

Increased yields for smallholder farmers from enhanced rock weathering

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Abstract

Meeting food demand in the Global South requires smallholder yield intensification. Conventional intensification using synthetic fertilizers embeds significant greenhouse gas emissions and imposes costs infeasible for resource-constrained farmers. We present results from 216 smallholder rice farmers across 42 villages in India showing a median 24.7% yield increase and over 20% increase in household income from enhanced rock weathering. This demonstrates a pathway toward intensification not dependent on synthetic fertilizers, with deployment costs offset by carbon finance.

Smallholder farmers produce about one third of the world's food supply, including more than 70% of the calories in Latin America, sub-Saharan Africa, and South and East Asia [Ricciardi et al., 2018]. Smallholders face persistent obstacles deriving from declining soil quality, limited access to affordable agricultural inputs and growing exposure to climate vulnerability from warming and extreme weather events [FAO and ITPS, 2015]. Meeting rising food demand will require yield intensification within these systems. To date, the conventional pathway to yield intensification relies on synthetic fertilizers. This embeds substantial greenhouse gas emissions into the intensification process [Menegat et al., 2022] and requires input costs that are not feasible for smallholders already struggling with debt or limited access to capital. More than 285 million smallholder households face an annual financing gap of over US \$200 billion [ISF Advisors, 2025]. These costs will also not be recovered when a significant portion of the production goes into subsistence.

Here we provide new data to assess the feasibility of an alternative pathway called enhanced rock weathering (ERW) which can deliver yield gains while restoring rather than degrading soils [Vanlauwe et al., 2014]. ERW has emerged as a promising, potentially scalable carbon dioxide removal (CDR) pathway that simultaneously addresses agricultural soil degradation. By applying finely ground silicate rock to agricultural soils, mineral dissolution drives a net transfer of atmospheric CO₂ into stable dissolved inorganic carbon, while releasing plant-available nutrients through geochemical weathering. As silicates weather, they supply calcium, magnesium, potassium, phosphorus, and silicon. Amorphous silicon is critically depleted in weathered tropical soils where rice cultivation predominates [Beerling et al., 2018]. The weathering process consumes protons, raising soil pH and providing a liming effect without separate calcium carbonate application. In a recent study, Kelland et al. [2020] demonstrated pH increases of 0.5–1.0 units following basalt amendment in field trials. Although the basics of ERW are well established and well grounded in basic soil science there are limited datasets that directly constrain how it yields for smallholders.

Here, we present results from a trial with smallholder Indian communities farming rice paddies. Rice provides 35–59% of caloric energy intake across South and Southeast Asian populations [Juliano, 1993], and in India, the world's largest rice producer, smallholder and marginal farmers with less than two hectares account for 86% of all farmers and collectively supply the majority of national paddy output [Government of India, 2019]. For these households, crop income represents approximately half of total household income [National Statistical Office, 2021], making yield gains in rice among the highest-leverage agricultural interventions available. We present

crop measurements from 216 farmers across 42 villages during the 2025 Kharif season drawn from five large-scale deployment projects conducted by Mati Carbon: GPM (3,068 ha, 16.4 t ha⁻¹), Seoni (2,204 ha, 25.7 t ha⁻¹), Nainpur (317 ha, 18.1 t ha⁻¹), and Shahdol (217 ha, 17.4 t ha⁻¹) in central India (Madhya Pradesh and Chhattisgarh), and Pakur (1,131 ha, 25.3 t ha⁻¹) in Jharkhand (Table 1). The four central Indian deployments used Deccan basalt sourced from the Mandla lobe of the Deccan Traps as feedstock, while the Pakur deployment received basalt sourced from the adjacent Rajmahal Traps. Across all sites, sample results indicate a median yield increase of 24.7% (mean 29.5%) (Figure 1).

Table 1: **Site-specific deployment and yield response summary statistics.** N is the number of paired farmer observations; \bar{x} , \tilde{x} , and σ denote the mean, median, and standard deviation of percentage yield change (ΔY), respectively; A is the total deployment area in hectares; \mathcal{A} is the basalt application rate in t ha⁻¹; M is the total basalt deployed in tonnes. See Figure 1 for the spatial distribution of sites and overall yield response histogram.

Location	N	\bar{x} (%)	\tilde{x} (%)	σ (%)	A (ha)	\mathcal{A} (t ha ⁻¹)	M (t)
GPM	85	24.6	23.5	10.6	3,068	16.4	50,427
Seoni	83	38.4	34.6	38.2	2,204	25.7	56,634
Pakur	32	13.3	12.2	6.6	1,131	25.3	28,566
Nainpur	10	33.2	25.0	24.1	317	18.1	5,755
Shahdol	6	54.7	56.4	18.3	217	17.4	3,775
Total	216	29.5	24.7	27.1	6,937		145,157

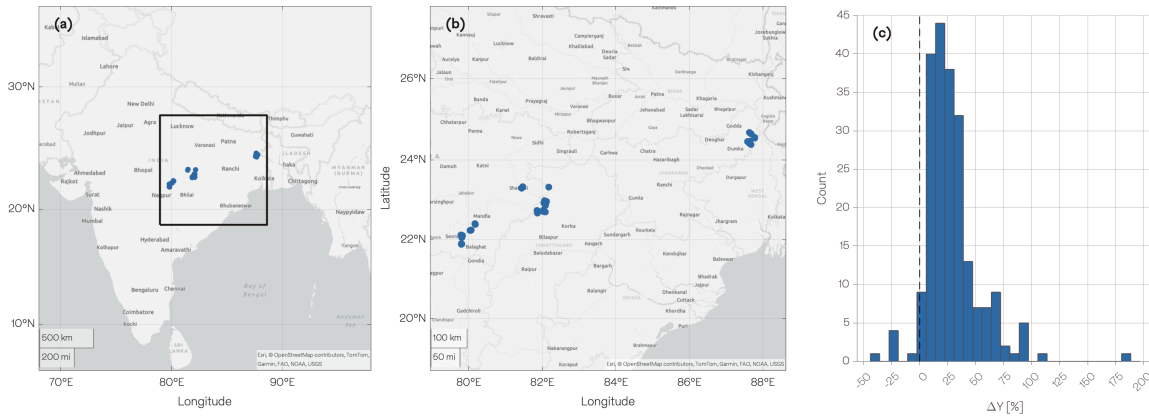


Figure 1: **Enhanced rock weathering deployment sites and yield response across smallholder rice farms in India.** (a) Map of India showing the locations of the five primary centers of deployment in the project. (b) Enlarged view of deployment sites with individual village-level locations. (c) Distribution of percentage yield change (ΔY) across all 216 paired farmer observations; the dashed line indicates zero yield change. Site-specific summary statistics are provided in Table 1.

At the 2025–26 government minimum support price (MSP) of ₹2,369 per quintal (100 kg) for common-grade paddy [Cabinet Committee on Economic Affairs, 2025], the observed median yield gain of 3.29 quintals per acre translates to different additional revenue depending on the applicable state-level procurement price. In Chhattisgarh, where a state-specific bonus under the Krishak Unnati Yojana brings the effective procurement price to ₹3,100 per quintal [Government of Chhattisgarh, 2025], the yield gain translates to approximately ₹10,180 (\$117) in additional gross revenue per acre per season. In Jharkhand, where a state bonus of ₹81 per quintal brings the effective price to ₹2,450 per quintal [Government of Jharkhand, 2025], the yield gain translates to approximately ₹8,050 (\$92) per acre per season. In Madhya Pradesh, where paddy is procured at the central

MSP of ₹2,369 per quintal, the yield gain translates to approximately ₹7,780 (\$89) per acre per season. To derive net income, incremental transport and packaging costs attributable to the additional yield are deducted. Transport costs are estimated at ₹460 per acre using a proportional payload allocation model (distance = 20 km; cost = ₹35 km⁻¹ for a 5-tonne truck; backhaul factor of 2; applied to incremental yield of 329 kg per acre), and packaging costs at ₹67 per acre based on ₹10.22 per 50 kg bag. Since basalt is provided at no cost to the farmer and cultivation practices remain unchanged, no other incremental costs are incurred. The resulting deductions are approximately ₹527 (\$6) per acre, representing 5–7% of gross revenue, yielding net per-acre income gains of approximately ₹9,660 (\$111) in Chhattisgarh, ₹7,520 (\$86) in Jharkhand and ₹7,260 (\$83) in Madhya Pradesh. All USD conversions use the 2025 annual average exchange rate of 87.16 INR/USD. Full calculation parameters, source values, and per-farmer line items are provided in [Dataset S1](#) (Dataset_S1.xlsx, sheet *References*). When scaled to representative farm sizes of 4.0 acres in Chhattisgarh, 3.9 acres in Madhya Pradesh and 2.4 acres in Jharkhand [[Government of India, 2019](#)], the per-farmer net income uplift is estimated at approximately \$443, \$325 and \$207 respectively per Kharif season. Weighted by the crop cut sample composition across the three states ($n = 216$), the average per-farmer income gain is approximately \$355 per season. Drawing on CPI-updated baseline household income data from the Situation Assessment Survey, 77th Round [[National Statistical Office, 2021](#)], updated to constant 2025 prices using MoSPI Rural CPI ([SI: Household Income](#)), these gains represent approximately 24%, 20% and 22% of mean annual agricultural household income in Chhattisgarh, Madhya Pradesh and Jharkhand respectively, a sample-weighted average of approximately 22% uplift on baseline income across the three deployment states.

Farmers in the lowest baseline productivity quartile experienced yield gains averaging 47%, compared to 18% for the highest quartile ($r = -0.41$; [Dataset S1](#)). This inverse relationship between baseline productivity and yield response suggests that ERW disproportionately benefits the most resource-constrained farmers, the demographic most underserved by conventional intensification pathways. Farm size showed no significant relationship with yield response ($r = -0.01$; [Dataset S1](#)), indicating that benefits scale proportionally across holding sizes. The absence of a farm size effect is notable given that many agricultural interventions exhibit scale dependent adoption and impact patterns, with larger holdings typically capturing greater benefit. ERW appears to bypass this dynamic, suggesting suitability for deployment across the full spectrum of smallholder farm sizes.

The agronomic case for basalt feedstock delivery to smallholder farmers carries independent economic weight that does not depend on carbon markets. Meeting rising food demand in developing economies will require further intensification of smallholder agriculture while the conventional pathway to intensification embeds significant greenhouse gas emissions into that process. [Menegat et al. \[2022\]](#) estimate that the synthetic nitrogen fertilizer supply chain was responsible for 1.13 GtCO₂e in 2018, representing 10.6% of agricultural emissions and 2.1% of global GHG emissions, with global fertilizer use projected to increase by more than 50% between 2012 and 2050. In India specifically, fertilizer policies introduced to boost agricultural productivity have created a sustainability challenge through heavy reliance on subsidized urea [[Gulati and Banerjee, 2015](#)]. The potential for future overuse of synthetic nitrogen would additionally result in increased nitrous oxide emissions, nitrate leaching, and long-term soil health decline [[Sapkota and Bijay-Singh, 2025](#)]. ERW generates yield gains without recurring expenditure on fertilizers, the basalt amendment is applied once and the cost is borne by carbon finance rather than the farmer.

The carbon removal co-benefit simply strengthens an already favorable investment case. Beerling et al. project extraction costs of approximately \$80–180 per ton CO₂ for permanent (>1000 year) carbon removal from ERW deployed on tropical croplands. Basalt has a theoretical maximum CDR potential of approximately 0.3 t CO₂ per tonne of rock upon complete dissolution, though realized yields depend on weathering kinetics, application rate, and climate. At application rates of 25–50 t ha⁻¹ and a conservative weathering fraction range of 25–50%, the implied CDR yield is approximately 0.7–3.7 t CO₂ ha⁻¹ in year one, generating US \$110–1,110 per hectare at carbon prices of \$150–300 per t CO₂; this CDR yield generates between US \$110 and US \$1,110 per hectare respectively. As discussed extensively elsewhere, the carbon revenue can therefore cover deployment costs, even within a single tropical growing season [[Beerling et al., 2018](#)]. Carbon trading programs encompassing ERW are still being developed, as carbon removal frameworks. However, voluntary markets and jurisdictional programs (e.g., UN Article 6.2 and 6.4) both provide current and future pathways for funding ERW at scale.

As ERW simultaneously delivers verified carbon removal, the deployment cost is recoverable through carbon markets rather than crop sales, decoupling the economics of soil improvement from the farmer's ability to monetize

their harvest. This is particularly significant for subsistence-oriented producers, for whom the approach of ‘invest in inputs, recovered through market sale’ does not apply. Moving forward, these programs, coupled with evidence for robust agronomic impacts, provide a mechanism whereby climate finance underwrites costs for a practice that directly increases incomes and food security for smallholder farmers, without imposing costs on the farmers. This intervention has the potential to break the central barrier of economic infeasibility that has excluded smallholders, who collectively face a US \$200 billion annual financing gap, from conventional input-led intensification.

These results, from a smallholder dominated region in India, indicate the need to continue to invest in basic research, for optimizing, and commercializing enhanced rock weathering.

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Declarations

J.S.J., T.M.D.M., I.J., D.P., A.M., J.B.S., and S.A. are employed by Mati Carbon PBC or Mati Carbon India Private Limited. N.J.P. serves as an unpaid scientific advisor to Mati Carbon and receives no compensation in any form.

Author contributions

J.S.J., T.M.D.M., and N.J.P. wrote the manuscript with input from all the authors. The study was initially designed by J.S.J. and S.A. I.J. and S.A. oversaw the crop-cut data collection, which was undertaken by Mati Carbon PBC employees. A.M., J.B.S., and D.P. compiled and quality-checked crop-cut data. Data and economic analysis was conducted by J.S.J. and T.M.D.M.

Supplementary Information

Minimum Support Price and Income Baseline

Rice MSP for Kharif 2025–26 is ₹2,369 per quintal for common grade paddy (₹2,389 per quintal for A grade paddy) [Cabinet Committee on Economic Affairs, 2025]. In Chhattisgarh, a state-specific bonus under the Krishak Unnati Yojana brings the effective procurement price to ₹3,100 per quintal [Government of Chhattisgarh, 2025]. In Jharkhand, a state bonus of ₹81 per quintal brings the effective price to ₹2,450 per quintal [Government of Jharkhand, 2025]. In Madhya Pradesh, paddy is procured at the central MSP of ₹2,369 per quintal. Additional income from ERW-driven yield uplift is calculated at the applicable state-level procurement price, as this determines the revenue farmers receive for each additional quintal produced.

Household Income

Baseline household income data were drawn from the Situation Assessment Survey, 77th Round (SAS-77), conducted by the National Statistical Office covering the agricultural year July 2018 to June 2019 [National Statistical Office, 2021]. The average monthly income of an agricultural household was approximately ₹9,677 in Chhattisgarh, ₹8,339 in Madhya Pradesh and ₹4,895 in Jharkhand, corresponding to annual household incomes of approximately ₹116,000, ₹100,000 and ₹59,000 respectively. As no subsequent round of the SAS has been conducted, this remains the most recent nationally representative estimate of agricultural household income at the state level.

To ensure comparability with the 2025 Kharif season in which yield impacts were measured and valued, SAS-77 baseline incomes were updated to 2025 prices using the MoSPI rural Consumer Price Index (CPI Rural, Base 2012=100). The All-India Rural CPI stood at 199.0 in October 2025, compared with 199.5 in October 2024, a year-on-year change of ~0.25%, reflecting mild deflation driven primarily by a sharp decline in food prices (rural CFPI: ~4.85% year-on-year) following strong monsoon harvests and reductions in GST. The CPI-adjusted baseline household incomes are therefore approximately ₹164,000 in Chhattisgarh, ₹141,000 in Madhya Pradesh and ₹83,000 per year in Jharkhand in constant 2025 prices.

Dataset S1

Dataset_S1.xlsx: Per-farmer paired crop-cut observations ($n = 216$), comprising farmer ID, deployment site, baseline (control) yield (quintal per acre), treatment yield (quintal per acre), percentage yield change (ΔY), and farm size (acres). This dataset underlies the heterogeneity analyses cited in the main text: the baseline-productivity correlation ($r = -0.41$) and the farm-size correlation ($r = -0.01$). The *References* sheet contains the full set of calculation parameters and source values supporting the per-farmer net income estimates in the main text.

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