Anonymous referee #1

Thanks to the authors for their thoughtful response to the reviews. I am recommending accepted subject to minor revisions based on a small modification that I suggest based on this new sentence:
"A restart of the collection effort of lime application variables by the USDA would greatly enhance the community's assessment of the climate mitigation of lime addition (Rissing et al., 2023)."
I would change this to better reflect the intent of the Rissing article. Perhaps something like "Similar to others who have recently argued for better data collection efforts to support a more sustainable food system (e.g., Rissing et al. 2023), we believe that a restart of the collection effort of lime application variables by the USDA would greatly enhance the community's assessment of the climate mitigation potential of lime addition."

Response:

Thanks for the reviewer's reading and approval of our work, and thanks to the reviewer's suggestion. We have changed the phrasing of the sentence according to the reviewer's recommendation.

"Similar to recent work which argued for better data collection efforts to support a more sustainable food system (Rissing et al., 2023), we believe that a restart of the collection effort of lime application variables by the USDA would greatly enhance the community's assessment of the climate mitigation potential of lime addition."

Anonymous referee #2

Suggestions for revision or reasons for rejection

(visible to the public if the article is accepted and published)

The revised manuscript is improved relative to the original submission. The addition of a pixel-level data product, the more cautious wording around climate mitigation, and the expanded discussion of regional land-use change all strengthen the paper. However, several of the main concerns raised in the first round remain only partially addressed. In particular, the temporal mismatch between the historical lime data and the explanatory variables remains substantial, the RF analysis is still interpreted more strongly than the data structure can support, partly due to CV sampling methodology. Overall, the dataset compilation has potential value, but the manuscript still need further improvement. I therefore do not consider the paper ready for acceptance in its current form and would recommend a further major revision.

Response: Thanks for the reviewer's careful reading of our work, which have greatly helped us further strengthen the manuscript. We believe our revised manuscript has addressed the reviewer's concern to the best of our ability. Below are our response and the fixes we made to the manuscript, according to the reviewer's comment and input.

Key concerns that remain insufficiently resolved

1. The temporal mismatch issue remains and has not been substantively resolved. Averaging climate and agricultural variables over 1978–1987 only partially alleviates the problem. Soil properties are still derived from a cross-decadal composite SSURGO product, and, more importantly, the manuscript uses the 2022 CroplandCROS product to identify the dominant crop in each county and then assigns historical pH recommendations on that basis. In other words, a modern crop distribution is being projected onto the 1978–1987 explanatory framework. This is a more serious issue than the "slight temporal mismatch" acknowledged by the authors.

Thanks for the reviewer's comment. We acknowledge that the time frame of the predictors does not match the decadal average time frame of our liming data (the case for pH recommendation), and in the case of soil variables includes our liming data time frame but is aggregated across a longer period. We appreciate

the reviewer raising this concern, which we should be more explicit in this discrepancy when stating the nuance and potential limitations, regarding this difference in time range.

However, to our knowledge, there are no publicly available historical dataset for soil variables (ex. Soil pH, CEC) and soil pH recommendations that farmers use as a reference before the 21st century, that can be used to resolve changes in time. As these variables are the main parameters and factors that influence the farmers' decision of whether to lime, it is hard for us to find a better data to explain the potential relation with liming patterns. This type of issue is common when conducting regional to global scale studies and other authors in this journal have also, unfortunately, used single time data sets to predict spatial patterns of variables in a different time frame.

Below are two examples

Rimondini et al. (2023) https://essd.copernicus.org/articles/15/3473/2023/

Shi et al. (2025) https://essd.copernicus.org/articles/17/517/2025/

We would also like to point out that the temporal trend of both crop type and soil characteristics, are much less than the spatial variability. Based on this comment, we now cite Ye et al., (2024) and added a citation Thai et al., (2026),

Thai, Saven, et al. "Mapping soil pH baselines, trends, and time-to-critical crop risk using harmonized legacy datasets: A large-scale assessment." *Journal of Environmental Management* 404 (2026): 129508.

which demonstrate an approximate change of crop type distribution and soil pH across the past decades, both of which are much less than its spatial variability.

Finally, we also conducted the same statistical analysis removing the pH recommendation data, and the soil properties, which the reviewers raised concern on the temporal time range and associated validity. We show the comparison results in the supplementary information. The R^2 of this analysis

without predictors, is significantly lower than the result using the original set of predictors. Thus, we believe that incorporating the data of pH recommendation, and the soil properties, still provides further predictive power and meaningful information that may explain the spatial variation of lime application patterns. We added the verbiage below to cover this issue

"We further average the agriculture (crops, fertilizers) and climate data across 1978-1987, corresponding to the last three census years (1978, 1982, and 1987) of lime application data. Soil, lithology, and pH recommendations are not temporally available in the yearly resolution. Lithology is not likely to have changed within decadal time scale, but soil properties and soil pH recommendations may have slightly changed over the decades. We acknowledge that this temporal mismatch presents a limitation of this analysis. However, to our knowledge there are no publicly available datasets for soil variables and before the 21st century (Hengl et al., 2026), and there is no information on the historical soil pH recommendation in agriculture management, which prevents a more robust information of their historical trend through time. Thus, the data we have is our best attempt to capture its spatial variability. Studies have also shown that the temporal trend of soil properties and crop types are much less than their spatial variation over the past decades (Thai et al., 2026; Ye et al., 2024a). Therefore, for purpose of explaining spatial controls, we consider it reasonable to include these variables in the statistical analysis. For comparison, we also did the same analysis but removed these predictors that are not entirely collected in the same period (shown in Fig. S6). We would like to highlight that further efforts in data products to resolve the change of soil properties and pH management will greatly benefit future research in this area."

2. The climate-mitigation framing remains too strong. The addition of an explicit statement that quantifying climate mitigation is beyond the scope of the study is a welcome improvement. However, the Introduction and Conclusion still frame the manuscript's broader significance primarily in terms of carbon removal and climate solutions. Since the manuscript does not provide any quantitative assessment of regional carbon budgets, partitioning between strong-acid and carbonic-acid weathering, or net CO_2 effects, this framing still appears

overstated.

Response:

Thanks for the reviewer raising this concern. We agree that our framing in the introduction and conclusion is relatively too strong and overweight in the climate mitigation quantification, compared to the data product we presented in this study. We have significantly reduced this discussion, and the revised manuscript now stressed the importance of lime applications in both agricultural management and potential climate mitigation in a more balanced approach. As for future research question we reframed as a more open "future works", rather than limiting to only the specific direction of "climate mitigation quantification"

Below are two sections which we reword the manuscript draft.

Introduction: We condensed the two paragraphs on strong-weak acid partitioning and carbon removal potential to one paragraph, only touching on these as relevant research directions but not going in too many details.

"….Aside from its importance in agricultural management, liming has recently gained attention in its potential climate impact (Raymond et al., 2025). The application of crushed rocks to agriculture fields, referred to as enhanced rock weathering (ERW), has emerged as a promising carbon dioxide removal and climate mitigation strategy (Beerling et al., 2020). Enhanced carbonate weathering, particularly through large-scale agricultural liming, could offer a more immediate approach to atmospheric CO_2 mitigation due to its faster weathering rate (Gaillardet et al., 1999; Liu et al., 2011). Furthermore, the application of lime has been shown to reduce the emission of nitrous oxide (N_2O) and methane (CH_4) emissions from soils (Khaliq et al., 2019; Shaaban et al., 2020), due to changes in the biotic and abiotic environment that are tied to soil pH (Zhang et al., 2022). However, since lime can act as either a source and a sink for atmospheric CO_2 depending on the weathering agent in the soils (Plummer & Wigley, 1976), and its carbon footprint can shift over time,

often transitioning from a source to a sink depending on environmental and management conditions (Semhi et al., 2000), it will be important to first develop a better understanding of when and where lime has been applied in the past. A spatially-explicit dataset of historical lime applications across regions is critical for future studies to further explore its relevance both in agricultural management and potential climate mitigation…"

Conclusion: We now stress also the importance of agriculture in general, not only for potential climate mitigation.

" Our study synthesizes historical lime application practices from 1910-1987 across both temporal and spatial dimensions. As liming has significant importance in modern day agriculture practices and recently gains attention for its potential role in climate mitigation, understanding historical spatial pattern of lime applications offers a critical observational baseline for future research efforts."

3. Land-use history has not been genuinely incorporated into the main analysis. The added discussion of cropland abandonment in the Southeast is helpful. However, the main analysis still does not quantitatively integrate cropland extent, harvested share, or land-use history alongside soil acidity and management factors within the core explanatory framework. This remains insufficient to support a strong mechanistic interpretation of the observed spatial patterns.

Thanks for the reviewer's comment. To incorporate land use/cropland use to the analysis, we changed some of our original predictors including harvested cropland area, pastured cropland area, and non-harvested/non pastured cropland area into percentages of cropland for each purpose. In addition to the total cropland area, which we already had as our predictor, this allows us to integrate land use changes, particularly the purpose of cropland area to the analysis framework. We redid the statistical analysis with these normalized parameters. After rerunning the statistical modelling, we quantitatively

demonstrated that harvested cropland area, pastured cropland area percentage has a positive correlation with lime applied/lime application rate, while non-harvested/non pastured cropland area percentage has a negative correlation. We demonstrated this in our updated Figure 9.

We updated all our figures in the main text and supplementary figures accordingly.

We added in the Result section to mention this added predictors.

"For lime-treated fraction, soil pH shows the highest permutation importance, exhibiting a strong negative correlation. Other important predictors included mean precipitation and sand percentage (positive correlations), and carbonate mineral stocks, cropland harvested percentage (negative correlations) (Fig. 9c). Partial dependence analysis shows that counties with lower soil pH, greater rainfall, higher sand content, lower carbonate minerals, and higher harvested cropland percentage exhibited a higher lime-treated fraction among croplands (Fig. S9)."

"The average application rate and lime-treated fraction can also be explained by regional climatic conditions, soil properties, and cropland usage (harvested cropland percentage, not harvested nor pastured cropland percentage)."

We also added in the Discussion section mentioning this result

"The relative ratio of total cropland in this region did not show a clear decline (Fig. S16). However, the percentage of cropland harvested (Fig. S17) shows a strong decrease in 1987, while the percentage of cropland that is neither harvested nor used as pasture (Fig. S18) shows a clear increase, potentially indicating gradual abandonment of cropland for other uses. Our statistical model also shows that percentage of cropland that is neither harvested nor pastured has a negative

correlation with the lime application rate (Fig. 9b), while the percentage of cropland shows a positive correlation with lime-treated fraction (Fig. 9c), demonstrating the potential influence of land use change in shaping the spatial variation of lime application."

"In summary, both climatic drivers (temperature precipitation), soil mineralogy (including soil pH, carbonate presence, wind erodibility, soil organic matter, and particle size distribution), and slight influence of cropland usage (harvested/pastured cropland percentage) together can explain the spatial variation of lime application rate and lime-treated fraction."

4. The practical relevance of the dataset remains limited by its county-level resolution and historical time frame. The revised manuscript is more careful in presenting the dataset as a historical baseline, which is more appropriate than the original framing. However, the manuscript still repeatedly implies substantial relevance for current management and future climate-related assessment. This continues to overstate the extent to which the dataset can be extrapolated to contemporary conditions.

Thanks for the reviewer's pointing this out. We acknowledge that this dataset is less useful in providing direct insights to understanding current lime application scenarios. The main purpose of the dataset is to provide spatial information on lime applications, which was not possible from (West & Mcbride, 2005). Thus, we have removed excessive wording that stressed the application of this dataset to current situation.

Despite not being able to have direct data in current lime applications, we believe that this spatially explicit data can still be useful for climate mitigation studies. A recent work in progress that utilizes this dataset is https://conf.goldschmidt.info/goldschmidt/2025/meetingapp.cgi/Paper/29785, which we hope more work will find this dataset useful. Future studies could further investigate the historical climate related data (soil carbon, river alkalinity signals) in different regions throughout this historical period (1910-1987) to

better assess the climate impact of liming.

We changed the conclusion paragraph accordingly to prevent unintended overstatement, and we specify these limitations and potential future applications in more nuance.

" Our study synthesizes historical lime application practices from 1910-1987 across both temporal and spatial dimensions. As liming has significant importance in modern day agriculture practices and recently gains attention for its potential role in climate mitigation, understanding historical spatial pattern of lime applications offers a critical observational baseline for future research efforts. We would like to highlight that the liming data being not available in the Census report after 1987 greatly limit the capacity of this research. Similar to recent work which argued for better data collection efforts to support a more sustainable food system (Rissing et al., 2023), we believe that a restart of the collection effort of lime application variables by the USDA would greatly enhance the community's knowledge of current agricultural liming practices. Future research could potentially build on these spatially explicit data of lime applications considering the variations in soil types, climate conditions, in comparison with historical climate-relevant data (eg. soil carbon stock, river alkalinity) during this period to comprehensively assess further agricultural or climate-mitigation questions."

Additional issues in the revised manuscript

1. The model validation strategy is not sufficiently robust. The manuscript uses random 5-fold cross-validation rather than spatial cross-validation. For county-level data with strong spatial gradients and clear spatial autocorrelation, random splitting can substantially overestimate predictive performance. Therefore, the reported R^2 values do not fully demonstrate the robustness of the explanatory model.

Thanks for the reviewer's comment. We acknowledge that indeed our original R^2 may have been inflated since the training set and testing set are neighboring or in proximity. To address this issue, we redid the 5-fold cross-validation, but splitting the 5-fold by states. In this sense the counties that are in the training set will be in different states from those that are used in the testing (validation) set.

From this revision, we report a lower R^2 value from around ~0.7 for the analysis of lime applied, lime application rate lime-treated fraction.

For the methodology section we reword as,

" To validate the model, we split our dataset (approximately 3000 counties in the contiguous USA) into 5 equal subsets, known as *folds*, based on the state of the county. We then performed 5-fold cross-validation, where each iteration trained the model on 4 of these folds and used the remaining fold as a testing set to evaluate model performance. Each fold served once as the testing set during the 5-fold cross-validation. This process ensures that the training data and testing set are from geographically independent regions (different states) and, in most cases, not of proximity. "

In the results section we changed the wordings to,

We also updated our Figure 9 and the associated figures in the supplementary information accordingly.

2. The statement of "limited overfitting" appears too optimistic. Training R^2 values of approximately 0.97–0.98 versus test R^2 values of 0.83–0.86 are not a trivial gap. When combined with the likely spatial leakage introduced by random cross-validation, the interpretation of model robustness should be more cautious.

Thanks for the reviewer's comment. We agree that there is certain degree of overfitting, particularly after we redid the state-based cross validation. We also feel that the training R^2 is less important in this context, as our main purpose is not to make prediction onto unknown space/time, but analyze the potentially related variables. We revised the associated sentence to,

" After removing the highly correlated predictors from the initial environmental

parameters (Fig. S5, Table S2), our Random Forest models demonstrated R^2 values averaging from 0.66 to 0.73 on state-level cross validation data (20% of data) (Fig. 9), showing substantial predictive skill when applied to geographically independent regions."

3. The stated study period is still inconsistent. The objective in the Introduction still refers to county-level coverage for 1950–1990, whereas the actual county-level dataset spans 1954–1987. This suggests that the revision has not been sufficiently checked for internal consistency.

Thanks for the reviewer's pointing this out. We have changed this error in the Introduction from "1950–1990" to "1954–1987".

4. There is a clear inconsistency between 1977 and 1978. In several places the manuscript refers to the last three census years as 1977, 1982, and 1987, whereas elsewhere and in the underlying data description the correct years are 1978, 1982, and 1987. This is not merely a typographical issue, because it affects the precision of the methodological description.

Thanks for the reviewer's comment. This was our error, as the Census Year is 1978. We have changed all the inconsistencies that were mentioned from 1977 to 1978.

5. The definition of the first RF response variable is inconsistent. In the Methods, the first response is described as annual lime applied normalized by county land area, whereas in the Results and Discussion it is repeatedly described as total lime applied per county. These are not equivalent quantities, and this inconsistency directly affects the interpretation of Fig. 9a.

Thanks for the reviewer pointing this out. The first response is indeed annual lime applied normalized by county land area. We revised all the inconsistency, changing all the relevant terms in the Results and Discussion section to "average annual lime applied per county (normalized by county land area)" .

6. The denominator for lime-treated fraction is still inconsistent. In some parts

of the manuscript, it is described relative to total agricultural land, while in others it is described relative to total cropland. If the original limed area includes pasture or other agricultural land, this inconsistency affects the metric definition, figure interpretation, and data-product documentation.

Thanks for the reviewer pointing out this inconsistency. The agricultural land here refers to total cropland area; thus we revised all the relevant terms to "total cropland". We agree with the reviewer that there may be some low percentage limed areas that may not be on total cropland but on other types of agricultural land. However, based on the existing resolution of the dataset, it is out of ability to discern this fraction. Thus, here rather than assuming an arbitrary ratio between limed cropland vs limed pastureland (eg. 90% vs 10%), for this analysis of lime treated fraction, we assumed all of the lime (100%) falls on cropland.

We also address this uncertainty in Section 2.3

" For the lime-treated fraction we made a simple assumption that that all lime is applied to cropland (Oh & Raymond, 2006), due to the fact that from the existing data resolution we could not discern the small fraction that could be applied to pasture or rangeland. We acknowledge that this simplification potentially led to some uncertainty in the lime-treated fraction."

And in Section 2.4

" We made a simplification here assuming that all the lime is applied evenly to cropland only (Oh & Raymond, 2006), while the relatively small fraction that may potentially be applied to pasture or rangeland is neglected (Oh & Raymond, 2006). This assumption, though may come with uncertainty, is necessary to spatialize liming rates at sub-county resolution."

7. The justification for the 10% cropland threshold remains insufficient. The manuscript states that this threshold was used to exclude counties with little agricultural activity, but no sensitivity analysis is provided, and it is not shown whether the main RF results are robust to alternative thresholds such as 5%,

15%, or 20%. Since feature rankings may depend on the set of counties retained, this choice requires stronger justification.

Thanks for the reviewer's comment. We added a sensitivity analysis with different thresholds (5%, 15%, or 20%) and showed that the rankings of the features are similar across different criteria of cropland. Thus, we kept our original choice of 10% for the main figure in figure 9 in this study. We demonstrated this comparison in Fig. S10, S11. We also added this information to the methodology section:

"We also tested other threshold of minimum cropland (5%, 15%, 20%) in relative to the total land area (shown in the SI), which demonstrated very similar ranking of features."

And also in the results section:

" For Fig. 9b and Fig. 9c, we also conducted sensitivity analysis using different thresholds of minimum cropland percentage (5-20%) in the county land area, which all shows similar results of permutation importance ranking (Fig. S10, S11)."

8. The physical meaning of the pixel-level variable remains unclear. The procedure first derives a county-level cropland-based rate by dividing county total lime by county cropland area and then multiplies this by pixel-level cropland density. The resulting value is closer to an area-weighted intensity per pixel area than a strict t ha^{-1} cropland yr^{-1} estimate. If the figure titles and data description continue to describe it as "per cropland area," the terminology is potentially misleading.

Thanks for the reviewer pointing this out. Indeed, our pixel level data can achieve a sub-county level resolution based on the pixel level cropland area. The values in each pixel don't directly suggest that X amount of lime is applied in that specific pixel. Rather, it represents an approximate representation of lime applied, if 1. Lime is applied evenly, and 2. All lime is applied to cropland. If that pixel only shows 50% of cropland density, the lime applied is multiplied by 50%.

Thus, we agree with the reviewer that the pixel level data can be better termed as an “cropland area-weighted liming intensity”

We changed the relevant paragraphs to address the change of better terminology.

Section 2.4

“We transformed the county level liming data into a pixel-level, cropland area-weighted liming intensity (t ha^{-1} yr^{-1}) by incorporating a temporal varying annual cropland area data product for the same region (Ye et al., 2024).”

Results 3.1

“Fig. 8 shows the spatial-temporal pattern of lime application per cropland area (t ha^{-1} yr^{-1}) application, transformed into pixel-level, cropland area-weighted liming intensity.”

Figure 8 caption

“Figure 8. Cropland area-weighted liming intensity (t ha^{-1} yr^{-1}) in 1km pixel resolution over the contiguous U.S. from 1954 to 1987.”

5. Data Availability

“..Pixel-level data in 1km resolution of cropland area-weighted liming intensity from 1954-1987….. The file PixelLevel_1km_t_ha_1954_1987.zip contains pixel-level estimates of cropland area-weighted liming intensity at 1 km spatial resolution, expressed in metric tons per hectare per year (t ha^{-1} yr^{-1}).”

9. The assumption that all lime is applied to cropland has broader implications

than currently acknowledged. This assumption affects not only the pixel-level product but also the interpretation of lime-treated fraction, since the original limed area may not strictly correspond to cropland limed area. This should be highlighted more explicitly as a limitation of the product rather than presented merely as a technical simplification.

Thanks for the reviewer's comment. We agree with the reviewer that this assumption will inevitably lead to broader implication than originally stated, which is the limitation of the data product. Here we stated more explicitly our assumption and associated limitation and uncertainty.

We address this uncertainty in Methodology Section 2.3

"For the lime-treated fraction we made a simple assumption that within each county all lime is applied evenly and only on cropland (Oh & Raymond, 2006), since from the existing data resolution we could not further discern the small fraction that could be applied to pasture or rangeland in a sub-county level. We acknowledge that this simplification and its associated uncertainty present a limitation to this analysis and data product."

Methodology Section 2.4

"We made a simplification here assuming that all the lime is applied evenly and only to cropland, following the methodology of Oh & Raymond (2006), while the relatively small fraction that could be applied to pasture or rangeland is neglected. This assumption, though may come with uncertainty, is necessary to spatialize liming rates at sub-county resolution."

Results and Discussion Section 3.1

"We acknowledge that the large spatial heterogeneity in lime use is influenced by finer-scale factors and historical cropland expansion that cannot be fully resolved

with the current county-level dataset. We also acknowledge our assumption that all lime is applied to cropland presents uncertainties and limitation to our analysis of lime-treated fraction and pixel-level lime intensity data (Fig. 8)."

10. The code is still not publicly available, limiting reproducibility. The Code Availability section still states that the code will be made public upon publication. For a data paper, this weakens reproducibility and prevents adequate evaluation during peer review.

Thanks for the reviewer's comment. The code for the production of this study is now made publicly available now on GitHub. https://github.com/samueltsao0302/A-spatially-explicit-dataset-of-agriculture-liming-across-the-contiguous-United-States.git

We also updated the code availability section in the manuscript accordingly.

"**6. Code Availability**

The code used for data processing, interpolation, and machine learning analysis is all publicly available on our Github repository at https://github.com/samueltsao0302/A-spatially-explicit-dataset-of-agriculture-liming-across-the-contiguous-United-States.git"

11. Phrases such as "closer to modern practices" remain too strong. The period 1978–1987 is indeed later than the 1950s, but it is still more than four decades removed from present-day management. Describing this period as closer to modern practice risks overstating the dataset's relevance to contemporary agricultural conditions.

Thanks for the reviewer's comment. We chose this period simply because it was the last years of our data. We removed this phrase on "present-day" as it might lead to overstatement in the communication of our reasoning.

The revised sentence is

“We further average the agriculture (crops, fertilizers) and climate data across 1978-1987, corresponding to the last three census years (1978, 1982, and 1987) of lime application data.”