



Nitrogen and phosphorus emissions to water in agricultural crop-animal systems and driving forces in Hainan Island, China

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Abstract

The NUFER (Nutrient Flow in food chains, Environment and Resources) model has been used to reliably quantify nitrogen (N) and phosphorus (P) emissions from agriculture land to water bodies. However, factors impacting agricultural N and P emissions at the island scale have rarely been studied due to the lack of high-resolution spatialization tools, which are critical for exploring mitigation options. Here, a high-resolution NUFER model was constructed based on geology, meteorology, land-use data, statistical data, and field investigation. The spatial characteristics of N and P emissions in Hainan Island, China, were quantified, and the driving forces were analyzed. We also explored effective measures to reduce emissions by 2035 using scenario analysis. Overall, 98 Gg N from agriculture entered water bodies in 2018, of which crop system contributed 70%; 15 Gg P entered water bodies, of which, animal system contributed 78%. Nitrate (NO_3^-) leaching (65%) and direct discharge of animal manure (69%) accounted for most of the N and P emissions, respectively. Plains contributed 89% of N and 92% of P emissions. Spatial overlay analysis showed that high N and P emissions were mainly concentrated in the western and northeastern plain areas. At the sub-basin scale, the Nandu River basin had the largest agricultural N and P emissions, accounting for more than 20% of all emissions. Scenario analysis showed that N and P emissions were significantly correlated with natural (e.g., elevation, slope, and soil texture) and anthropogenic (e.g., rural income, population density, planting structure, and livestock density) factors. We further analyzed the emissions of N and P can be reduced by 71 Gg and 14 Gg by 2035, respectively, via reducing food chain waste and consumption, importing more food, and improving production efficiency, but especially prohibiting the direct discharge of livestock manure. This high-resolution quantification of agricultural N and P emissions to the water bodies provides an exploration of the most effective options for reducing agricultural non-point source (ANPS) pollution at the island scale.

Keywords Nitrogen · Phosphorus · Hainan Island · Agriculture · High resolution · Driving forces

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Introduction

Nitrogen (N) and phosphorus (P) are essential nutrients for biological life and are critical to agricultural production and human health (Galloway et al. 2008). In the past few decades, the growth in China's population has greatly increased the demand for agricultural products. Along with a substantial increase in the scale of agricultural production, fertilizers and fodder usage has increased (Hou et al. 2018), and China has become the world's foremost fertilizer consumer and livestock product producer (Bai et al. 2016; Chadwick et al. 2015; Hou et al. 2018). However, the excessive use of N and P has caused varying degrees of pollution in natural ecosystems such as water bodies, soils, and atmosphere, and is especially apparent in the eutrophication of coastal areas (Wang et al. 2021). The

agricultural system currently acts as the primary source of N and P emissions (Yu et al. 2019; Hou et al. 2018). Globally, runoff from farmland and pastures carrying excess N and P nutrients has been identified as the leading cause of eutrophication of coasts and oceans in the last century (Vigouroux et al. 2021). Nutrient export from agricultural land is much higher than that from other land-use types such as forests and grasslands (Rodríguez-Gallego et al. 2017). According to the second pollution source survey report in China, 47% of N and 68% of P entering water bodies came from agriculture, with 51% and 36% of those emissions coming from crop system; furthermore, the animal system themselves only uptake about 42% and 57% of the N and P nutrients supplied to them, respectively (MEEP 2020). Excessive input of N and P is a critical factor that determines the eutrophication risk in water bodies. This problem is further exacerbated by the inefficient utilization of N and P in China's crop and animal systems, which means that, compared to the USA, the European Union, and Japan, a larger proportion of applied nutrients are not being used and are instead lost to the environment (Ma et al. 2012; Bai et al. 2016; Zhang et al. 2021).

Hainan Island is China's only tropical provincial island that contains a complete agricultural industry chain. With the understanding that Hainan Island will be established as a Pilot Free Trade Zone in 2035, an increase in its population has led to rapid growth in agriculture, which will lead to increases in nutrients exported from agriculture and subsequently increase the risk of severe eutrophication (Sun et al. 2020). Eutrophication has become a regular occurrence on a number of Hainan Island's coasts in recent years (Herbeck et al. 2013; Zhang et al. 2020a, b; Huang et al. 2017), and the island has become one of the regions with the highest eutrophication risk in the world (Yang et al. 2016).

Large-scale experimental sampling is generally lacking in agricultural non-point source (ANPS) pollution research, and local-scale experiments are difficult to extend to the macro-regional level (Kaushal et al. 2011). Therefore, obtaining high-resolution spatial characteristics of N and P loss at the macro level has become critically important to the study of agricultural nutrient emission study. A large number of factors, including natural (e.g., temperature, precipitation, elevation, slope, and soil texture) and anthropogenic (e.g., rural income, population density, planting structure, and livestock density) factors, influence agricultural N and P emissions (Zhao et al. 2019; Gu et al. 2013). The agricultural production patterns of plains and hilly areas also differ greatly. Differences in emission characteristics can also translate into different sensitivities to various driving factors. Exploring and quantifying the natural and anthropogenic factors that generate changes in N and P emissions are essential to establish effective strategies for reducing excessive N and P emissions to water.

Many hydrological simulation models have been applied to analyze the characteristics of ANPS in systems, such as SWAT and AnnAGNPS (Cheng et al. 2021; Li et al. 2015). However, the terrain of Hainan Island is not a single system; it has a radial pattern with multiple independent basins, so it is impractical to study all the basins of Hainan Island as a system. Furthermore, these models required large amounts of measured data and information that are difficult to obtain at the provincial level in tropical islands, which limits their application (Zhao et al. 2019). Alternative approaches include the export coefficient method, which provides researchers with a way to determine controlling elements without monitoring basins water quality, and the nutrient export model, which is a basin-scale model that simulates nutrient input and output with relatively little data, and can be used to estimate the N and P emissions of rivers or oceans at a global scale. Recently, the NUFER (Nutrient Flow in food chains, Environment and Resources) model has been used to measure the migration processes of N and P across an entire food chain. This method can estimate N and P losses at each step of the food chain, including inputs of chemical fertilizers, organic fertilizers, atmospheric deposition, nitrogen fixation, seed uptake, irrigation from crop system, and fodder from animal system. N and P are absorbed by crops and animals as they are passed along the food chain, or are lost as discharge into water bodies, atmospheric emissions, or retained in the soil (Ma et al. 2010; Bai et al. 2016). So far, the spatial pattern of N and P emissions to water bodies from agriculture has not been systematically quantified in Hainan Island, especially at a high resolution. The effects of factors at fine spatial scales have not yet been studied, which limits the potential for effective mitigation strategies in the future.

The primary purposes of this study were to quantify agricultural N and P emissions to water at a high-resolution spatial scale, analyze the factors impacting N and P emissions, and explore mitigation strategies for Hainan Island. To achieve these goals, we first collected statistics on Hainan Island and selected the parameters of the NUFER model that are applicable to Hainan Island. Second, we determined the distribution coefficients of N and P loss based on the land-use data from 2018. Third, we explored the forces driving the variability in N and P emissions to water considering both natural and anthropogenic factors via linear regression analysis. Finally, we simulated several scenarios to explore mitigation options and their potential efficacy in Hainan Island. This study produced a high-resolution map of agricultural N and P emissions to water that can be used to explore driving forces and model reduction options at the island scale.

Materials and methods

Study area

Hainan Island is China's second-largest island and the only province in China that is located entirely in the tropics. It is located in the northern South China Sea and faces the Leizhou Peninsula across the Qiongzhou Strait (Lu et al. 2021). Hainan Island covers an area of approximately 3.39×10^4 km² and owns 42.3% of China's sea area (Zhang et al. 2013). Affected by the monsoon climate, the rainy season in Hainan Island is from May to September, and the dry season is from October to April. The annual average temperature ranges from 22.8 to 25.8 °C, and the annual average precipitation ranges from 961 to 2439 mm (Zhang et al. 2020b; Fang et al. 2020). Hainan Island has radially arranged terrain, with mountainous areas in the middle surrounded by plains. Hainan Island is usually divided into 26 sub-basins, of which, the three largest basins are the Nandu River, Changhua River, and Wanquan River basins. Hainan Province is relatively behindhand in development, but its proportion of agricultural output has always been first in China (National Bureau of Statistics). Agriculture in Hainan Island is concentrated in the coastal plains. The crops grown on the island are mainly rice, vegetables, tropical fruits, and cash crops, and the livestock and poultry breeding industries are dominated by pig and meat poultry. Any wastewater produced in the basins basically flows directly into the ocean. According to statistics in 2019, 195 km² of the coast of Hainan Island experienced eutrophication.

Estimation of N and P emissions to water bodies from agriculture

N and P emissions to water bodies from agriculture come from both crop and animal systems. The crop system N and P enter the water bodies via leaching, runoff, and erosion, while the animal system N and P enter the water via the leaching and direct discharge along the livestock management chain. An improved high-resolution-based NUFER model with local natural parameters was used to estimate N and P emissions. The NUFER model follows the principle of mass conservation and can be used to estimate the nutrient input, migration, transformation, and output from different crop and animal systems (Zhao et al. 2019; Velthof et al. 2009; Ma et al. 2010; Bai et al. 2016). Below are the formulas of N and P losses in crop system:

$$N, P_{erosion} = N, P_{topsoil} \times LF_{erosion,max} \times fp \times \min(flu, frc, fs) \quad (1)$$

$$N, P_{runoff} = N, P_{application} \times LF_{runoff,max} \times flu \times \min(fp, frc, fs) \quad (2)$$

$$N, P_{leaching} = E, P_{surplus} \times LF_{leaching,max} \times flu \times \min(fp, frc, ft, fc) \quad (3)$$

where Eqs. (1)–(3) are N and P erosion, runoff, and leaching from crop system, respectively. $N, P_{erosion}$, N, P_{runoff} , $N, P_{leaching}$ are the N and P emission to water bodies via soil erosion, surface runoff and leaching, respectively, unit: t; $N, P_{topsoil}$, $N, P_{application}$, $N, P_{surplus}$ are the N and P content in the soil surface, applied in arable land and surplus in soil; $LF_{erosion,max}$, $LF_{runoff,max}$, $LF_{leaching,max}$ are the maximum fraction of soil erosion, surface runoff and leaching, respectively; fp , flu , frc , fs , ft , fc are the reduction coefficients of precipitation, land use, soil depth, soil type, temperature, and soil organic matter content, respectively. The detail of parameters and specific values used can be seen in the Supplemental Information (SI).

For crop system, we used agricultural data (Table S2) at the town level from 2018 and calculated the $N, P_{topsoil}$, $N, P_{application}$, and $N, P_{surplus}$, then used the spatial data (Fig. S1) to establish the distribution of N and P reduction coefficients (1)–(3) map respectively (Fig. 1). Finally, $N, P_{topsoil}$, $N, P_{application}$, and $N, P_{surplus}$ were evenly allocated to the arable land and economic forest of each county according to the land-use data with a resolution of 30 m × 30 m.

For animal system, N and P are discharged into water via leaching and direct discharge along the livestock management chain (including housing, storage, and treatment stages). Therefore, we first calculated the total N and P emissions by multiplying the excretion rate (Table S3) by the number of livestock in each animal category. Based on the total emissions along the animal management chain, we calculated the amounts of N and P directly discharged or leached by multiplying by their respective expected proportions. Finally, the N and P emissions from the animal system were evenly distributed among the rural settlements of each town based on the premise that all the manure will be used in farmland for crop cultivation. N and P emissions from animal systems were also evenly allocated to the rural settlements according to housing, manure storage, and treatment stages (Zhao et al., 2019). To reduce the uncertainty in the results, we further conducted an overlay analysis on N and P emissions and aggregated the results into a 1 km × 1 km grid.

Data collection

Data used in this study included statistics, investigation data, parameters extracted from the literature, and spatial data. The statistical data came from the statistical yearbook of counties and towns, and included the crop planting area, sowing amount, livestock number, chemical fertilizer application, and population in 2018. Then, we estimated organic fertilizer application, straw return rate, return rate of manure to field, and fertilizer management methods from a

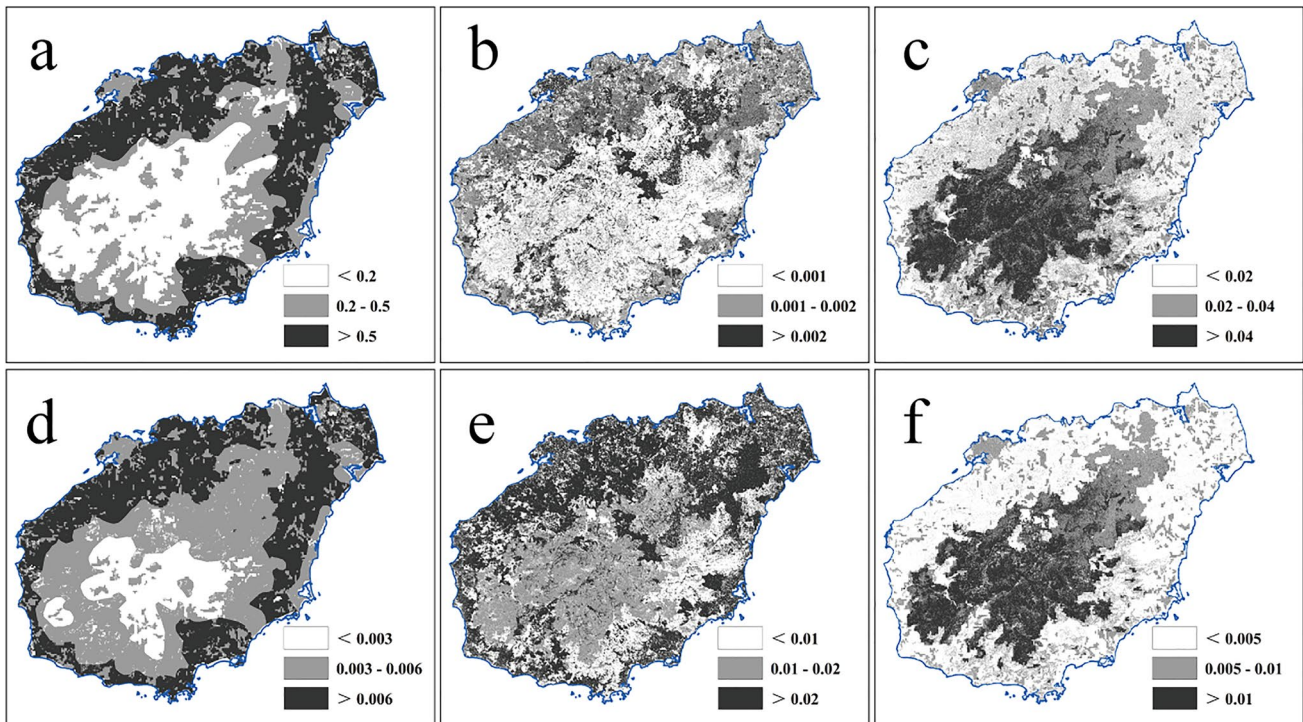


Fig. 1 Distribution of leaching, erosion, and runoff losses coefficient of N and P in crop system. (a for N leaching; b for N erosion; c for N runoff; d for P leaching, e for P erosion; f for P runoff.)

systematic farm investigation covering 106 individual farms in 18 counties and 195 typical towns in Hainan Island. These investigation data included crop fertilization, crop product/straw destination, planting and management methods, information on livestock housing, manure storage, and treatment by farmers; N and P contents of crops and animals were obtained from the literature (Bai et al. 2016; Ma et al. 2010). The spatial data of land use, soil type, soil texture, precipitation, temperature, elevation, income, and population density came from the Resource and Environment Science and Data Center (<http://www.resdc.cn>). The spatial data of precipitation was derived from monthly data of 88 stations in Hainan Province, and the inverse distance weighting method was used to interpolate the values in ArcGIS.

Driving forces analysis

The losses of agricultural N and P were related to both natural and anthropogenic factors. In this study, five natural factors, namely temperature, precipitation, elevation, slope, and soil texture, and two anthropogenic factors, rural income and population density, were determined based on the data for each town. We further explored the relationship between planting structure, livestock density, slope, soil texture, and the output of N and P in plains and hilly areas, respectively.

In this study, the township boundary map (excluding Sansha City) was used, and the geographic coordinate system was set to WGS1984 in ArcGIS10.2.

Many models can measure the relationship between impact factors and variables; these include linear and non-linear, univariate and multivariate regression models. In this study, the relationships between N and P and agricultural losses were generally described as a simple linear, so the univariate linear regression method was used for analysis (Gu et al. 2013). The SPSS (Statistical Package for the Social Science) statistical software (v22.0) was used for the regression and statistical analysis, and the significance levels was set at $P < 0.05$.

Scenarios in 2035

In the macroscopic model of nutrient management, different scenarios were adopted to achieve specific goals. China's goal to have zero growth of fertilizers and the FAO's predictions for animal products were both considered, and five scenarios were set up to simulate the potential to reduce N and P losses in different animal system by 2035. Following Bai et al. (2016) and Zhao et al. (2019), the animal and crop systems were combined to further explore the future agricultural N and P management in terms of food consumption, import, and production efficiency. In this study, six scenarios

were established to predict how different agricultural N and P management strategies in Hainan Island will manifest in 2035:

- (1) *S0*: BAU (Business As Usual). The number of animal products is based on the linear extrapolations published by the FAO, which estimate the population growth rate and the growth rate of crops and livestock products under the 2035 development goal of Hainan Free Trade Port. In this case, we assumed that an increase in demand for livestock products will occur in the animal system. System production efficiency, and feed and fertilizer management practices will remain the same as in 2018.
- (2) *S1*: Consuming and Wasting Less (CWL). Food chain waste will be reduced, so crop yields, meat, and fertilizer consumption will be reduced compared to *S0*. In addition, the recommendations in the Chinese Dietary Guidelines (2016) will be adopted.
- (3) *S2*: Importing More Food (IMF). The food self-sufficiency rate will be maintained at 90%, and the output of local crops, livestock, and poultry will be reduced.
- (4) *S3*: Producing More and Better (PMB). The production efficiency of rice, vegetables, and fruits will increase; hence, the quantity of chemical fertilizers will be reduced accordingly. In addition, the direct discharge of livestock manure will be completely eliminated by 2035; manure returned to the field will be used as efficiently as possible.
- (5) *S4*: Combination of *S1* and *S3*
- (6) *S5*: Combination of *S1*–*S3*

Results

Agricultural N and P emissions to water in Hainan Island

The estimated total N emission to water from agricultural systems in Hainan Island was 98 Gg yr⁻¹ in 2018, with 70% from crop system and 30% from animal system (Fig. 2). Leaching loss from crop system was the largest contributor (65%), followed by direct discharge in livestock manure to water bodies (16%). The two largest sources were N fertilizer and fodder, which contributed 53% and 36% to total N input to crop and animal systems, respectively. The total P emission to water from agricultural systems was 15 Gg yr⁻¹ in 2018, of which 15% was from crop system and 85% came from animal system (Fig. 2). The largest pathway was the direct discharge of livestock manure, which contributed 69%. P fertilizer and fodder were the two largest sources, which accounted for 63% and 33% to the total P input to the crop and animal agricultural systems, respectively.

There was great spatial variability in the distributions of N and P emissions from agriculture (Figs. 3 and 4). Plains and hilly areas contributed 89% and 11% of the total N emission, respectively. The highest N emission intensities occurred in areas with concentrated livestock industry and coastal plains. From the perspective of sub-basins, the highest average N emission intensity was 8 t km⁻² yr⁻¹, which occurred in the Nandu River basin, and contributed 20% of the total N emission to water. The highest N emission intensity occurred in Jiuqu River basin, where it reached 12.3 t km⁻² yr⁻¹ (Fig. 5a, b). The plains area contributed 92% of the total P emissions to water. In contrast to the spatial pattern of N, the highest density of P was concentrated in rural settlements and plains near the central and northern regions, rather than near the coast, where it reached 0.9 t km⁻² yr⁻¹. Nandu River basin contributed 22% of the total agricultural P emissions, and Shibi River basin had highest P emission intensity (4.2 t km⁻² yr⁻¹).

Spatial overlay analysis showed that high N and P emissions were mainly concentrated in the western, northern, and northeastern plains areas of Hainan Island (Fig. 6).

Driving forces of agricultural N and P emissions to water

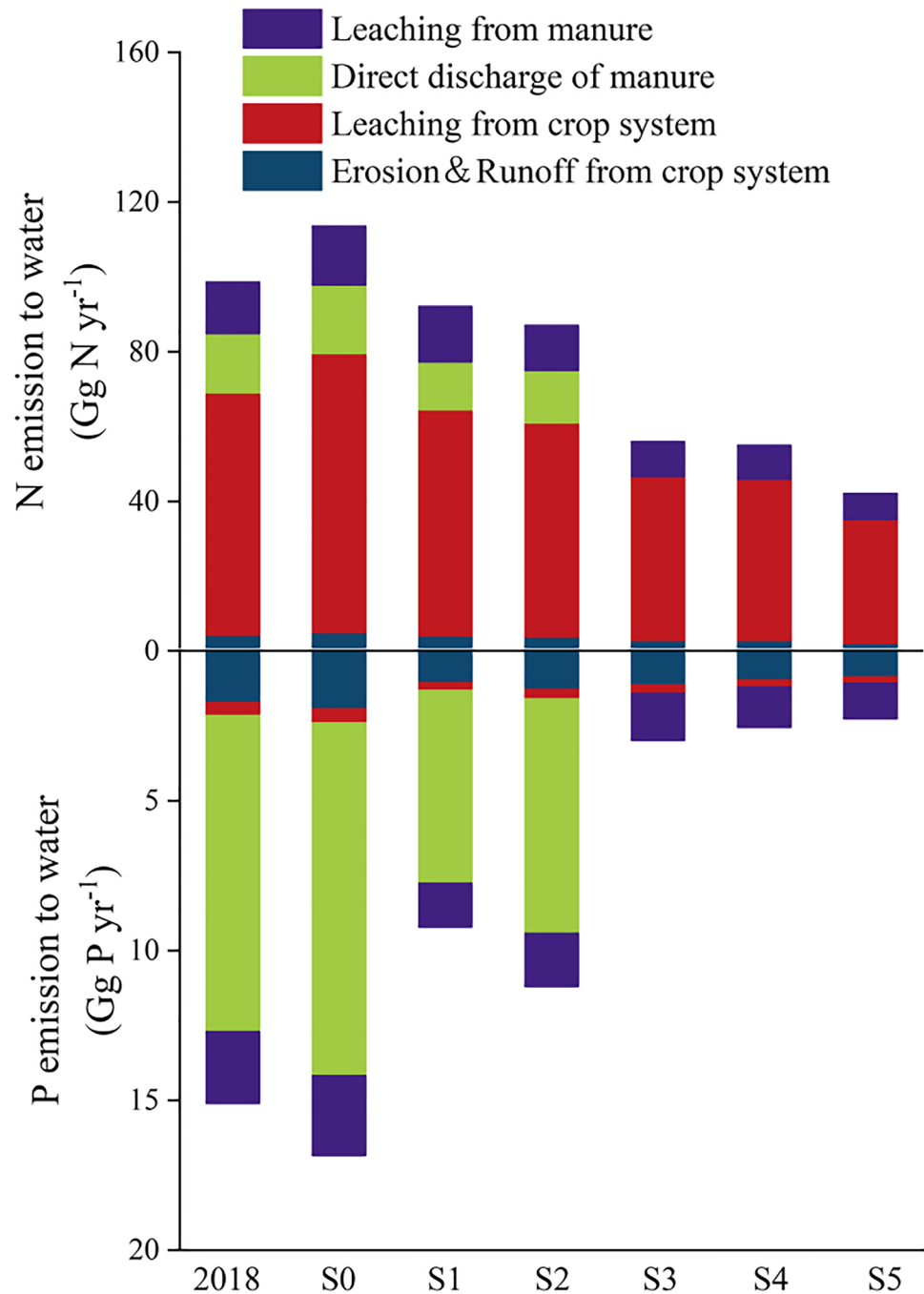
The statistical data were converted to normal distribution, and analysis showed that the N and P emissions had different correlations with natural and anthropogenic factors (Fig. 7). Both N and P emissions were negatively related to elevation and slope but positively related to share of loam land and rural income, indicating that high N and P emissions were more likely to occur in rural areas on the plains with loam land.

Both N and P emissions were influenced by natural and anthropogenic factors, but to different extents in plains and hilly areas (Figs. 8 and 9). N emissions were positively related to the share of rice and vegetable, and the density of pig, cattle, and poultry but negatively related to slope, which was more obvious in hilly areas. In plain areas, N emissions were positively correlated with share of rice, vegetable, and loam land. P emissions were positively related to slope, share of rice and loam land, and density of pig, cattle, and poultry. These relationships indicated that the effects of anthropogenic factors were similar on N and P emissions, while natural factors have different effects on N and P emissions.

N and P emissions in 2035 under different scenarios

In general, as the population increases from 2018 to 2035, N and P emissions will increase due to the increasing demand for livestock products. However, if effective management

Fig. 2 Agricultural N and P emissions to water in the Hainan Island in 2018 and 2035 under the different scenarios. BAU: Business As Usual, IMF: Importing More Food, CWL: Consuming and Wasting Less, PMB: Producing More and Better



measures are adopted, N and P emissions can be maintained at relatively low levels in the future (Fig. 2).

Under the BAU (*S1*) scenario, the island's N and P emissions will increase by 15% and 17%, respectively. Nitrate (NO_3^-) leaching will increase by 15%, and the direct discharge of P in livestock manure will increase by 12% (Fig. 2).

Reducing food loss and optimizing human diet (CWL, *S2*), increasing food imports (IMF, *S3*), and improving production efficiency (PMB, *S4*) scenarios all produced an

effect on reducing N and P emissions by 2035, compared to *S1*. Under the PMB (*S4*) scenario, direct discharge of N and P in livestock manure will completely disappear in 2035; hence, this scenario was more effective in reducing emissions than the CWL and IMF scenarios (Fig. 2).

If the above-mentioned policies were combined, nutrient emissions will remain at lower levels in the future. For instance, at the sub-basins scale, the average emission densities of N and P would be lower than $4.3 \text{ t km}^{-2} \text{ yr}^{-1}$ and $0.2 \text{ t km}^{-2} \text{ yr}^{-1}$, respectively, under the PMB + CWL scenario

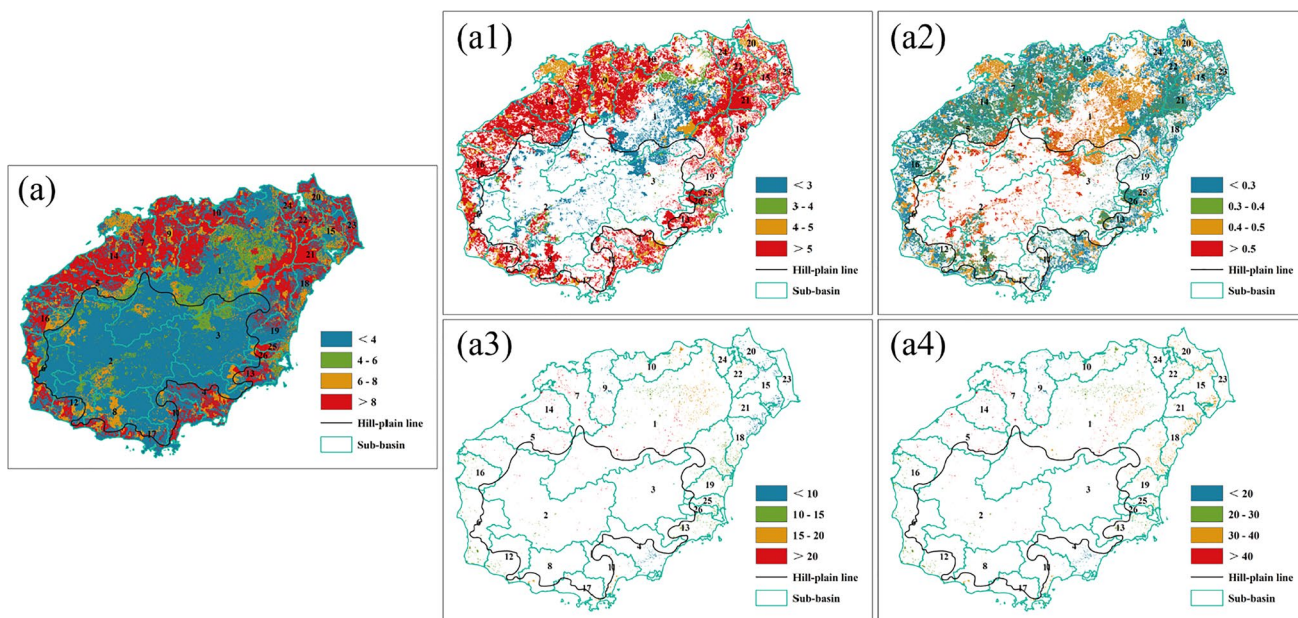


Fig. 3 Spatial distribution of agricultural N emission in the basins of Hainan Island in 2018 (Unit: $t\ km^{-2}\ yr^{-1}$). **(a)**: N emission to water; **(a1)**: N leaching in crop system; **(a2)**: N erosion & runoff in crop system; **(a3)**: N leaching from animal manure management chain in animal system; **(a4)**: N direct discharge from animal manure management chain in animal system. 1: Nandu river; 2: Changhua river; 3: Wanquan river; 4: Lingshui river 5: Zhubi river 6: The west rivers

7: Beimen river 8: Ningyuan river 9: Wenlan river 10: The north rivers 11: Tengqiao river; 12: Wanglou river; 13: Taiyang river; 14: Chun river; 15: Wenjiao river; 16: Ludai river; 17: Sanya river; 18: Shibi river; 19: Jiuqu river; 20: Zhuxi river; 21: Wenchang river; 22: Yanzhou river; 23: Northeast rivers; 24: Jiangdong district; 25: Longshou river; 26: Longwei river

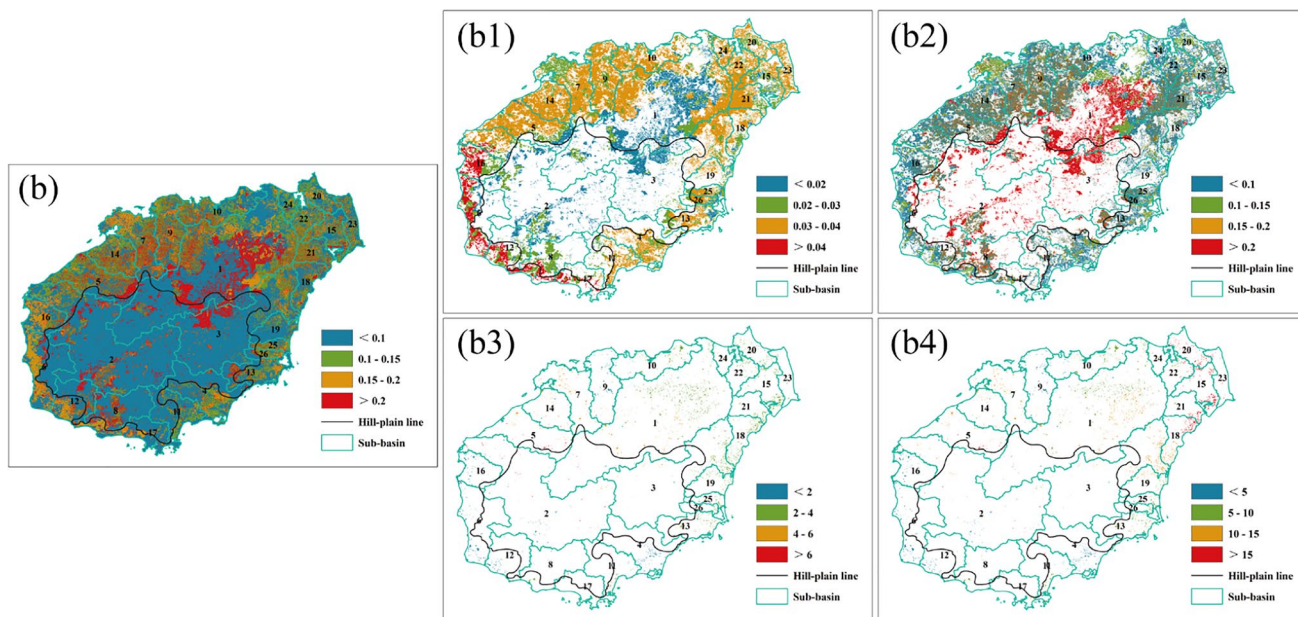


Fig. 4 Spatial distribution of agricultural P emission in the basins of Hainan Island in 2018 (Unit: $t\ km^{-2}\ yr^{-1}$). **(a)**: P emission to water; **(b1)**: P leaching in crop system; **(b2)**: P erosion & runoff in crop system; **(b3)**: P leaching from animal manure management chain in animal system; **(b4)**: P direct discharge from animal manure management chain in animal system. 1: Nandu river; 2: Changhua river; 3: Wanquan river; 4: Lingshui river 5: Zhubi river 6: The west rivers

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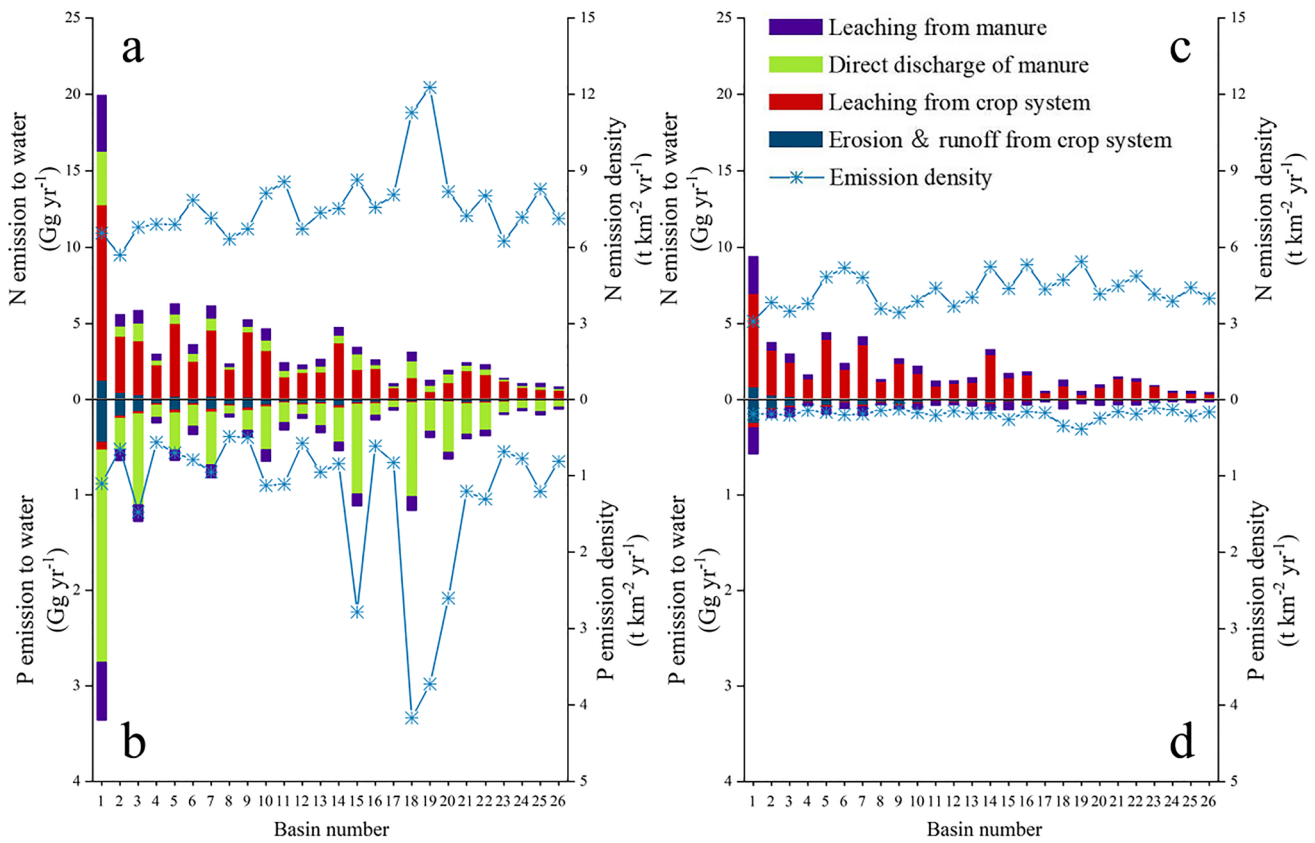
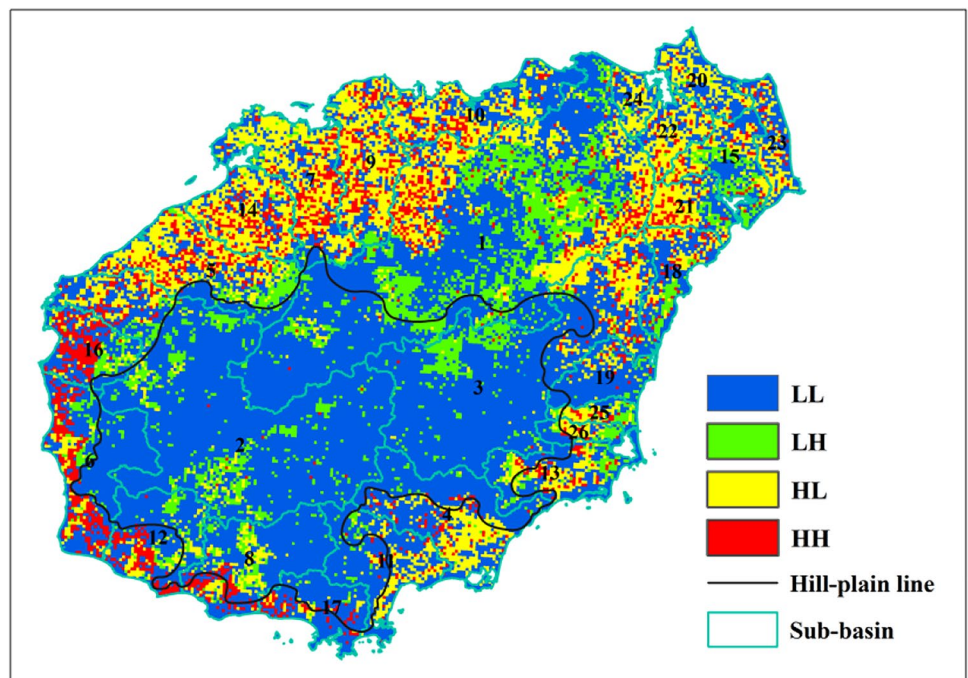


Fig. 5 Agricultural N and P emissions to water and emission densities in the sub-basins in 2018 (a, b) and 2035 under the PMB + CWL scenario (c, d)

Fig. 6 Zones of N and P emissions in 2018 in Hainan Island (LL: Low N and P emissions; LH: Low N emission and high P emission; HL: High N emission and low P emission; HH: High N and P emissions) 1: Nandu river; 2: Changhua river; 3: Wanquan river; 4: Lingshui river; 5: Zhubi river; 6: The west rivers; 7: Beimen river; 8: Ningyuan river; 9: Wenlan river; 10: The north rivers; 11: Tengqiao river; 12: Wanglou river; 13: Taiyang river; 14: Chun river; 15: Wenjiao river; 16: Luodai river; 17: Sanya river; 18: Shibi river; 19: Jiuqu river; 20: Zhuxi river; 21: Wenchang river; 22: Yanzhou river; 23: Northeast rivers; 24: Jiangdong district; 25: Longshou river; 26: Longwei river



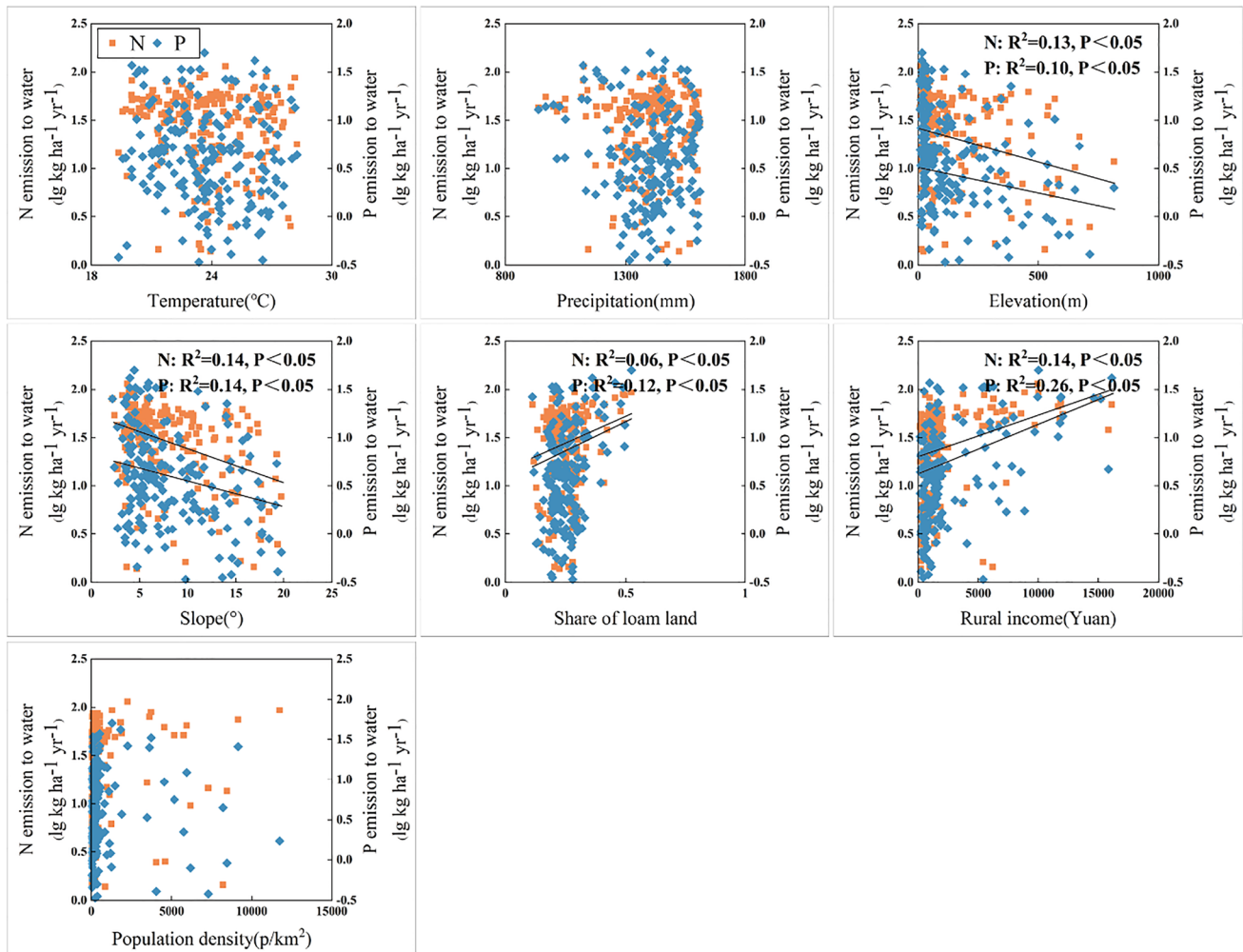


Fig. 7 Relationships between natural factors (temperature, precipitation, elevation, slope, soil texture), anthropogenic factors (rural income, population density), and N and P emissions to water. Red dots represent N, blue dots represent P, the data were based on towns-level

(Fig. 5c, d). Under the S5 (CWL + IMF + PMB) scenario, total N and P emissions to water bodies will be reduced by 71 Gg N and 14 Gg P, respectively, by 2035 (Fig. 2).

Discussion

Uncertainty and validation

In this study, the uncertainty of our results was mainly related to the sources of the statistics and the data obtained from field investigations. For the statistics, we referred to official publications from government departments. Governmental data at the county and town levels usually have errors of less than 10%. Therefore, we used town-level data to calculate social-economic indicators to minimize statistical errors. In our field investigation, the data on the manure treatment methods (composting, returning to the

field, direct discharge, biogas fermentation, etc.) were collected via direct observation or consultation with farmers, which resulted in some errors. In order to reduce the uncertainty of the results, we aggregated N and P emissions into 1 km × 1 km grids via overlay analysis to highlight the hot-spots with high N and P emissions.

We estimated that an average 5.02 t km⁻² yr⁻¹ N was leached from agriculture in Hainan Island, which was similar to the estimation (4.63 t km⁻² yr⁻¹) by Zhou (2011) in Hainan Island, slightly higher than the estimation (3.81 t km⁻² yr⁻¹) by Wu (2014), higher than the estimation (3.76 t km⁻² yr⁻¹) by Yu (2019) in China, and 3.1 times that (1.60 t km⁻² yr⁻¹) of the EU-27 (Velthof et al. 2009). This relatively high result may be explained by the inclusion of soil textures in our model, which affects leaching rates. More than half of the soil in Hainan Island is sandy, which has a high N leaching rate (Salm et al. 2007; Koops et al. 1996). For P emissions from the crop system, our estimation showed that

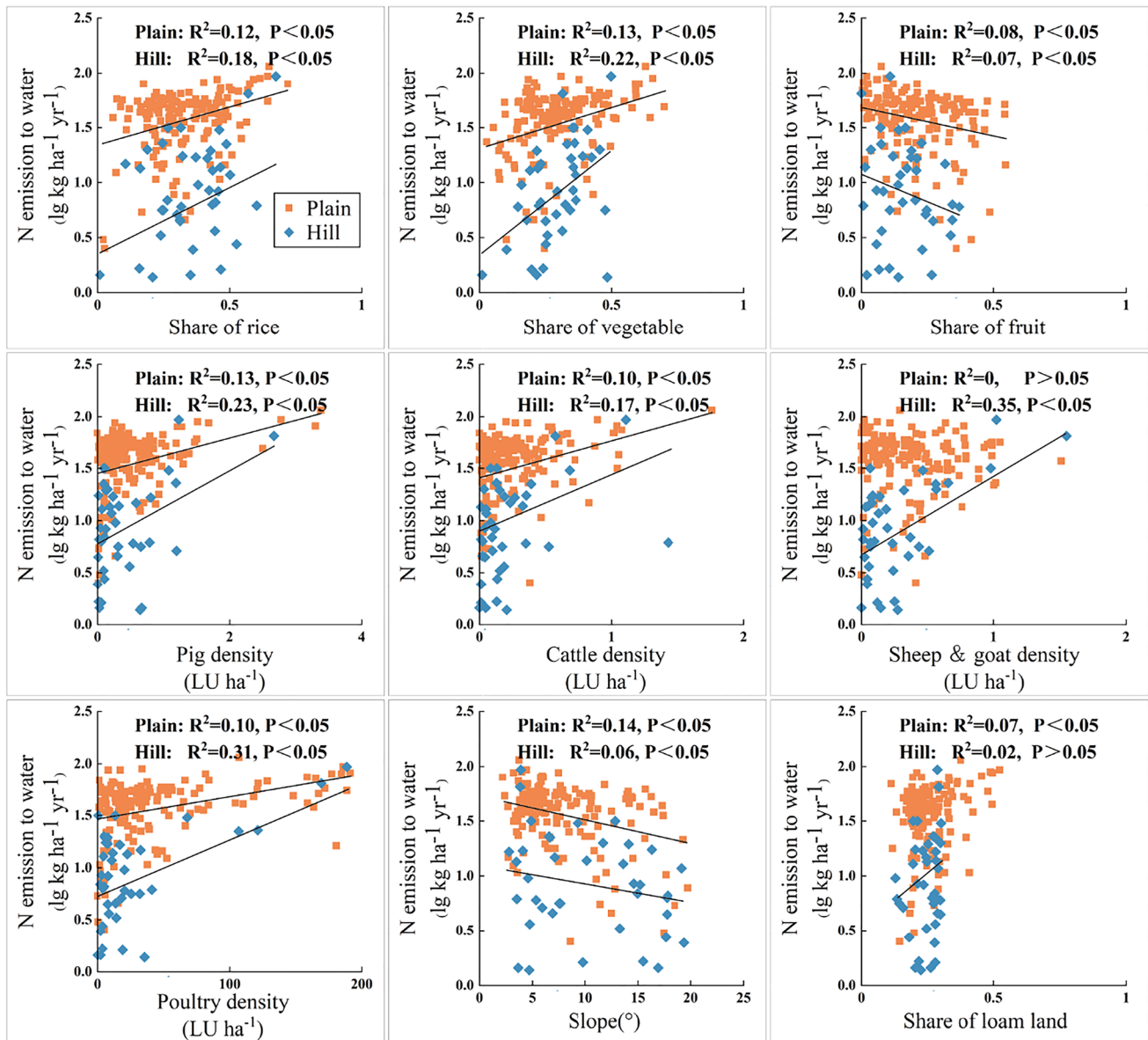


Fig. 8 Relationships between planting structure, livestock density, slope and soil texture, and N emission to water on the basis of towns-level data in the plains and hilly regions, respectively

the P loss rate in Hainan Island was 0.25 t km² yr⁻¹, which was lower than the estimation (0.36 t km⁻² yr⁻¹) by Zhou (2011), slightly lower than the estimation (0.30 t km⁻² yr⁻¹) by Wu (2014), and slightly higher than the averages (0.21 t km⁻² yr⁻¹) reported in China (Han et al. 2021).

The results of several local studies were used to validate our results of estimation. For coastal rivers, we estimated that 5.92 Gg N and 1.52 Gg P entered into water from agriculture in Wenjiao River and Wenchang River basins, which were slightly lower than the estimation of N (6.11 Gg) and higher than the estimation of P (1.05 Gg) by Liang et al. (2021). We estimated that 1.57 Gg N was lost from agriculture in Beimen River basin, which was slightly higher

than the results (1.38 Gg) of investigation by Hainan Water Conservancy and Hydropower, Survey and Design Institute (2014). For surface runoff from agriculture, we have estimated that 1.90 Gg N and 0.22 Gg P entered into water in Songtao Reservoir, which were similar to the results of investigation (1.39 Gg N and 0.28 Gg P) by Hainan Provincial Department of Water Affairs (2014). There were 0.82 Gg N and 0.22 Gg P that entered into water in Chitian Reservoir, which were slightly higher than the estimation (0.68 Gg N and 0.14 Gg P) by Hainan Provincial Department of Water Affairs (2014).

There were also some uncontrollable factors that may have produced uncertainty in the results, such as changes in

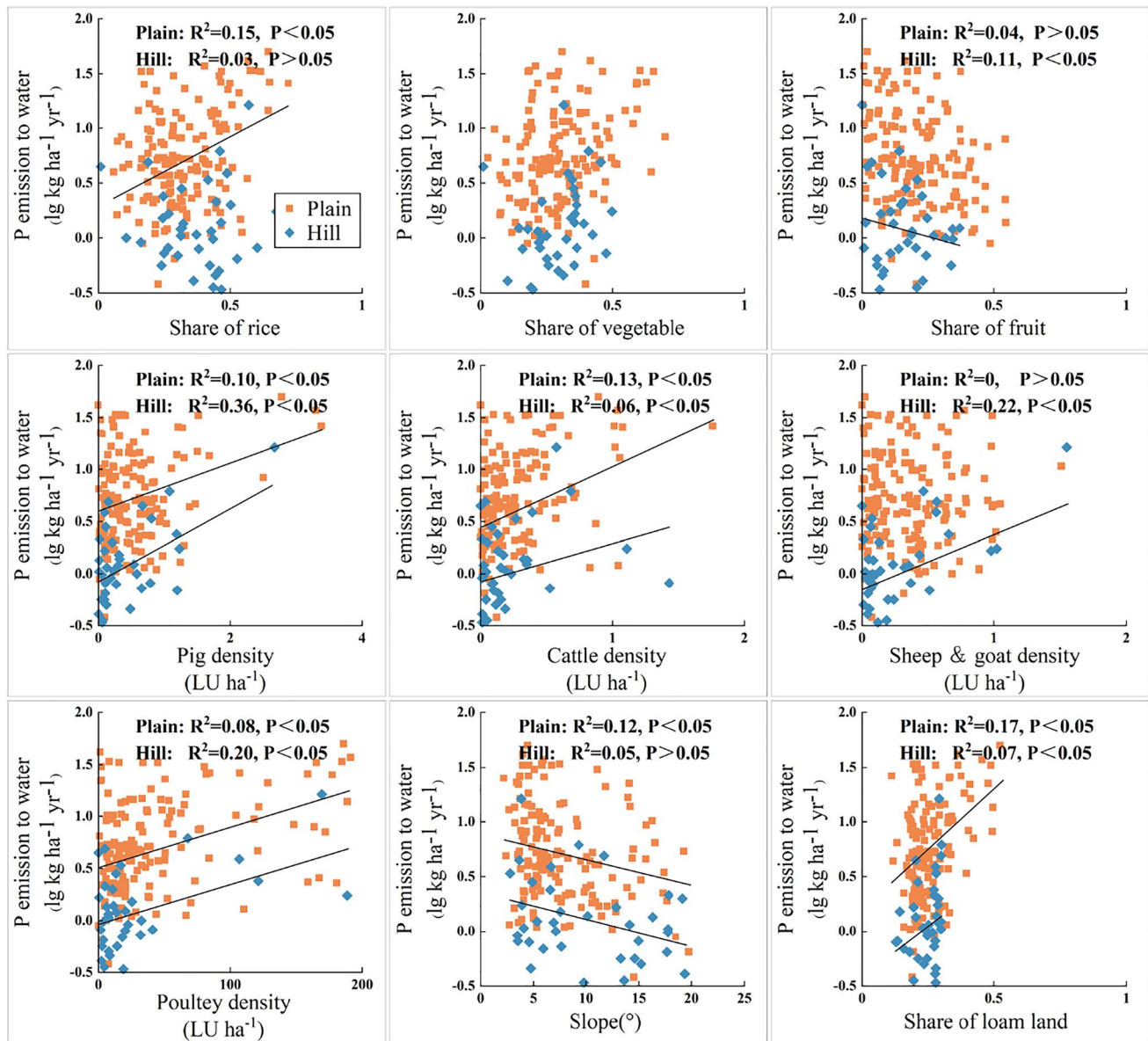


Fig. 9 Relationships between planting structure, livestock density, slope and soil texture, and P emission to water on the basis of towns-level data in the plains and hilly regions, respectively

N and P contents in crops caused by transformation during field fertilization or natural factors, or the volatilization of livestock manure when it was transferred to the field. Further surveys combined with field experiments will better help obtain more accurate parameter information to improve the model.

Driving forces of agricultural N and P emissions to water

Considering the unique and complex topography of Hainan Island, N and P emissions from agriculture were not only correlated with anthropogenic factors, but also natural

factors. Our results showed that N and P emissions were significantly negatively correlated with elevation and slope but positively correlated with share of loam land and rural income, which indicated that N and P losses mainly occurred in rural areas of the plains where covered a large amount of croplands. The analysis also showed that N and P emissions were not significantly correlated with temperature, precipitation, and population density, which indicated that the characteristics of abundant rainfall and high temperatures brought by the tropical monsoon climate of Hainan Island had little impact on agricultural N and P leaching.

In plains, N emissions were positively correlated with livestock density and share of rice and vegetable but

negatively correlated with slope, which mainly reflected that agricultural production was mainly concentrated in flat plain areas. The P emissions were negatively correlated with slope, which may be because soil erosion was the main pathway by which P lost in crop systems. The obvious positive correlation between the soil erosion effect of slope and P emission has been previously observed (Yan and Gao 2021; Remund et al. 2021). Our results showed that P emissions on the plains were positively correlated with the share of loam land, indicating that the loam land areas were more suitable for the development of agriculture, which was similar to the results of Zhao et al. (2019).

However, currently there is no definitive way to accurately measure the characteristics of N and P losses at a macro level. This is because losses of N and P are not only related to the factors discussed above, but also to various factors that are difficult to observe, such as soil depth, changes in nutrient material forms, and the migration and transformation of elements. In order to better explore the losses of agricultural nutrients at the macro level, considering the above levels will be the focus of future research.

Potential risks of water resources and the significance of future management

Our estimates of the N leaching rates of Hainan Island were higher than previous study for the island (Zhou 2011), as well as estimates in China (Yu et al. 2019) and 27 European countries (Velthof et al. 2009). The high N leaching presents a potential threat to groundwater quality, especially in coastal zones, which are vulnerable to seawater intrusion. Hainan Island has an abundance of rainfall and frequent typhoons, which will increase the risk of P loss (Zhao et al. 2019). Currently, nutrients that enter the water bodies of the island will eventually flow into the South China Sea, where they aggravate the future eutrophication risk in the coastal zone of Hainan Island. Measures must be taken to mitigate this risk and prevent increases in eutrophication in the future.

Several of our scenarios clearly demonstrated how N and P emissions will change with or without management measures. Reducing agricultural product waste and consumption and importing more agricultural products would significantly reduce future N and P emissions. However, improving production efficiency and prohibiting the direct discharge of livestock manure were the most effective measures, which have the potential to reduce N and P emissions by 57% and 85%, respectively, by 2035. The largest source of N and P in farmland was chemical fertilizers. Therefore, it is necessary to explore and improve chemical fertilizer application technology while ensuring the stability of agricultural yields.

Replacing chemical fertilizers with organic fertilizers may also be a sustainable option.

Our estimates for the effectiveness of these measures may be conservative. For one, we did not consider pesticides due to their volatility. Furthermore, in order to ensure the safety of agricultural water resources under the construction of the Hainan Free Trade Port, the government will need to vigorously promote improvement measures. Actions such as strengthening irrigation infrastructure (such as trickle irrigation) to conserve water resources or reducing the excessive application of chemical fertilizer to further reduce the loss of nutrients will further ameliorate N and P emissions in the future. This study provides insights into potential approaches for reducing the risk of eutrophication due to agriculture emissions.

Conclusion

We constructed a high-resolution NUFER model to quantify the spatial characteristics of N and P emissions throughout Hainan Island, analyzed the main influencing factors, and proposed the corresponding mitigation options for Hainan Island. Overall, total N and P emissions from agriculture in 2018 were 98 Gg yr⁻¹ and 15 Gg yr⁻¹, respectively, in Hainan Island. Nitrate (NO₃⁻) leaching (65%) and direct discharge of livestock manure (69%) contributed the most to N and P emissions, respectively. Emissions to water were significantly correlated to both natural and anthropogenic factors. High densities of N and P emissions were mainly concentrated in the plains. If food chain waste and consumption are reduced, more food is imported, and production efficiency is improved by 2035; N and P emissions can be reduced by 71 Gg and 14 Gg, respectively. This study has provided a high-resolution view of agricultural N and P emissions into water bodies on Hainan Island and explored promising mitigation strategies for reducing of ANSP emissions at the island scale. Further work focusing on improving parameter accuracy and integrating micro-scale factors into models will improve our estimates and potentially reveal novel strategies for improving agriculture emissions.

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resources, validation; **SF**: data curation, investigation; **YZ**: investigation; **CY**: resources, investigation, writing—review and editing, funding acquisition.

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Declarations

Ethics approval We declare that we have complied with ethical responsibilities before submitting the manuscript.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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