years. RD was added in 2019 at a rate of 6.7 tons per hectare (3 tons per acre) as recommended by the manufacturer, Rock Dust Local LLC (Bridport, VT, USA).

The Many Hands Farm (hence referred to as the MA-Farm) is an organic farm located in Barre, Massachusetts (Figure 1A) in the hill terrain of the central location of the state (Figure 1E). Based on the Köppen climate classification, the climate is borderline Dfa and Dfb, with humid, continental mild to hot summers and no dry season. The mean annual temperature is 8.1 °C, and the farm receives 1295 mm of precipitation based on a 30-year average [11]. The coldest month has a daily low of −10 °C and the warmest month has an average daily high of 28 °C. The MA-Farm is in USDA Plant Hardiness Zone 5a, and the outdoor growing seasons are approximately 5 months per year. Soils at the MA-Farm are sandy loam Inceptisols, formed from ablation glacial till (Figure 1F,G). Contrary to NRCS mapping, the soils are young, rocky Inceptisols (Table 1), which may have been Spodosols prior to deforestation and conversion to agricultural lands. The plots studied at the MA-Farm are no-till and are used for the rotation of root and vegetable crops: Brassicaceae, Cucurbitaceae, Solanaceae, Betoideae, and Apiaceae. Approximately 6.7 tons of ha^{-1} (3 tons per acre) of basalt RD were added to the RD-added field in 2015, also following the manufacturer's guidance.

Soil sampling at both farms occurred in the spring of 2021 prior to tillage and planting. The VT-Farm had winter wheat (*Triticum aestivum*) present, while the MA-Farm had fallow with Brassicacea stalks. Three non-edge locations in the RD-added field and the adjacent control field were chosen at both farms. At each of the three sampling locations in each field, one soil pit was excavated using spades down to at least a 0.8 m depth and sampled in 5 cm × 10 cm × 10 cm blocks for the top 20 cm and 10 cm × 10 cm × 10 cm blocks. The VT-farm's soils were sampled up to a depth of 110 cm, corresponding to the bottom of the Bw horizon, while the MA-farm's soils were sampled down to 80 cm, at the bottom of the Bw horizon and the top of the Bx horizon. In total, there were six soil pits at the MA-Farm and six soil pits at the VT-Farm. Each 5 cm- and 10 cm-deep rectangular block was carefully removed from the face of the soil pit, put into 7.6 L LDPE bags, and brought back to the University of Massachusetts Amherst for processing. Soil bulk density was determined using the dry soil mass collected from each block.

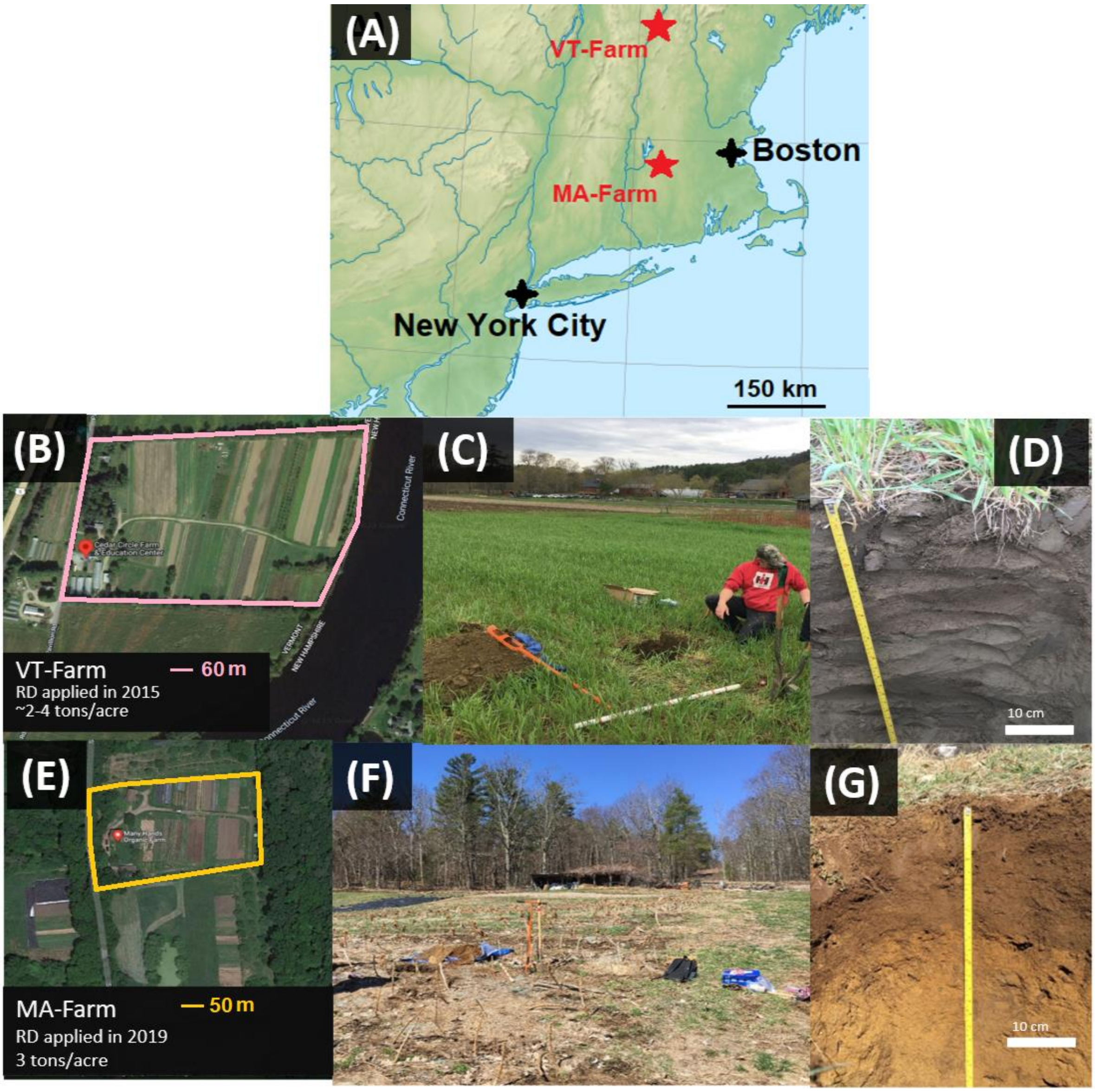

Figure 1. Panel 1 (**A**) shows the location of the two studied farms. Panel 1 (**B**) shows the VT-Farm and fields. Panel 1 (**C**) shows the collection of soils and 1 (**D**) shows the soil profile at the VT-Farm. Panel 1 (**E**) shows the MA-Farm and its fields. Panel 1 (**F**) shows the collection of soils and 1 (**G**) shows the soil profile at the MA-Farm. https://spj.science.org/doi/full/10.34133/remotesensing.0093 (accessed on 10 December 2024).

Table 1. Description of farm location, climate, and soil properties. Lat is latitude, Long is longitude, MAT is mean annual temperature, and MAP is mean annual precipitation.

Farm	Tillage	Year Certified Organic [1]	Lat	Long	Elevation	MAT [2]	MAP [2]	Soil Great Group	Soil Texture
			dms	dms	m	°C	cm		
VT-Farm	Conventional tillage	2004	43°48′	72°11′	122	5.4	98	Typic Udifluvents	Silt Loam
MA-Farm	No-Till	2002	42°25′	72°09′	309	7.1	107	Typic Dystrudepts	Sandy Loam

[1] United States Department of Agriculture Certified Organic. [2] PRISM climate data [11].

2.2. Aggregate Separation, Particle Size, and Mineralogy

The formation of large macroaggregates (soil peds) was examined, which were separated through dry sieving of field-moist soils using the combination of sieving procedures described by Helgason et al. [12]. Briefly, 500 g field-moist soils were sieved using a custom 50 mm sieve and a 2 mm sieve for 15 s on a Retsch sieving machine (Retsch GmbH., Haan, Germany). The retained, very coarse aggregates (>2 mm) were collected. The soil that passed through the 2 mm sieve was also collected to determine the non-coarse aggregate mass, including both loose soils and microaggregates together. All visible plant residues, fauna, and stones were removed before and again after the sieving procedure.

To determine the particle size distribution of the soils, a modified Bouyoucos hydrometer method was used [13]. First, loss-on-ignition (LOI) was used to remove organic matter. Next, 100 mL of the 1 M sodium hexametaphosphate (HMP) solution was added to the soil for at least 8 h to disperse soil particles. This HMP-soil slurry was washed out into a 1000 mL graduated cylinder with DI water. The hydrometer readings were taken at 1.0 min, 1.5 min, 1.5 h, and 2 h after mixing to the closest 0.5 g L^{-1} to determine the settling of sand and silt particles, with the clay particles being inferred from the remaining mass in the solution [13].

Mineralogical characterization of the soil and basalt samples was performed via X-ray Diffraction on random powder mounts and orientated mounts for in-depth clay mineral identification. For quantification, approximately 0.5 g of each sample was mounted on a glass slide and analyzed between 5° and 55° 2θ (0.02° resolution, 1° min^{-1}) using Rigaku Miniflex-2, equipped with a Cu Kα X-ray source. Quantification was performed using the Rietveld whole pattern profile fit module in PDXL2 (Rigaku Corporation 2007–2017). In-depth clay characterization consisted of comparing peak positions and intensities across three dedicated treatments for each sample: air drying, ethylene glycol solvation, and 400 °C heat treatment for 35 min, according to [14,15].

2.3. Soil Chemical Analyses

A 2:5 soil−water slurry was used to determine soil pH. A 4.0 g subsample of the bulk soil was combined with 10 g of a 0.1 M CaCl2 solution. The slurries were shaken for 1 h using a reciprocal shaker and filtered through a Whatman 40 filter. The pH of the supernatant extract was measured with a pH meter (8015 VWR).

For the total organic C measurement, a 1.0 g subsample of the bulk soil was acidified with 2 mL of 1 M HCl to remove any inorganic C. The subsample was then re-dried, ground with an agate mortar and pestle, and passed through a 0.10 mm sieve. Next, 15 mg of the ground, acidified subsample was weighed and folded in tins and analyzed for C using a Costech Elemental Combustion System 4010 analyzer (Costech Analytical Tech Inc., Valencia, CA, USA). Every 10 samples included a blank and two continuing calibration verification (CCV) materials: acetanilide and atropine. Recovery rates for CCV were 100.1%, and the coefficient of variation (CV) was 0.3%.

Soils were extracted for plant-available nutrients. For this extraction, 2.00 g of soil was weighed into 50 mL centrifuge tubes, extracted with 30 mL of unbuffered 0.1 M ammonium acetate via shaking for 8 h, and set still for an additional 16 h to reach a dynamic equilibrium. The soil slurry was then centrifuged at 3000 rpm for 1.5 h, and the supernatant was collected. Soils were not ground to avoid creating fresh surfaces for the dissolution of newly exposed minerals. With every 20 samples, a preparation blank, a duplicate, and a CCV were included. San Joaquin Soil 2709a from the National Institute of Standards and Technology (NIST, Gaithersburg, MD, USA) was used as a CCV. The extracts were analyzed for Ca, Mg, K, P, B, Mn, Cu, and Zn with an Agilent 5110 Inductively Coupled Plasma Optical Emission Spectrometer (Agilent Technologies Inc., Santa Clara, CA, USA). Due to background contamination and wavelength interferences, the limits of quantification (LOQ) were as follows: Ca 0.10 mg L^{-1}, Mg 0.10 mg L^{-1}, K 0.10 mg L^{-1}, P 0.05 mg L^{-1}, B 0.03 mg L^{-1}, Mn 0.03 mg L^{-1}, Cu 0.03 mg L^{-1}, and Zn 0.03 mg L^{-1}. There were no certified values for plant exchangeable concentrations for the NIST San Joaquin soil; however, CV was within 7% for all elements. The CVs for CCVs were as follows: Ca 0.2%, Mg 0.2%, K 0.3%, and P 0.1%, which were at 1 mg L^{-1} and B 0.3%, Mn 0.3%, Cu 0.4%, and Zn 0.3%, which were at 0.1 mg L^{-1}.

2.4. Batch Reactors

Batch reactors were conducted using three New England soils (MA, VT, and NH) to evaluate if the element release rates matched the field observations and if the physical composition of the RD affected nutrient releases. Three A horizon soils from three agricultural soils (Table 2) were used: Chatfield soil series (Typic Dystrudepts), collected from Whatley, MA, Glover soil series (Lithic Dystrudepts), collected from Weathersfield, VT, and Rumney soil series (Fluvaquentic Endoaquepts), collected from Haverhill, NH. All three soils were organic pasturelands or croplands and had not been limed or received synthetic fertilizers in the past 10 years. In brief, 5.000 g $\pm$ 0.010 g of soil was weighed into each tube and immersed in 30 mL of a treatment solution in acid-washed 50 mL centrifuge tubes. In total, sixteen unique treatments were applied with five replicates. Control: Only the VT-Farm soil, which was repeated four times, with each of the addition rates controlling for differences among batches. Three treatments were tested: The control (which only had soil and no RD added), RD Treatment 1 (which included 0.4 g of RD corresponding to 5 tons of the ha^{-1} application of the commercially available Holyoke Basalt, mixed homogeneously within 10 cm of the soil) and RD Treatment 2 (which also included 0.4 g of RD, a further sieved rock powder with a higher proportion of silt). RD Treatment 1 contained the unaltered commercial product at ~80% sand, ~18% silt, and 2% clay) while RD Treatment 2 was a refined product with ~60% sand (~38% silt and 2% clay). For the refining process, 1 kg of commercial basalt from Rock Dust Local was dry-sieved to <0.05 mm to remove sand-size particles, which were added back to the finer particles at pre-determined rates to generate the desired sand content. This was done to simulate potential sieving to finer particles conducted by a manufacturer. RD was not crushed, achieving a higher clay content because crushing can be cost-limiting in RD production.

Table 2. Batch reactor soils physicochemical properties.

	Soil Series	**Soil Great Group**	**Texture**	**Soil pH**	**%SOC**
VT-Soil	Glover	Lithic Dystrudepts	sandy loam	5.4 $\pm$ 0.3	2.3 $\pm$ 0.4%
MA-Soil	Chatfield	Typic Dystrudepts	sandy loam	5.2 $\pm$ 0.3	1.7 $\pm$ 0.4%
NH-Soil	Rumney	Fluvaquentic Endoaquepts	sandy loam	5.1 $\pm$ 0.2	2.1 $\pm$ 0.4%

For each batch reactor, 30 mL of an artificial soil solution of 10 mM NaCl at pH 6.5 with a 10 mM acetic acid/Na-acetate solution was used. The solutions were shaken with an Eberbach table-top reciprocating shaker at 180 oscillations per minute for 14 d. The samples were then centrifuged at 2500 RPM for 1 h, supernatant decanted, and filtered to <0.45 µm. Batch reactor solutions were acidified to pH 1 with 0.2 g of 15 M HNO_3. The extracts were analyzed for Ca, Mg, K, P, B, Mn, Cu, and Zn with an Agilent 5110 Inductively Coupled Plasma Optical Emission Spectrometer (Agilent Technologies Inc., Santa Clara, CA, USA). Batch reactor extract solution LOQs and element CVs were 0.007 mg L^{-1} and 1 to 3%, respectively.

2.5. Basalt Rock Dust (RD) Total Elemental and Mineralogical Analyses

A HF-HNO_3 total digestion of the rock dust was used to determine the total elemental composition. To ensure complete digestion, digests were conducted with triplicate 20 mg subsamples, which were placed in three 30 mL PFA vials. For the digestion procedure, 2.5 mL of 15.6 M HNO_3 and 2.5 mL of 28.9 M HF were added, which were sealed with a cap and heated to 170 °C for 48 hrs. After the initial digestion step, the mixture was cooled down to 25 °C, the cap was removed, and materials were dried down to a moist paste, and resuspended with 2 mL of 15.6 M HNO_3 three times to ensure the removal of all SiF6. After the following dry down, the final paste was resuspended in 5 mL of 7.8 M HNO_3, resealed with the cap, and heated at 170 °C for 24 hrs. The solution was then diluted to 50 mL using 18.2 MΩ·cm deionized water. The digestion was repeated with a procedural blank and two USGS rock standard reference materials. These total digestions were analyzed with an Agilent 5110 Inductively Coupled Plasma Optical Emission Spectrometer (Agilent Technologies Inc., Santa Clara, California, USA). SRM recovery rates were 93 to 101% for macronutrient and micronutrientsthe instrumental LOQs and element CVs were presented at the end of Section 2.3. The RD total elemental composition is in Table 3.

Table 3. RD total macro and micronutrient concentrations determined by total digestion with ICP-OES analysis. The same RD was used in both organic farms and in the laboratory batch reactors. The RD was Blue Ridge Basalt sold by Rock Dust Local, Inc. (Bridport, VT, USA) and was sourced from metamorphosed basalts in Virginia.

Ca	**Mg**	**K**	**P**	**Mn**	**B**	**Cu**	**Zn**
mg kg^{-1}	**mg kg^{-1}**	**mg kg^{-1}**	**mg kg^{-1}**	**mg kg^{-1}**	**mg kg^{-1}**	**mg kg^{-1}**	**mg kg^{-1}**
71,001 ± 2400	36,010 ± 1550	7327 ± 690	525 ± 42	1538 ± 83	104 ± 17	61 ± 5	120 ± 11

The mineralogical composition and abundance of the rock dust was determined by X-ray Diffraction (XRD) using a Rigaku MiniFlex II equipped with a Cu Kα X-ray source. Approximately 0.5 g of rock dust, ground and sieved to <50 µm, was pressed and powder mounted on a glass slide and analyzed between 5 and 55° 2θ at 1° per minute at a 0.02° resolution. The Rietveld refinement analysis was performed to quantify diffractograms by using the whole profile module in the PDXL2 2.1 software from the Rigaku Corporation 2007–2017 [16]. RD mineral composition is given in Table 4.

Table 4. RD mineralogical composition determined by X-ray Diffraction. The idealized mineral composition is provided and % is g^{-1}.

Labradorite	**Chlorite**	**Albite**	**Muscovite**	**Hedenbergite**
$(Ca,Na)(Al,Si)_4O_8)$	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_8$	$NaAlSi_3O_8$	$K_2(Al_2O_3)_3(SiO_2)_6$	$CaFeSi_2O_6$
%	%	%	%	%
38 ± 4	22 ± 4	15 ± 3	5 ± 2	18 ± 4

2.6. Data Analyses and Statistical Tests

Descriptive statistics, as well as parametric and nonparametric statistical tests, were calculated in Matlab (Mathworks, Natick, MA, USA). In-text values either report minimum and maximum values; arithmetic mean values ± 1 standard error (SE) are presented in the text and in the figures. Standard error was computed from the standard deviation of the three replicate soil pits or from the four replicates in the batch reactors, and the square root of the N. Concentrations of SOC, plant-available macronutrients, and plant-available micronutrients were converted to a per unit area basis using soil bulk density and the depth of the collection. Variabilities in concentration and pool data are presented using standard error of the triplicate soil pit samples and propagation of analytical error. Since sample sizes were small and did not meet the criteria to be parametric, the nonparametric Kruskal–Wallis test was, thus, used for comparisons among three or more samples, and post hoc Wilcoxon Signed Rank tests.

3. Results and Discussion

3.1. Differences in Soil Physical and Chemical Properties with RD

In the first hypothesis, it was expected that improvements in physical and chemical soil health properties from the application of basalt RD at both farms would be observed. The tilled soils at the VT-Farm had less coarse aggregates than the MA-Farm, which agrees with many previous studies showing that tillage alters aggregation [17]. As a prime example, the meta-analysis by Liu et al. [17] found increases of 45% in coarse aggregates (>2 mm) across 89 studies. The median very coarse aggregates and median coarse aggregates for the whole soil profiles at the MA-Farm were 14% and 7%, respectively. Significant differences in coarse and very coarse aggregation were observed at the VT-Farm but not the MA-Farm. Coarse aggregates were significantly greater for RD added than no RD in the top 30 cm of the soil profile at the VT-Farm (Figure 2). Furthermore, very coarse aggregates were significantly greater for RD added than no-RD soils in the top 60 cm of the soil profile at the VT-Farm (Figure 2). The median very coarse aggregates and the median coarse aggregates for the whole soil profiles at the VT-Farm were 35% and 15%, respectively. At the VT-Farm, very coarse aggregates decreased with depths for the RD-added field but increased with depth for the no-RD field.

These results partially support the hypothesis that the addition of RD would improve soil aggregation, which is an important soil health metric regarding soil compaction, water infiltration, soil stability, and preventing soil erosion [18,19]. Comparing the entire soil profile at both farms, the results show a 4% to 20% increase in median aggregate abundance, which is comparable to increases in aggregates from the addition of biochar of 16% higher aggregation in a meta-analysis conducted by Islam et al. [20] from 119 studies. If only examining the top 20 cm, the results show 15% to 25% increases in aggregation with the addition of RD, which exceeds the aggregation of biochar [20]. Microscopy-based techniques are needed to evaluate how RD is promoting aggregation, and techniques for microaggregate analyses are also warranted. The weathering of RD may allow for the production of secondary Al and Fe oxyhydroxides that may promote organo-mineral complexes, and increases in belowground biomass from RD may be indirect from the RD addition. One potential limitation to the formation of aggregation at the MA-Farm is that the addition of RD did not significantly alter the soil particle size composition, and significant changes in aggregation typically are driven by changes in the amount of silt and clay particles [17,21]. Another aspect is that the heterogeneity in soil aggregation across the MA-Farm fields likely limited the ability to identify a significant effect, which would require higher sampling density and likely laboratory conditions to adequately assess. Despite different textures at the two farms, aggregation was improved, and this suggests that the coarse sandy soils and moderate silt loam textures can both be positively affected by RD applications.

Significant differences in soil pH and SOC in response to RD at the two farms were observed. The median soil pH and median %C for the whole soil profiles at the VT-Farm were 5.59 and 1.66%, respectively. At the VT-Farm, soil pH did not change with depth for the fields and was not significantly different with RD addition. SOC was significantly greater with the RD addition in the top 20 cm but decreased below a 20 cm depth to concentrations similar to the no-RD field (Figure 3). The median soil pH and median %C for whole soil profiles at the MA-Farm were 5.36 and 3.04%, respectively. Significantly higher soil pH for the RD-added field for most of the top 60 cm soil occurred (Figure 3). However, SOC was only significantly higher for the RD-added field for the top 10 cm of soil but was similar to the no-RD field below 10 cm (Figure 3). The different responses in pH to RD applications may stem from the use of limestone across all fields at the VT-Farm, while the MA-Farm does not consistently apply lime.

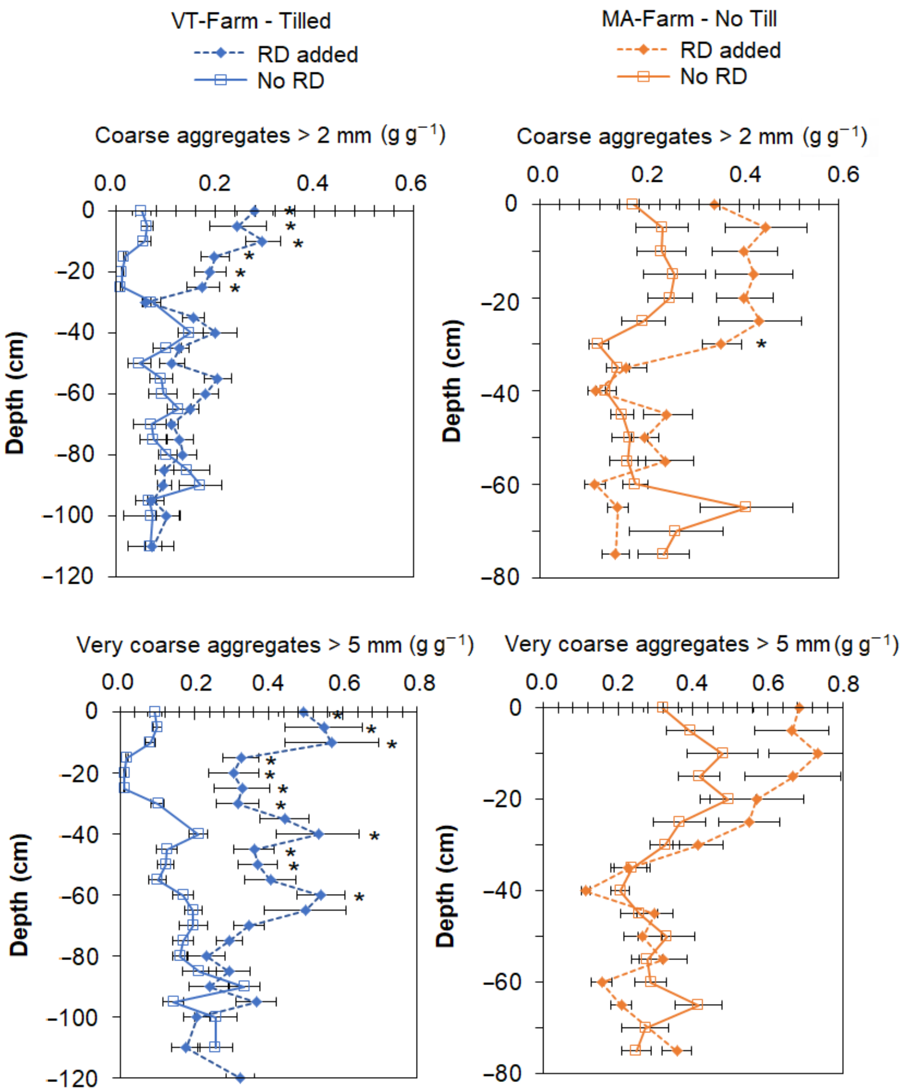

Figure 2. Comparison of coarse aggregates and very coarse aggregates in the RD-added and no-RD field soil profiles at the VT-Farm and the MA-Farm. *N* = 3 for each field. (*) indicates a significant difference ($p < 0.05$) by Wilcoxon rank sum test.

These results also partially support the hypothesis that the addition of RD would improve two key soil health metrics: soil pH and SOC. The increases in SOC can help with water infiltration, water storage, aggregate stability, soil microbial communities, and nutrient storage [22–24]. Soil pH is important for promoting microbial activity, nutrient availability, and root growth [25]. Comparing the top 20 cm of the soil profile at both farms, there were significant increases, as indicated by the results denoting an absolute 1.7% to 2.9% increases in SOC concentrations and a 0.5 pH unit increase at the MA-Farm. The increase in SOC was 69% to 135% in the top 20 cm of soil at both farms, which is comparable to increases in SOC from the addition of biochar of 67% up to 105% in a meta-analysis conducted by Chagas et al. [26] of 169 studies. This is particularly important as biochar and other soil amendments add SOC directly while RD was able to increase SOC stabilized in soil for net increases in C sequestration. It was hypothesized that the weathering of RD is promoting the formation of organo-mineral complexes, through increasing soil alkalinity [8] and Al and Fe secondary oxides [9]. Moreover, increases in belowground biomass and derivative products by plants, such as roots, root exudates, and rhizosphere C may also be important; these increases are indirectly promoted by RD addition [27,28].

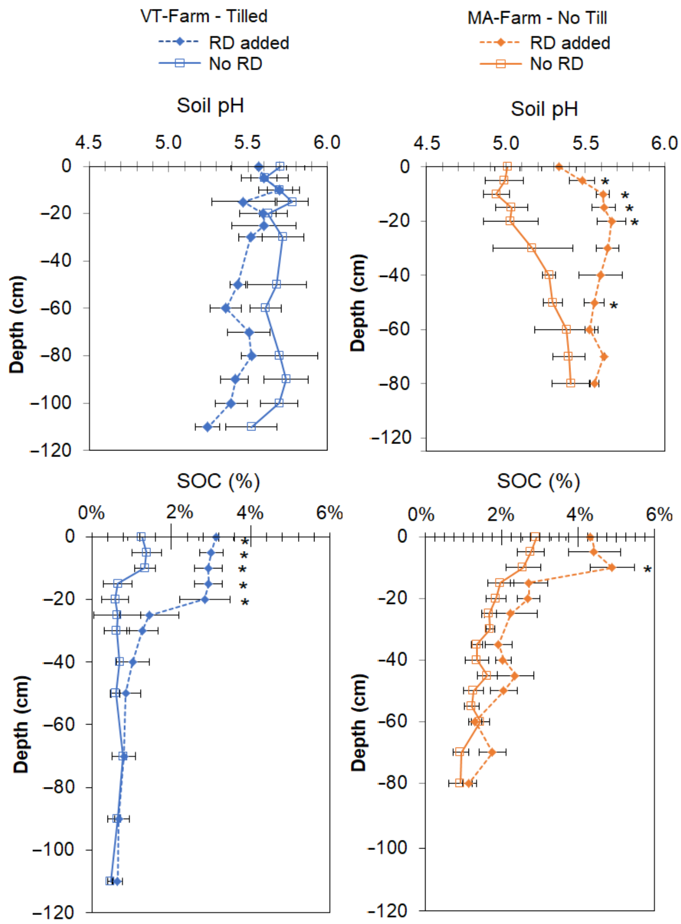

Figure 3. Comparison of soil pH (0.01 M $CaCl_2$) and SOC in the RD-added and no-RD field soil profiles at the VT-Farm and the MA-Farm. *N* = 3 for each field. (*) indicates a significant difference ($p < 0.05$) by Wilcoxon rank sum test.

3.2. Differences in Soil Inorganic Macronutrients and Micronutrients with RD

In the second hypothesis, it was expected that the weathering of applied basalt RD would result in increases in plant-available macronutrients and micronutrients at both farms. At the VT-Farm, median plant-available concentrations of Ca, Mg, K, and P throughout the soil profile were 529 mg kg^{-1}, 55 mg kg^{-1}, 110 mg kg^{-1}, and 0.6 mg kg^{-1}, respectively. The plant-available Mg and K were at the optimum concentrations for field and forage crops according to the University of Vermont Soil Test, but plant-available P was in the low concentration range [29]. The low P concentration is likely due to the UVM Soil Test, which uses Modified Morgan extract since acetate is a stronger extractant for P than Cl^{-1} [30]. The MA-Farm had higher plant-available concentrations of Ca, Mg, and P; the MA-Farm median plant-available concentrations of Ca, Mg, K, and P throughout the soil profile were 870 mg kg^{-1}, 106 mg kg^{-1}, 91 mg kg^{-1}, and 1.21 mg kg^{-1}, respectively. Comparing the values with the nutrient recommendations for field crops in Massachusetts, Mg was optimum, Ca and K were low, and P was very low [31]. Similarly to the VT-Farm's soils, the use of acetate as part of the Modified Morgan extract is able to more effectively exchange P into a solution.

The results show that there were element-specific effects from RD at the two farms. Plant-available Ca and Mg significantly increased in the top 35 cm for both the VT-Farm and the MA-Farm (Figure 4). Plant-available K had some significantly higher concentrations for RD-added fields in the top 30 cm at both farms (Figure 4). These results highlight that the addition of RD increased the concentrations of plant-available Ca, Mg, and K to an extent, which agrees with the majority of studies testing RD's effects on soil Ca, Mg, and K [4]. However, it should be noted that 44%, 39%, and 36% of studies did not find significant effects on Ca, Mg, and K, respectively, as demonstrated in the review by Swoboda et al. [4]. This is likely due to the use of different lithologies for the RD, which include granite, dunite, gneiss, and feldspars, as well as different test soils, such as Ultisols, Alfisols, and Oxisols, in the studies reviewed by Swoboda et al. [4]. The increases in Ca, Mg, and K are likely sourced from abiotic or biotic weathering of the added basalt but can also be due to indirect processes of enhanced belowground growth, increased SOC increasing sorption, and increased soil pH [5,9,32]. However, the belowground growth of biomass and the concentration of inorganic nutrients are not expected, and it was not observed in field trials by Kelland et al. [5]. The increased SOC concentrations and soil pH likely increased the sorption and retention of base cations, which are the likely mechanisms [4,5].

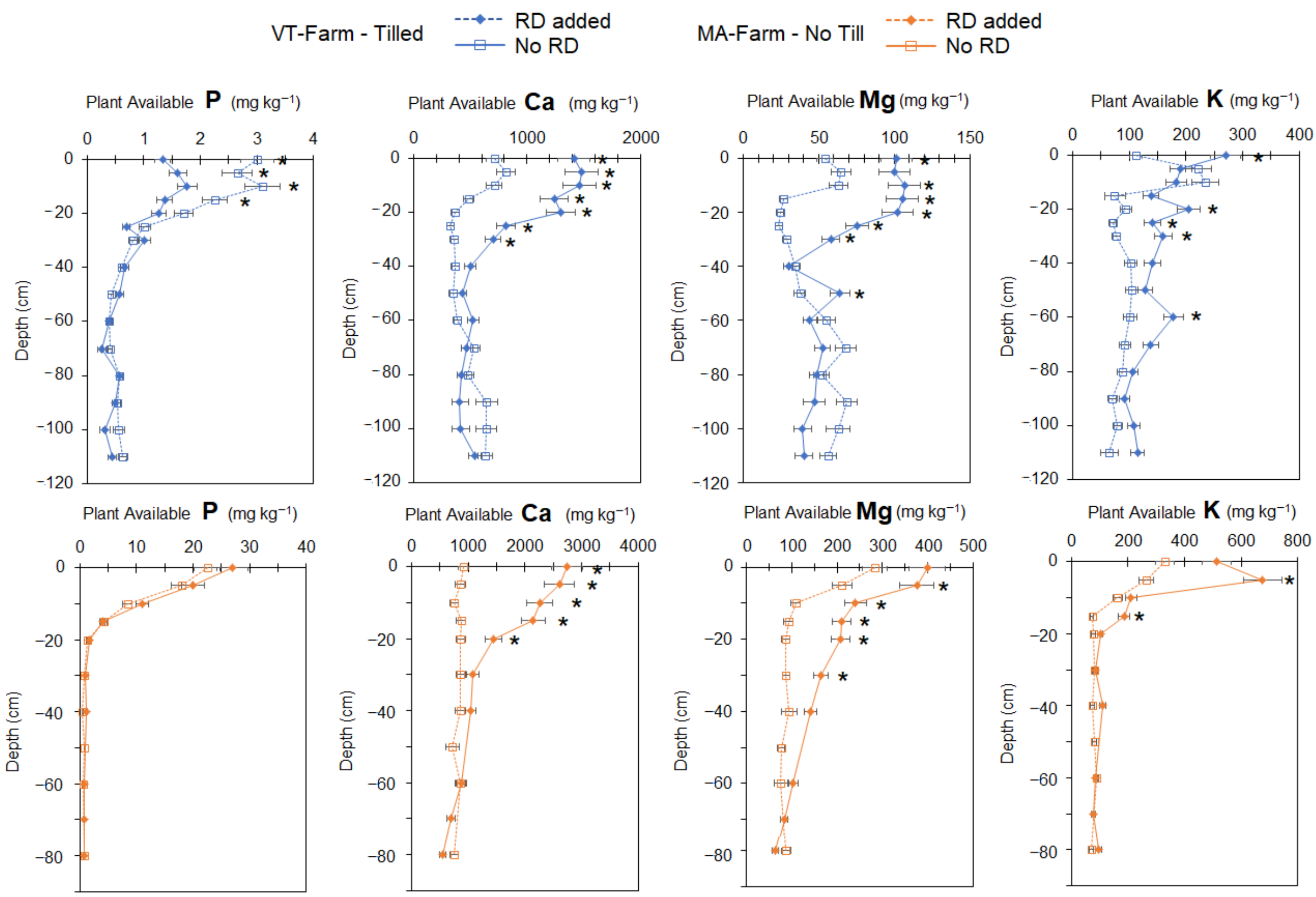

Figure 4. Plant available macronutrient soil profiles in the RD-added and no-RD field soil profiles at the VT-Farm and the MA-Farm. $N = 3$ for each field. (*) indicates a significant difference ($p < 0.05$) by Wilcoxon rank sum test.

In contrast to the hypothesis, no significant differences in plant-available P for the MA-Farm and significantly lower concentrations in the top 20 cm for VT-Farm (Figure 4) were observed. The lower overall plant-available P at the VT-Farm may have been more susceptible to changes compared to the higher plant-available P at the MA-Farm. This partially agrees with previous studies, as shown by the studies reviewed by Swoboda et al. [4], which found that 64% of studies did not find significant increases in P, and one of the fourteen studies found decreases in soil P. The sorption of P by secondary Fe oxyhydroxides is well-studied [10], and an increase in Al and Fe from basalt RD is most likely responsible for the decrease in plant-available P in the study. It is important not to assume that this decrease in readily exchangeable P will negatively impact plant nutrition, as the rhizosphere and root-fungal processes can increase its solubility and uptake [33,34].

Trace elements serve essential roles in plant growth and are commonly understudied in agricultural systems and their release from RD addition has been understudied or characterized with respect to contamination [4]. Only four of the main micronutrients, B, Mn, Cu, and Zn, were examined as they are essential for cellular division, cell wall components, photosynthesis, N metabolism, and enzyme components [35,36]. Considering plant-available micronutrients, VT-Farm had median plant-available concentrations of B, Mn, Cu, and Zn throughout the soil profile were 0.20 mg kg^{-1}, 1.01 mg kg^{-1}, 0.22 mg kg^{-1}, and 0.38 mg kg^{-1}, respectively. MA-Farm had higher plant-available micronutrient concentrations than the VT-Farm, likely due to less weathering and transport of the soil parent material. MA-Farms had median plant-available concentrations of B, Mn, Cu, and Zn throughout the soil profile were 0.67 mg kg^{-1}, 2.70 mg kg^{-1}, 0.32 mg kg^{-1}, and 0.66 mg kg^{-1}, respectively. Plant-available B concentrations were within the typical soil range of 0.2 to 1.0 mg kg^{-1} [35,37] for both soils. Plant-available Mn concentrations were in the range 1.4 to 3.9 mg kg^{-1} typical of grain soils [35,37]. Lastly, plant-available Cu and Zn concentrations were also in the 0.26 to 5.0 mg kg^{-1} range typical of grain soils [35,37].

Plant-available micronutrients showed limited increases from RD addition at the two farms. Plant-available B significantly increased in the top 20 for both the VT-Farm and MA-Farm (Figure 5). Plant-available Mn, Cu, and Zn concentrations were largely unaffected by the RD addition throughout the soil profiles at both farms (Figure 5). Converse to the hypothesis, no significant differences in plant-available P for the MA-Farm and significantly lower concentrations in the top 20 cm for VT-Farm occurred (Figure 3). It may be hypothesized that the aluminosilicate host minerals for B, Mn, Cu and Zn were undergoing limited rates of dissolution, preventing their enrichment in the two farm soils. Furthermore, the heterogeneity of the agricultural soils generated substantial variability, limiting the ability to detect a significant addition from the basalt RD weathering.

3.3. SOC and Nutrient Pool Differences

Pools were calculated using the bulk density per depth and measured SOC and plant available nutrient concentrations per unit mass, then summed for all depths to establish their pools per unit area. At the two farms, SOC, Ca, Mg, and K pools in the top 30 cm were significantly higher in soils with RD added. Mirroring our concentration results, micronutrients were not consistently different among the two farm soils (Table 5). These differences match the significant differences observed in their concentrations. It was possible that differences in porosity and bulk density would alter the significant differences observed in SOC and nutrient concentrations, but this was not the case, as differences in pools matched those of the concentrations. For only the VT-Farm, soil pools of P decreased with the RD addition while Mn increased. For only the MA-Farm, soil pools of B increased with RD addition. The greater increases in SOC, Ca, Mg, and K for the MA-Farm, with no-till and coarser texture with sandy loam may indicate that farm-specific characteristics may strongly influence the level effect for RD. In particular, the RD combined with no-till at the MA-Farm, may allow for greater SOC and greater SOC-sorption sites that promote the retention of Ca, Mg, and K. Furthermore, the weathering of RD may promote greater oxyhydroxides for sorption and retention of Ca, Mg, and K. Similarly, the increased pH and higher SOC likely from decreased microbial mineralization of organic matter, and increased the sorption capacity of the soil. Lastly, the coarse-textured sandy loam soils at the MA-Farm may promote greater mineral dissolution, allowing for a more rapid release of Ca, Mg, and K.

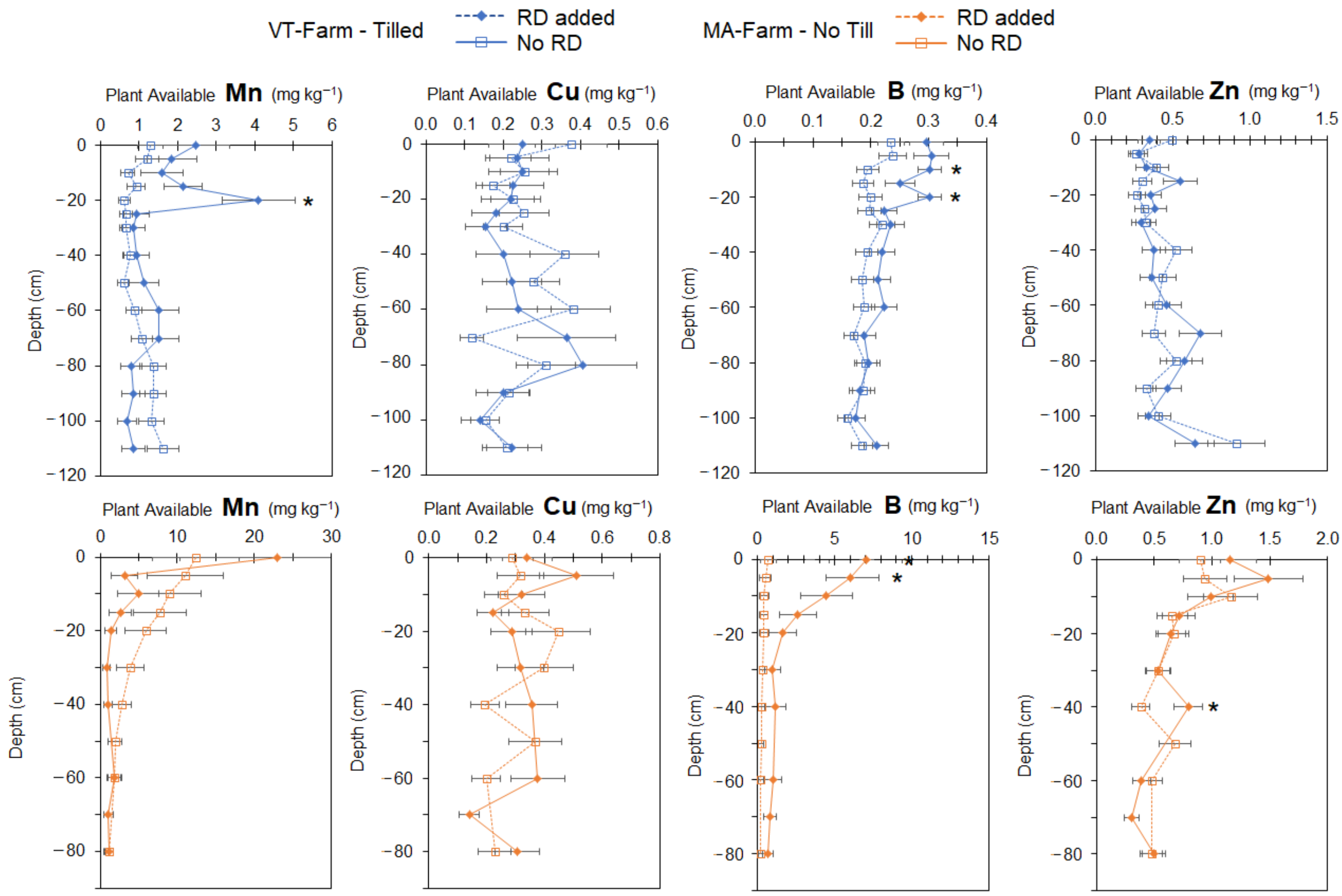

Figure 5. Plant available micronutrient soil profiles in the RD-added and no-RD field soil profiles at the VT-Farm and the MA-Farm. *N* = 3 for each field. (*) indicates a significant difference ($p < 0.05$) by Wilcoxon rank sum test.

Table 5. Soil pools in the top 30 cm for soil organic carbon (SOC), plant-available macronutrients, and plant-available micronutrients among the two farms and the RD treatment and control. Δ is the range in potential change with RD applied, comparing combinations of the lowest and highest pools. (*) indicates a significant difference ($p < 0.05$) between RD and control at each farm.

Farm	Treatment	SOC	Ca	Mg	K	P	Mn	Cu	B	Zn
		Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
VT-Farm	Till	6.3 ± 1.4	1.9 ± 0.2	0.15 ± 0.02	0.47 ± 0.05	8 ± 1 *	3 ± 1	0.9 ± 0.1	0.7 ± 0.1	1.2 ± 0.2
VT-Farm	RD, till	9.5 ± 1.6 *	4.5 ± 0.5 *	0.34 ± 0.03 *	0.65 ± 0.07 *	5 ± 1	7 ± 1 *	0.8 ± 0.1	0.9 ± 0.1	1.3 ± 0.1
	Δ	0.2–6.2	1.9–3.3	0.14–0.24	0.06–0.30	−1–−15	2–6	–	–	–
MA-Farm	No Till	11.4 ± 1.6	2.7 ± 0.3	0.45 ± 0.05	0.52 ± 0.06	29 ± 3	27 ± 4	1.1 ± 0.3	1.5 ± 0.2	2.6 ± 0.3
MA-Farm	RD, No till	17.9 ± 2.9 *	6.5 ± 0.8 *	0.86 ± 0.08 *	0.93 ± 0.11 *	34 ± 4	19 ± 2	1.0 ± 0.2	12.0 ± 1.2 *	2.9 ± 0.3
	Δ	2.2–11.3	2.5–4.9	0.28–0.54	0.24–0.58	–	–	–	8.4–12.4	–

3.4. Batch Reactor Experiments Testing RD Nutrient Release Rates

In the third hypothesis, batch reactor experiments were conducted to confirm the results of the increased nutrient release rates for (Ca, Mg, and K) but also the decrease in P from the RD addition. There are several drawbacks to using a batch reactor and other laboratory weathering experiments, as they utilize artificial conditions that lack biological contributions from microorganisms and chemical effects of the rhizosphere, and they have weathering rates that are significantly higher than field observations. However, these controlled experiments were needed to ensure that the field observations were not artifacts of cropping methods, plant debris, or other soil amendments applied to the fields.

The batch reactor results confirm that some macronutrients significantly increased from RD weathering, but others are soil-dependent. Ca and Mg release rates were significantly increased across soils, except for Mg in the NH soil (Figure 6). The dissolution rates of common minerals within basalt (anorthite and diopsite, which are comparable to labradorite and hedenbergite, respectively) are one to two order magnitudes higher than granitic Ca-bearing minerals (hornblende and albite) [38].

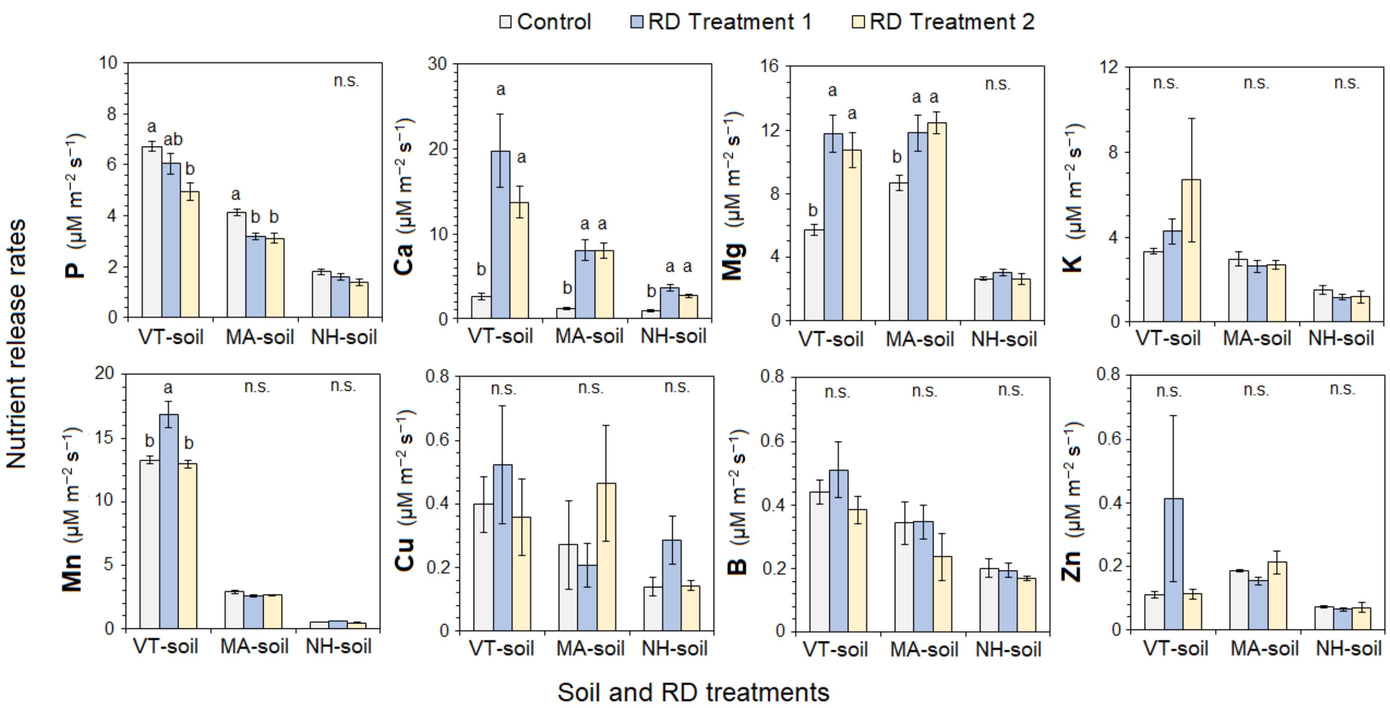

Figure 6. Batch reactor results of weathering release rates for macronutrients and micronutrients for the three test soils (see Table 2). Treatment 1 utilized the original particle size composition of the basalt RD (80% sand, 18% silt, and 2% clay) while Treatment 2 was refined to (60% sand, 38% silt, and 2% clay). 'n.s.' indicates no significant difference ($p > 0.05$) among the three treatments for each soil while different letters (a and b) indicate a significant difference ($p < 0.05$) among the three treatments. Treatments with a shared letter were not significantly different.

Both treatments resulted in a median increase of a ~500% higher Ca release rate across the three soils. This confirms the field observations that base cations Ca and Mg are significantly influenced by the addition of RD. However, the batch reactor results also show that K release was not significantly increased by the RD addition (Figure 6). It can be speculated that the duration of weathering was not long enough to see the dissolution and release of K from muscovite in the RD [39]. More likely, the increased K in the field trials may have been a result of higher SOC stored within the field soils, as opposed to RD weathering increasing plant-available K. The batch reactors confirm that RD negatively impacted P, as P release rates significantly decreased by −11% to −27%, with the addition of RD for the VT soil and MA soil but not the NH soil. The decrease in P agrees with the field observations. We hypothesize that the release of Fe from the RD is driving the precipitation of Fe oxyhydroxides that are adsorbing P.

The micronutrient batch reactor results show that there was no significant increase from the RD addition. Mn release rates were significantly increased for the VT soil but not the MA or NH soils (Figure 6). Release rates of B, Cu, and Zn were not significantly increased by the addition of RD. These results partially confirm that micronutrients (Mn, B, Cu, and Zn) were not significantly influenced by the addition of RD. Moreover, the duration of the weathering experiment (14 d) was likely not long enough to see the dissolution and release of micronutrients substituted with aluminosilicates [38]. Furthermore, the increased B in the field trials may have been a result of higher sorption to SOC, like that observed for K. Further investigations are needed, with emphasis on accessory mineral changes that are key sources for micronutrient releases during soil weathering and mineral dissolution.

3.5. Conclusions and Future Directions

In the combined field and laboratory batch reactor experiments, the results have shown that the addition of basalt RD can significantly improve physical (aggregation) and chemical properties (pH, SOC, Ca, Mg, and K) in organic farm soils. Some significant improvements occurred in coarse soil aggregation, increased soil pH, and increased SOC, with the addition of RD in both tilled and no-till field soils. The potential mechanism is RD-released Fe, which formed secondary Fe oxyhydroxides that aided in decreasing SOC mineralization and promoted organo-mineral complexes (Figure 7). The addition of fine particles may not have significantly altered the soil texture; thus, it may be hypothesized that it was the weathering of the basalt RD that led to soil health improvements. However, one cannot rule out the potential indirect feedback of improved crop growth that may have caused an improvement in the aggregation and SOC.

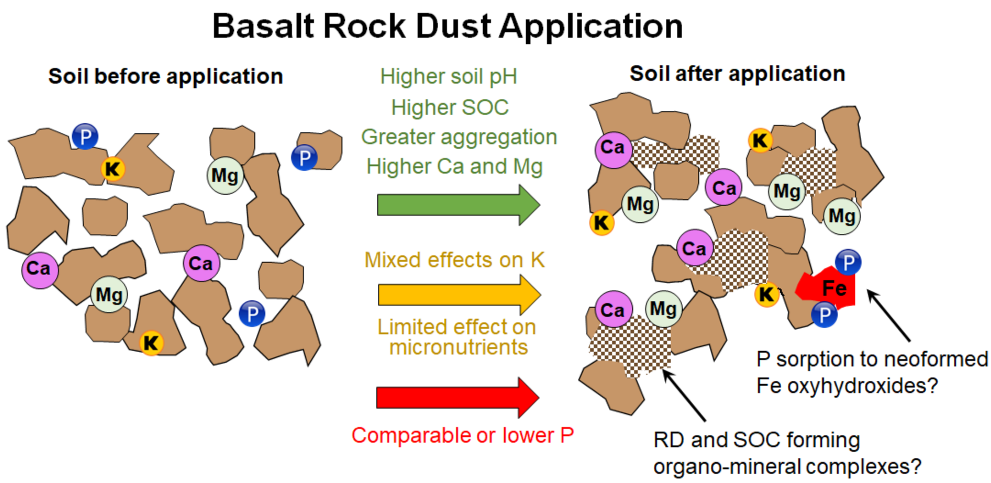

Figure 7. Conceptual figure summarizing our field and batch reactor findings and the potential effects on soil following basalt RD application. Our data indirectly suggest that RD and SOC are forming organo-mineral complexes and reducing SOC mineralization; plant-available P decreases due to Fe oxyhydroxides formed by RD weathering. However, additional experiments are needed to confirm these mechanisms.

In addition to physical and chemical soil health properties, significantly higher plant-available Ca, Mg, and K concentrations and pools occurred in the agricultural soils. These increases in Ca and Mg can be attributed to the weathering of basalt RD, as the batch reactor experiments showed significant increases in Ca and Mg. However, K was not significantly increased in the laboratory batch reactor experiments. The field trials had higher K, which may have resulted from indirect processes such as increased sorption by higher soil pH or greater SOC present in the field soils. The study found comparable or lower plant-available P in the field soils and laboratory batch reactor experiments. The higher soil pH, higher SOC, and formation of secondary Fe oxyhydroxides likely led to greater sorption of P (Figure 7). Decreased plant-available P may not be a concern for soil health as the plant roots can solubilize P in the rhizosphere through biotic and abiotic processes. Moreover, the greater P sorption may enhance nutrient efficiency overall by preventing leachate losses. However, since crop response to RD was not evaluated, these possible processes were not evaluated and should be considered speculative.

Further studies are needed to critically evaluate basalt RD as a soil amendment. The elemental and mineralogical composition of basalts varies and may result in different impacts on soil health and nutrient abundance. This study only evaluated the field soils and batch reactors under one application rate. Greater or lesser application rates of basalt RD may enhance or diminish the effects found in the study. Lastly, trace elements are understudied in RD, yet they are essential elements but may be detrimental to plants at elevated concentrations. Future studies should consider trace elements having both effects on soil health.

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