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Projecting global fertilizer consumption under shared socioeconomic pathway (SSP) scenarios using an approach of ensemble machine learning

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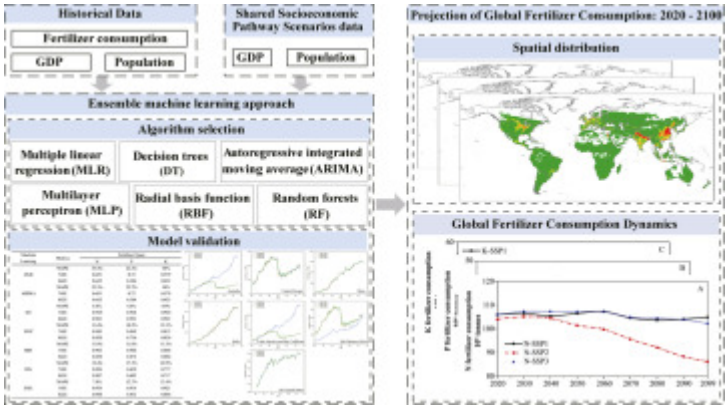
Highlights

- The ensemble machine learning approach demonstrated its reliability for fertilizer consumption prediction.
- The global N and P fertilizer consumption may decrease from 2020 to 2100, while K fertilizer may buck the trend.
- The hotspots of N fertilizer consumption may shift from China to Latin America and the Caribbean.
- The future global fertilizer consumption varies significantly under various socioeconomic development paths.

Abstract

Comprehensively projecting global fertilizer consumption is essential for providing critical datasets in related fields such as earth system simulation, the fertilizer industry, and agricultural sciences. However, since previous studies have not fully considered the socioeconomic factors affecting fertilizer consumption, huge uncertainties may remain in fertilizer consumption projections. Here, an approach ensembled six machine learning algorithms was proposed in this study to predict global fertilizer consumption from 2020 to 2100 by considering the impact of socioeconomic factors under shared socioeconomic pathway (SSP) scenarios. It indicates that the proposed approach provides a rational and reliable framework for fertilizer consumption prediction that stably outperforms the single algorithms with relatively high accuracy (Nash-Sutcliffe efficiency of 0.93, Kling-Gupta efficiency of 0.89, and mean absolute percentage error of 10.97%). We found that global N and P fertilizer consumption may decrease from 2020 to 2100, while K fertilizer may buck the trend. N fertilizer consumption showed a declining trend of −1%, −17.13%, and−3.43% under the SSP1, SSP2, and SSP3 scenarios in 2100, respectively. For P fertilizer, those were−0.68%, −9.68%, and−2.03%. In contrast, global K fertilizer consumption may increase by 18.03%, 9.18%, and 6.74%, respectively. On average, N, P, and K fertilizer consumption is highest in China, and the lowest is in Kazakhstan. However, the hotspots of N fertilizer consumption may shift from China to Latin America and the Caribbean. This study highlighted the ensemble machine learning approach could potentially be a robust method for predicting future fertilizer consumption. Our prediction product will not only contribute to a better understanding of global fertilizer consumption trends and dynamics but also provide flexible and accurate key data/parameters for related research. The Projected Global Fertilizers Consumption Datasets are available at doi:https://doi.org/10.5281/zenodo.8195593 ↗ (Gao et al., 2023).

Graphical abstract



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Introduction

Fertilization has long been regarded as a key measure to increase agricultural production (Tilman et al., 2002; Zhang et al., 2015; Mogollón et al., 2018a; Powers et al., 2019; Nedelciu et al., 2020; Randive et al., 2021). However, fertilization also has a profound impact on the agricultural system, terrestrial ecosystem, water, land, and atmospheric environment (Mueller et al., 2012; Iizumi et al., 2013; Bodirsky et al., 2014; Isbell et al., 2015; Jiang et al., 2018). Therefore, highly reliable fertilizer consumption datasets are critical in related research. For example, crop models have been widely applied to predict future grain yield under the impact of climate change (Olesen et al., 2011). However, fertilization, as the most critical model parameter, has been largely ignored or simplified (Asseng et al., 2015; Yue et al., 2015), which may potentially cause great uncertainty in the research results. This raises an urgent need to predict future fertilizer consumption and to acquire datasets and key parameters that can simulate the earth system process, fertilizer marketing, and agricultural production. However, how to predict future fertilization reasonably is not only important but is also a difficult scientific problem that needs to be resolved urgently.

One of the methods that has been widely used is an expert opinion-based approach. This approach predicts future fertilization using experts' opinions combined with historical fertilizer consumption records (Neset and Cordell, 2012). For example, based on the change rate of historical fertilization, the Food and Agriculture Organization (FAO) predicted that world demand for nitrogen (N), phosphorus (P), and potassium (K) for fertilizer use will reach 111,591, 49,096, and 40,232 thousand metric tonnes, respectively, by 2022 (Food and Agriculture Organization of the United Nations, 2016). Blanco (2011) predicted global N, P and K fertilizer supplies from 2015 to 2050 under various socioeconomic development pathways using a linear function based on historical data from 2002 to 2015. However, projections of future fertilizer consumption based on expert opinion are often considered too subjective. In addition, this approach usually regards fertilization as a function of time, but the exact factors that lead to the change in the rate of fertilizer utilization are others, e.g., population, gross domestic production (GDP), and area of arable land. Therefore, without considering these factors, there is a great uncertainty in using an expert opinion-based method to predict fertilization.

Fertilization prediction by regressing historical fertilizer consumption with multiple variables, such as population (Zhang and Zhang, 2007), grain yield (Tenkorang and Lowenberg-Deboer, 2009), fertilizer price (Deadman and Ghatak, 1979), GDP (Pacheco et al., 2022) and cultivable area (Jalil and Kabir, 2008), is therefore proposed. For example, Tenkorang and Lowenberg-Deboer (2009) first obtained a regression model of historical fertilizer application and grain yield and then predicted the future demand for fertilizers based on the stimulated grain yield by crop models and the proportion of N, P, and K

fertilizers. Although the fertilizer consumption prediction model can be established through regressing historical fertilization records with multiple impact factors. Regression models are still fundamentally empirical and face great difficulties in extrapolating from space and time.

Compared to expert opinion-based approach and regression analysis, mechanism models predict fertilizer consumption based on the fertilizer cycling processes in the earth system. This approach predicts future fertilizer consumption by achieving a certain grain yield goal, with the support of a mechanism model that considers the complex interactions between fertilization influencing factors (Jeuffroy and Recous, 1999; Chisanga et al., 2015; Salo et al., 2016; Amin et al., 2017; Li et al., 2019). For example, Salo et al. (2016) simulated future N demand for achieving spring barley yield goals using 11 widely applied crop models. And Mogollón et al. (2018a) predicted the P demand by meeting future crop production using two-pool soil P model under different SSP scenarios. In general, the mechanism model predicts the potential fertilizer consumption with the goal of future crop yields and seems is a theoretically ideal method. However, such an approach heavily relies on the geochemical cycle process, and the impact of socioeconomic factors is rarely considered.

Although the fertilizer application is closely related to the geochemical environment. However, farmers usually are not clear about the precise amount of fertilizer that needs to be applied to achieve certain crop yield goals in practice (Zhou et al., 2010; Wang et al., 2018; Chen et al., 2022). This implies that fertilizer application is not only related to geochemical process, but also strongly associated with socioeconomic factors such as farmers' ability to pay for fertilizer and their experience in fertilizer application. However, the impact of these socioeconomic factors on fertilizer consumption have not been well evaluated even in the mechanistic models.

Based on the above and motivated by predict future fertilization reasonably coupling socioeconomic factors, the objectives of this study were to (1) develop an approach that predicts fertilization by ensemble six machine learning (ML) algorithms considering socioeconomic factors, (2) use the approach to estimate the consumption of global fertilization under selected 3 SSP scenarios, and (3) determine how future socioeconomic development will affect global fertilizer consumption and its spatial-temporal patterns.

Section snippets

Basic idea

For predicting future fertilization reasonably coupling socioeconomic factors, the key lies in the selection of reasonable socioeconomic predictor variables, to explore objective knowledge of the correlation between fertilizer consumption and predictor.

Among the various socioeconomic factors affecting fertilizer consumption, the population is the most critical one. Population is the key driving force of agricultural production which leads to a consequential change in fertilizer consumption (…

Validation of the fertilizer consumption prediction

The performance of the six selected ML algorithms and the EML approach in predicting N, P, and K fertilizer consumption varied greatly (Table 2) in terms of the average NSE, MAPE, and KGE values, which ranged from 0.579 (MLR and ARIMA) to 0.954 (EML), 6.8% (DT) to 23.4% (MLR) and 0.384 (MLR and ARIMA) to 0.923 (DT), respectively. Among these, the EML was superior by significantly outperforming the other ML algorithms (Table 2, Table B.1 - Table B.3 in Appendix B), with the highest NSE, KGE, …

The trends of future global fertilizer consumption

In this study, it was predicted that the global consumption of N and P fertilizers will decrease while K fertilizer will increase from 2020 to 2100 (Fig. 3). The decrease in N and P fertilizer consumption was the largest under the SSP2 scenario, followed by SSP3, and the smallest in SSP1 (Fig. 3A, B). In contrast, global K fertilizer consumption increased the most under the SSP1 scenario, followed by SSP2 and SSP3 (Fig. 3C). The above results indicated that different socioeconomic development …

Conclusions

The present study proposed a fertilizer consumption prediction approach ensembling six machine learning algorithms, which demonstrates its predicting ability with lower uncertainty and higher precision. A high spatial resolution (5′×5′) dataset of future global N, P, and K fertilizer consumption from 2020 to 2100 under SSP1, SSP2, and SSP3 scenarios was produced.

Global consumption of N and P fertilizers was predicted to decline, while K increased from 2020 to 2100. On average, the countries …

CRediT authorship contribution statement

Yulian Gao: Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Kecui Dong:** Data curation, Methodology, Resources, Software, Validation, Visualization. **Yaojie Yue:** Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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