



Research Article



Management of nitrogen nutrient flow under legume practice from La Teresa basin to the Batabanó Gulf

José Miguel Febles Díaz¹  · José Manuel Febles González¹ · Julia Azanza Ricardo¹ · Thalia González Calvo² · María Sotelo Pérez³

Received: 14 March 2022 / Accepted: 22 August 2022

Published online: 11 September 2022

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Abstract

Nitrogen management in a karst basin is examined through the establishment of legumes *Leucaena leucocephala* and *Phaseolus vulgaris* in pasture and crop areas respectively, with the objective of enriching the nutrient flow interrupted by the construction of dams and canals built during the 1990s, which have altered the natural patterns of hydrological variation and transport to the sea. The different soil treatments show low values of overland fluxes to the sea between 0.9623 and 0.9624 kg ha⁻¹ yr⁻¹ for crops, discretely increasing by 0.02% in pasture and by 0.28% for crop + pasture according to the geomorphic potential of the basin. For land use conditions, a positive economic nitrogen balance was estimated in the range of 55–1560 for crops and 22–2400 USD ha⁻¹ yr⁻¹ for pastures, the latter showing positive balances at the lowest fixation rates, confirming that cover management with legumes maximizes gains and minimizes losses for both agricultural and marine ecosystems, providing a source of indirect fertilization downstream where agricultural areas are located.

Article highlights

- In the flat karst region, geomorphological potential is the main factor in predicting the dynamics of sediment movement.
- Leguminous land use has a weak effect on alleviating pressures on the island's oligotrophic marine ecosystems.
- In both crop and pasture, a positive annual economic balance of N was found in the range of 55–2400 USD ha⁻¹ yr⁻¹.

Keywords Karst · Havana-Matanzas plain · *Leucaena leucocephala* · Soil cost

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s42452-022-05138-1>.

✉ José Miguel Febles Díaz, jmifebles@gmail.com; José Manuel Febles González, jmifebles@yahoo.com; Julia Azanza Ricardo, jaricardo@instec.cu; Thalia González Calvo, tgonzalez2496@yahoo.com; María Sotelo Pérez, maria.sotelo.perez@urjc.es | ¹University of Havana, Havana, Cuba. ²Arizona State University, Tempe, USA. ³University of Rey Juan Carlos, Madrid, Spain.



SN Applied Sciences

(2022) 4:267

| <https://doi.org/10.1007/s42452-022-05138-1>

1 Introduction

The waters of the Gulf of Batabanó are oligotrophic waters [1, 2] under strong historical pressure, due to the execution of various hydro-technical works during the 1970s (reservoirs) for the development of agricultural programs [3, 4], in which the Dique Sur (South Dike) stands out. These actions have notably influenced nitrogen and phosphorus inputs from the land to the sea, as these, act as an obstacle, along with the drastic reduction of fertilizer imports during the so-called Special Period in Cuba (1991–1996) as shown in Table 1 and Fig. 1 [5, 6].

Natural factors such as the low geomorphic potential for runoff, typical of a karstic plain, combined with the effects of engineering works built along the plain, have led to a reduction in the amounts of nutrients reaching the sea from the land. Hence, this brings about a decrease in the natural rate of biogeochemical cycles.) These results agree with those of Baisre [4, 7, 8] and Claro et al. [9] who find a decrease in total biomass (Fig. 2) and fish length in the gulf since the early 1990s. This

declining trend coincides with the completion of the Dique Sur (South Dike) between 1985 and 1991 [10] and the completion of the last dam in 1991 [11].

Studies carried out in Cuba on soil management to date do not contemplate its influence on the marine ecosystem. These studies focus on soil management for its fertility, either via compost, or legumes, among other practices such as those carried out by [12–15] and others. In addition, research methods for comparing agricultural systems (conventional and organic) are established as well as highlighting which ones have better socio-economic benefits and less soil degradation [16–18]. From the marine science side, there are no studies that delve into this topic, focusing only on the coastal zone at the mangrove-marine or beach-marine water interface [19–21]. This apparent disconnection is perhaps due to the fact that the waters of the Cuban gulfs do not present great degrees of eutrophication and the volumes of nutrients that reach the waters due to agriculture are low, but they leave aside that the problem of oligotrophication of the gulfs can be alleviated or maintained in a stable situation avoiding its depletion owed to agricultural changes.

Table 1 Use of earthworm humus in different crops [5]

Crops	Soils	Dose (t ha ⁻¹)	Decrease in inorganic fertilizers (%)
Potatoes	Ferrallitic Red	5	25–50
Tobacco	Yellowish Ferrallitic Leached Quartzite	4	65 (Phosphoric and potassic)
Banana	Brown without carbonates	10	50
Tomatoes	Ferrallitic Red	4	25–50
Garlic	Alluvial	4	100 (nitrogenous)
Onion	Brown without carbonate	4	50–75
Bell pepper	Ferrallitic Red	4	25
Sweet potato	Ferrallitic Red	4	25

Fig. 1 Inorganic N fertilizer inputs to Cuba from 1961 to 1999 (data from the International Industrial Fertilizer Association, taken from Baisre, [6])

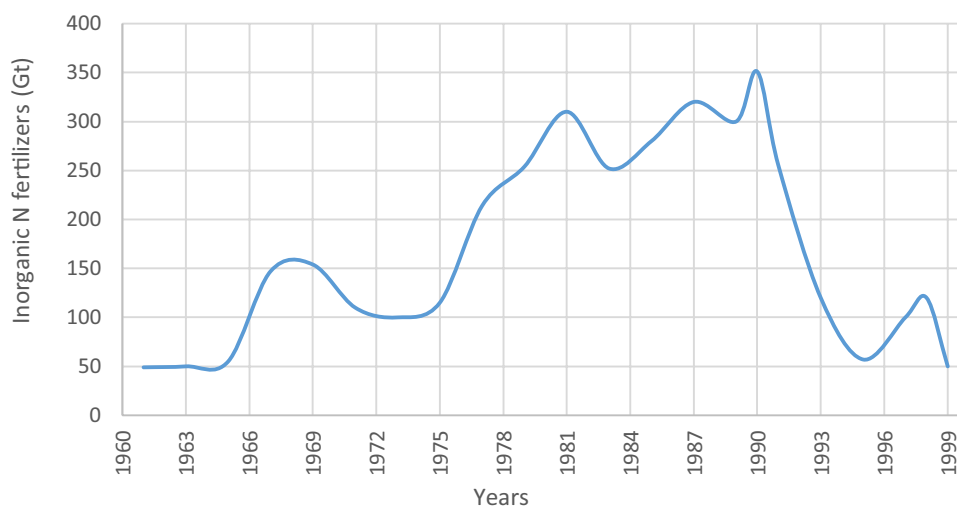
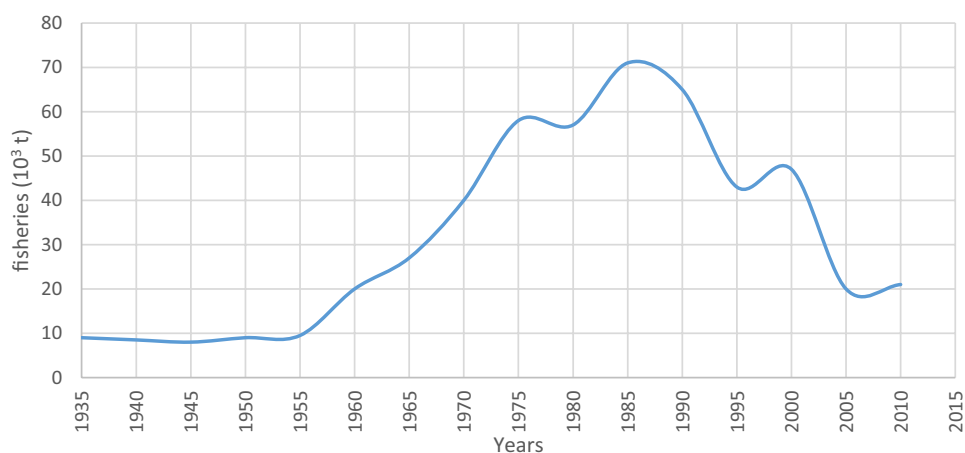


Fig. 2 Total Cuban catches within the Exclusive Economic Zone from 1935 to 2010 [8]



In the last decade, there have been no studies that manage soil and oligotrophic marine water resources and their interrelationships in the territory. This type of approach is the basis for knowing the main variables that determine the system and the physical characteristics of the study area or/and type of soil management. In this research, soil management focused on the potential rates of nitrogen fixation, the surface extent of this practice in the basin, and the drift of nitrogen to the sea in each of the different combinations of the two elements mentioned above. Knowledge of these elements allows estimating the cost–benefit balance of the soil resource under legume management. All of the above will contribute to better management, planning, and creation of better policies to manage Cuba's natural resources.

1.1 Legume choice, *Phaseolus vulgaris*, and *Leucaena leucocephala*

The choice of crops was made based on the existing specialized literature, social and cultural factors, and experience with the plant. Bean (*Phaseolus vulgaris*) was chosen in the areas of temporary crop use, since the insertion would not present alteration in eating habits, in addition to complementing the culinary cultural heritage of this crop. *Leucaena leucocephala* for pasture areas because of the large number of research studies carried out on the country.

The beans present in a countless number of species, with great nutritional values of 20.2–23.4 g per 100 g of protein [22]. According to the study by González Robaina et al. [23], beans in Cuba is a crop that requires little irrigation demand (280–380 mm for 1.6–2.98 t ha⁻¹), considering this a rainfed crop. Yields greater than 100% can be expected from this crop when the necessary water is applied to satisfy its water demand. Several times this demand can be solved with the rains, as can be seen in the

results of Flores et al. [24] in Zacatecas, Mexico. Another study was conducted by Torres and Mendoza [25] in Nicaragua, where six different treatments were used for the bean crop, fertilization (non-application, chemical, and organic), weeds (control and non-control) and was subjected to the comparison of two tillage systems: conventional and conservation tillage. It was concluded that the best yields were found in the fertilizer application treatment with weed control and traditional tillage, but not the one with the best cost–benefit, being the control treatment with weed control.

Although dry bean is a poor N₂ fixer (fixes 30–50 kg N ha⁻¹) compared to other grain legumes (fixes 80–100 kg N ha⁻¹), dry beans add about 6 × 10⁵ mg N annually in farming systems globally [26]. When inoculated with *Rhizobium*, some dry bean cultivars were reported to fix N 40–125 kg N ha⁻¹ [27], and 65–73 kg N ha⁻¹ [28].

The use of leguminous plants is a common practice in livestock farming, either to feed them directly or as fertilizer due to their capacity for nitrogen fixation or as the stubble that is incorporated into the soil. Based on research conducted in the last decade on the island, it is proposed to use *L. leucocephala* cv. Cunningham as a legume for fertilizing pasture fields in a silvopastoral system [29, 30].

Fattening cattle in a silvopastoral system with *Leucaena leucocephala* and natural and/or improved pastures, mainly with mixed genotypes of Cebú and Cebú (*Bos primigenius indicus*), allows average individual gains in animal fattening [30–32], livestock capacity [33–36] and milk production [37–40].

According to the literature, their fixation rate ranges from 90 to 170 kg N ha⁻¹ yr⁻¹ [41], 100 to 500 kg N ha⁻¹ yr⁻¹ [42], and 300 kg N ha⁻¹ yr⁻¹ [43]. The average rate of transfer of this nitrogen to the associated pasture in each of these studies was 30%, reaching 50% in some cases, as in the first study referenced.

In this context, we used the methodology and principles used in the research carried out by Febles et al. [44]. This reveals and highlights the importance of applying soil erosion models of the areal domain in karst environments of intermittent surface streams; which, although they do not offer an exact simulation of real situations, allow obtaining approximate results, according to the assumed simplifications and applying them at plot or basin scale. This article aims to manage the dynamics of nutrient fluxes under leguminous management in order to obtain the maximum benefit for soil and marine resources.

The present study has been divided as follows. Section 2.1 presents the physical-geographical characteristics of the study area. The following subsection 2.2 shows the models used for the simulation and provides the reasons for the choice of legumes. Section 3.0 presents the results achieved, which are subdivided into Sect. 3.1 pasture and 3.2 crops 3.3 economic evaluation. Subsequently, the results are discussed in Sect. 4.1, the role of nitrogen fixation in the basin, in Sect. 4.2 the export of this element to the sea, the management proposal is made in Sect. 4.3, and the representativeness of this result to the rest of the southern zone of Cuba in Sect. 4.4.

2 Materials and methods

2.1 Geographical location

The research was carried out in the La Teresa Karst basin located on the southern coast of Cuba (Fig. 3); belonging to the Southern Havana-Matanzas Karst plain (Table 2). Limited to the north by the coordinates 82° 7' 0" W and 22° 55' 0" N, to the east 82° 15' 0" W and 22° 47' 0" N; to the west 82° 0' 0" W and 22° 55' 0" N and to the south by the coastline.

The basin was mapped following the watershed lines, according to Strahler's methodology [45]. It also has a surface hydrography with intermittent currents.

2.2 Climatic regime

According to the Köppen-Geiger Climate Classification, 1991–2020 [46], this can be considered tropical with alternating humidity, with a long rainy period and a less humid one. In general, the rainy season extends from May to October and the less humid period extends from November to April (Fig. 4).

It is estimated that the amount of precipitation that falls annually in the province of Mayabeque ranges from 1200 to 1600 mm [47] (Fig. 4), and the average temperature ranges between 24 and 26 °C.

2.3 Geological-geomorphological characteristics

The geomorphology corresponds to a cumulative plain with a flat terrace system (Fig. 3) consisting of carbonate rocks and marsh deposits [48].

2.4 Soils and land use

The predominant soils correspond to the Red Ferralitic Grouping [49, 50], basically used for various crops and pastures (Fig. 5).

Red Ferralitic soils, despite having high clay content, have low plasticity, high capillary elevation, and low hygroscopicity, which favors their use for a wide range of plant species [52]. In terms of soil use, sugarcane is the only crop that continues to be cultivated under traditional agricultural management.

2.4.1 Nitrogen fixation rate

As discussed above (Sect. 1.1), nitrogen fixation values of 30, 40, 50, and 125 kg N ha⁻¹ yr⁻¹ for crops and 90, 100, 300, and 500 kg N ha⁻¹ yr⁻¹ for pasture were taken, covering the low, intermediate, and high scenarios. These practices are used in 10, 20, 30, and 40% of the area employed in these uses, with 40% being the highest range.

2.4.2 Soil nutrient content

The concentration of nutrients (Fig. 6), concerning N in the soil of the basin, is medium (0.14–0.25%) [53, 54] with higher values towards the center of the territory.

The P concentration in the soils is moderate to very high (10–17 moderate, 17–25 high, greater than 25 ppm very high) [54, 58], with higher values in the southern part. Finally, K concentration in the soils is low (less than 44 ppm) [54, 58, 59].

2.5 Soil erosion

Mean annual erosion, according to Febles et al. [44], is 0.6 ± 0.1 (t ha⁻¹) (Fig. 7), being classified as very low according to Geler [60]. The transport capacity of surface flow (G) was the limiting factor of erosion.

The low rates are the result of a gentle slope and the mechanical composition of the predominantly clayey soils (85%), which have a high degree of resistance to detachment by raindrops. The highest erosion rates were estimated in the cultivated sectors, both in short and prolonged periods.

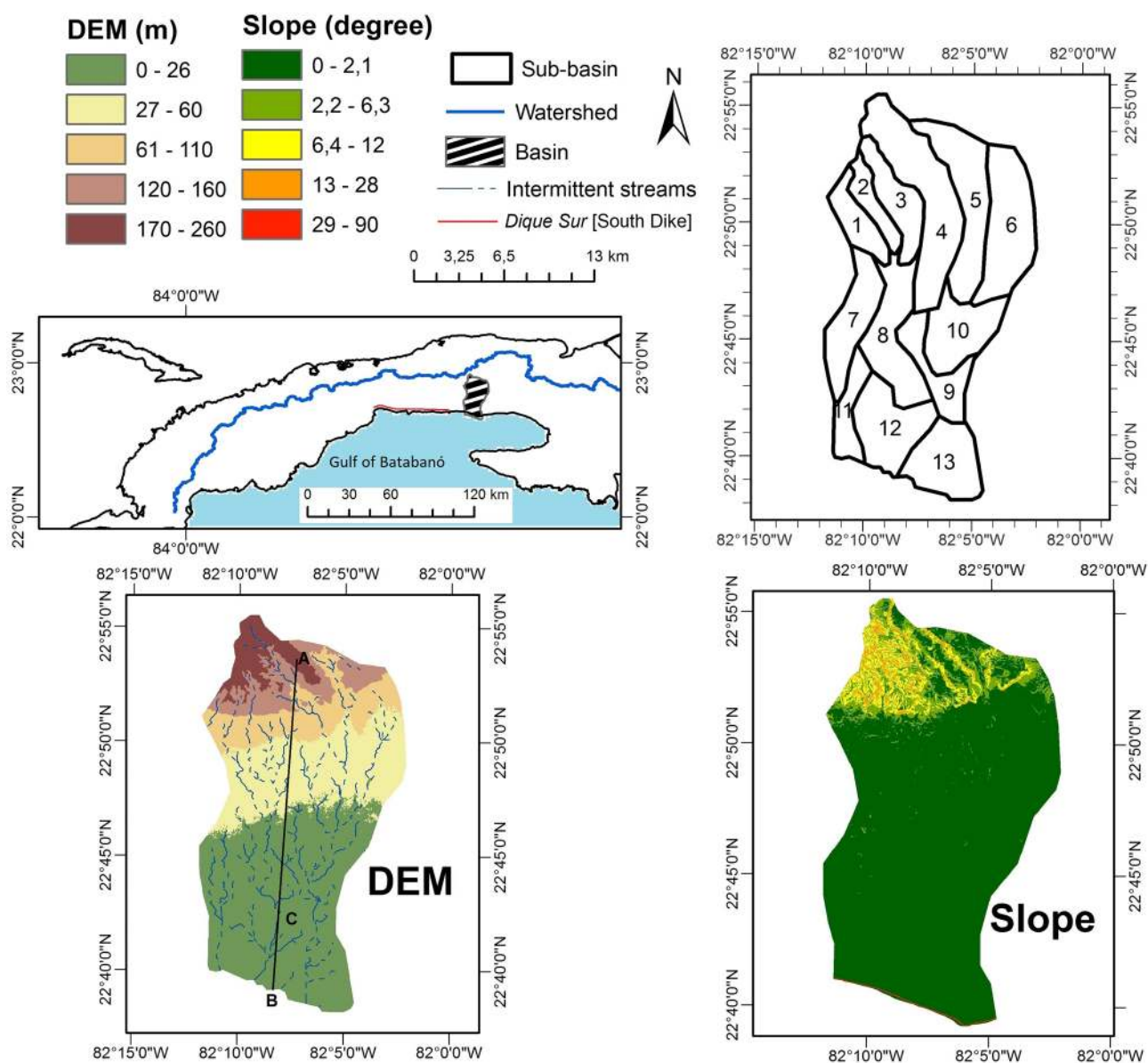


Fig. 3 Location and physical-geographical characteristics of the basin in the Southern Karstic Plain Havana—Matanzas, Cuba

Table 2 Main morphometric parameters of the La Teresa karst basin (Taken from Febles et al. [44])

Description	Unit	Values	Interpretation
Basin shape	–	0.40	Very wide
Drainage density	km km ⁻²	0.81	Under
Average slope	Grado; %	1.64; 2.87	Soft
Area of catchment area	km ²	362	–
Average depth	m	49	–

2.6 Nutrient flux and export of nutrients to the sea

According to Febles et al., 2020, the highest export rates

in the basin were recorded in those sectors occupied by various crops on clay-textured soils (Fig. 5A, B). These sectors are also the most eroded (Fig. 7) and with the greatest loss of nutrients. Sub-basins No. 6 and 10 are those with the highest values (Fig. 8).

The zonal-spatial pattern in nutrient export is higher in the middle sector of the basin and lower in the other two sectors, associated with the effectiveness of sediment traps in the upper sector and the low geomorphic potential near the coastline (Fig. 8).

Nutrient export of nitrogen and phosphorus was 35 ± 1 t (1.0 ± 0.02 kg ha⁻¹ yr⁻¹); 2.3 ± 0.4 t (0.064 ± 0.01 kg ha⁻¹ yr⁻¹) respectively. These are classified as low when compared to other studies, none of these developed in karst regions.

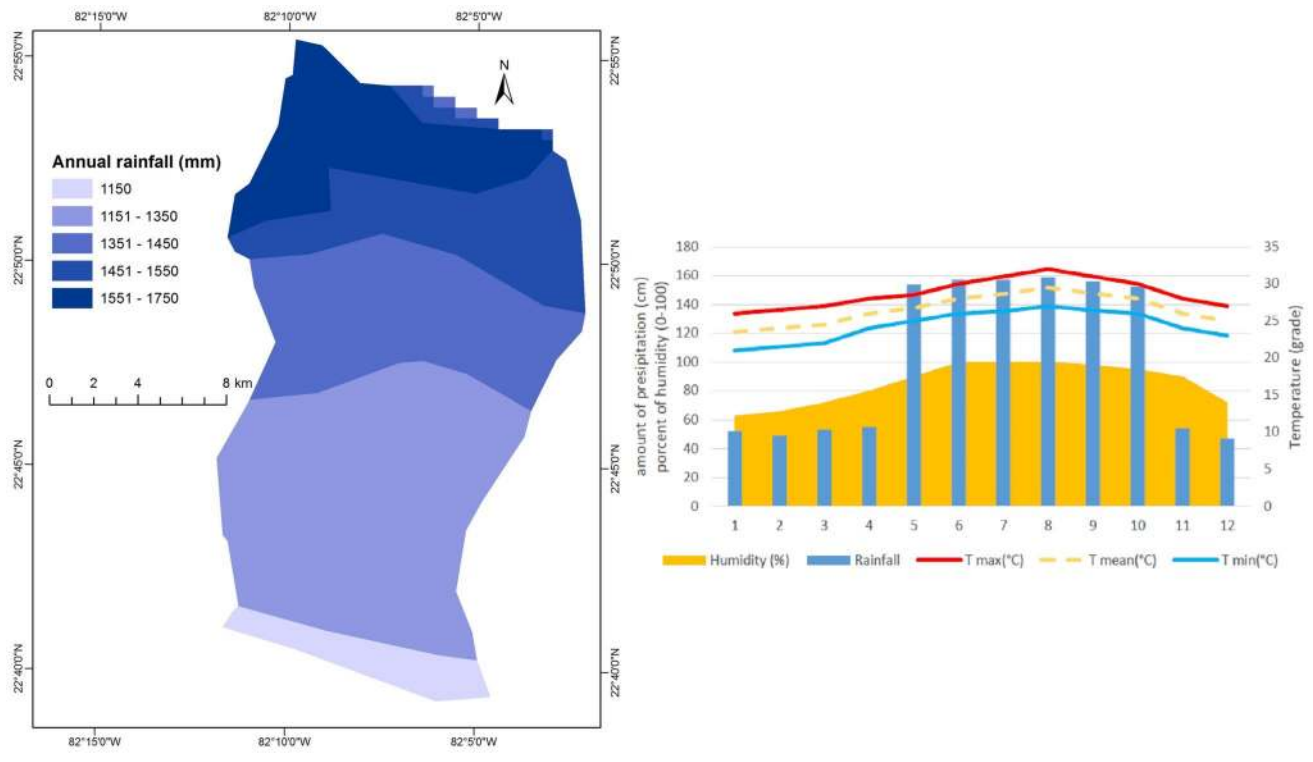


Fig. 4 Accumulated rainfall between 2010 and 2018 in the basin [47]

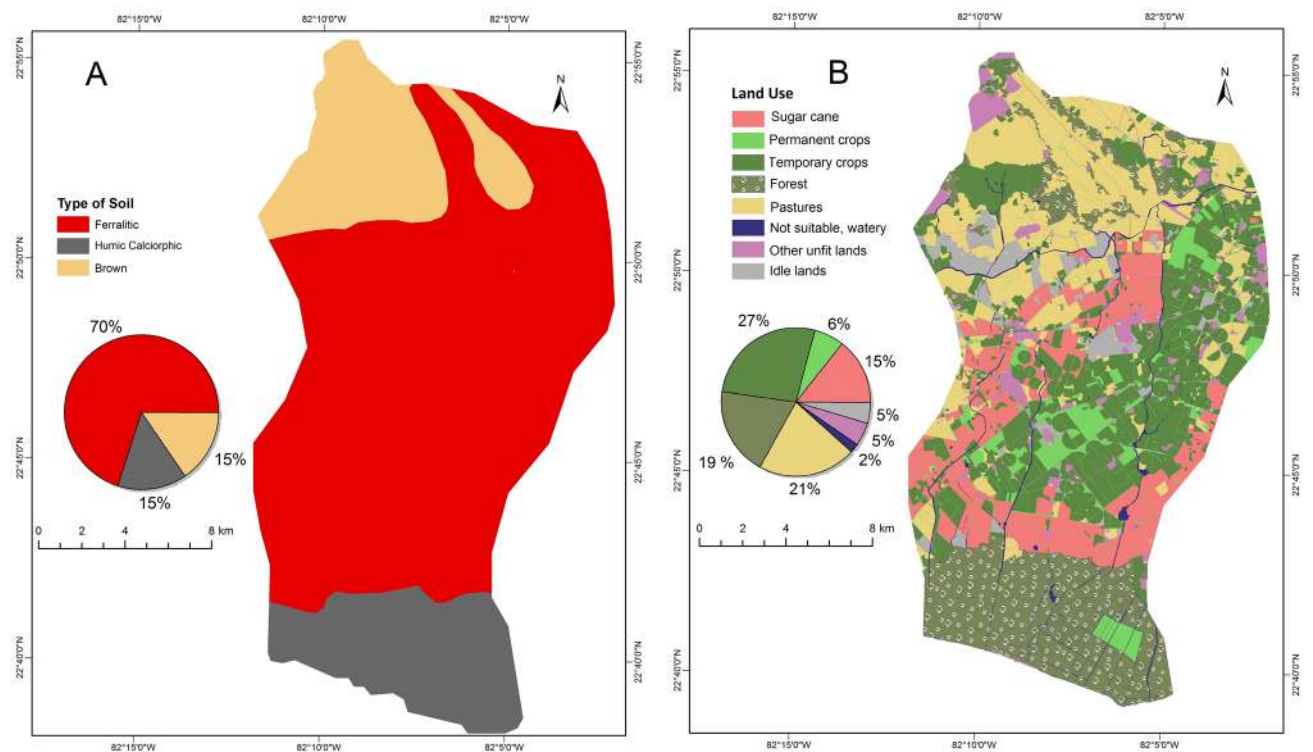


Fig. 5 **A** Soil distribution1 [50] and **B** conditions of uses in the basin [51]

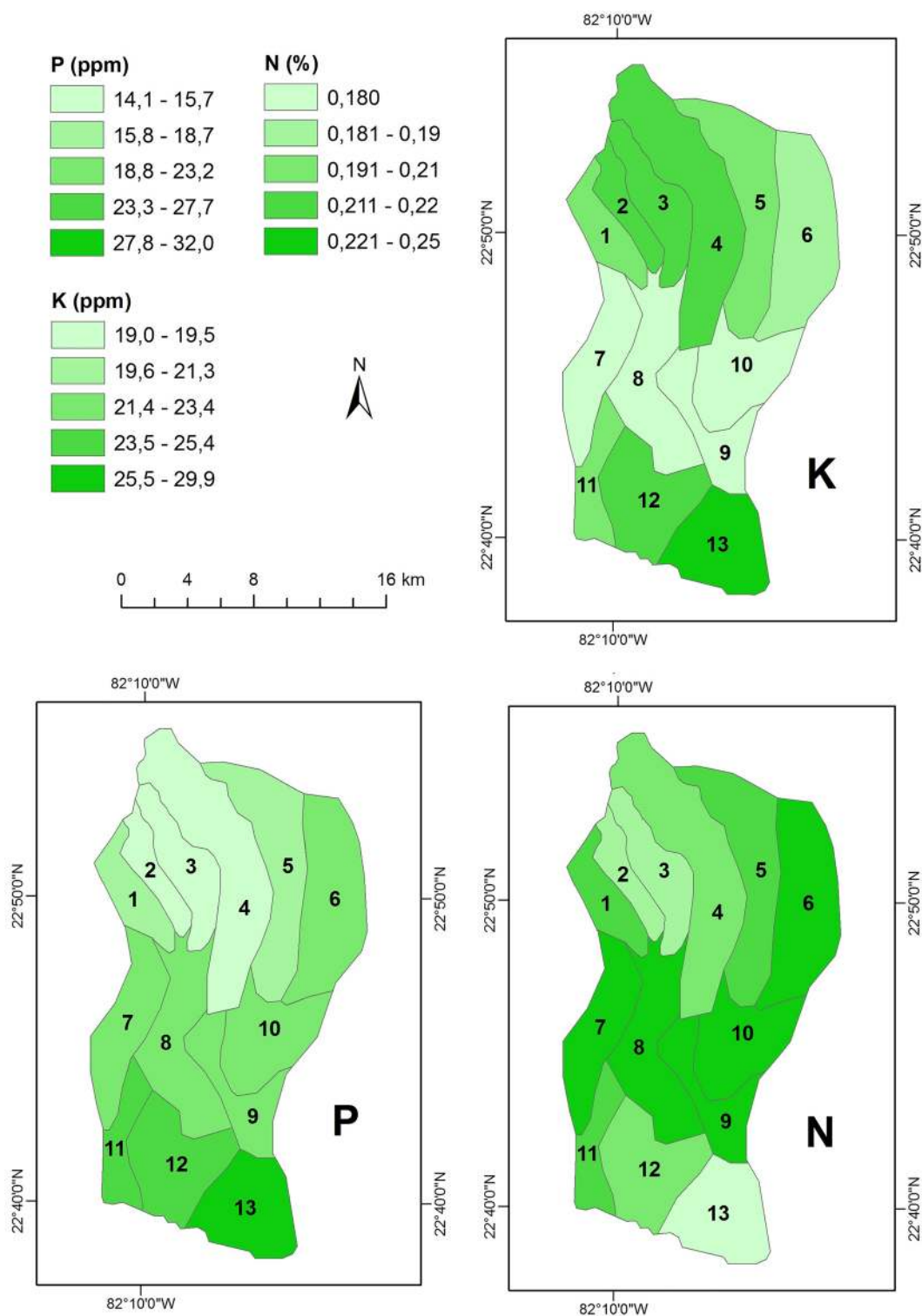


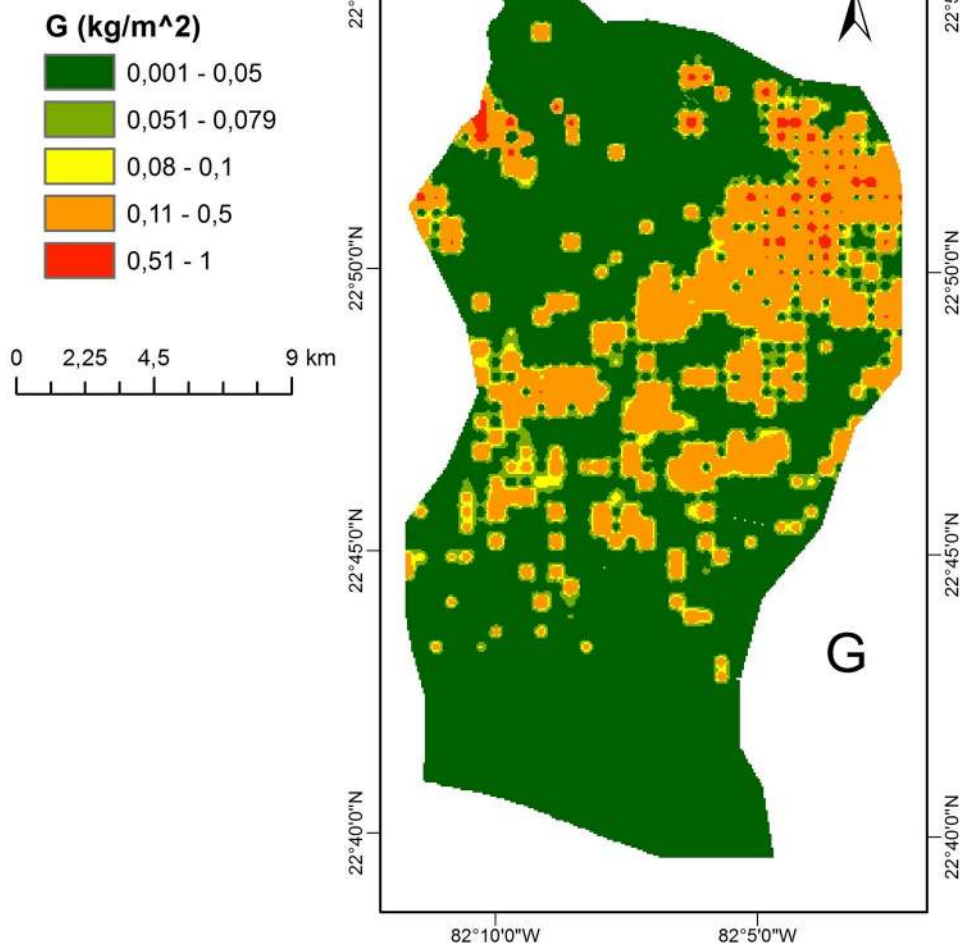
Fig. 6 Concentration of nutrients P [50], K and N [55–57] in the soils

These low values are a consequence of the low erosion rates of the Red Ferralitic and Alfisol soils since they present moderate to high values (Fig. 6) of nutrients [44].

2.7 Methodology used

The management principles proposed by Febles et al. [44]

Fig. 7 Soil erosion rate of the La Teresa Karst basin in the Southern Karst Plain Havana—Matanzas, Cuba [44]



were applied to determine the optimal management of soils in the La Teresa Basin under legume management, which exert the least possible pressure on marine ecosystems. These indicate maintaining the speed of biogeochemical cycles and increasing the concentration of nutrients in soils.

This study focused only on one chemical element of fundamental importance for agriculture, nitrogen, through the organic management of legumes. Ten thousand possible scenarios were simulated of nitrogen fixation by legumes in different surface extensions and the export of nutrients to the Gulf of Batabanó in different spatial configurations taken at random. The selected areas of use were those currently occupied by temporary crops and pastures (Fig. 4B) since they allow flexible management as they are not strategic crops such as sugar cane or permanent crops. The simulation was performed in a Python console, under the methodology of Febles et al. [44] and

Febles et al. [61] the first for estimating nutrient fluxes and the second for estimating soil particle fluxes (Fig. 9).

2.8 Calculation of nutrient fluxes

To calculate the amount of soil eroded (Fig. 9), the Morgan, Morgan and Finney (MMF) parametric erosion model [62] was applied, based on the dynamics of erosion processes, soil properties, climatic characteristics, and conditions of use, which made it possible to evaluate the magnitude of losses.

The equation of Verstraeten and Poesen [63] was used to calculate nutrient export. This equation was designed for use in small basins to quantify sediment-bound nutrient transfer based on measurements of sediment volumes and nutrient content. It is most effective when erosion rates are medium to low, such as those characteristics of a karst plain.

MMF model:

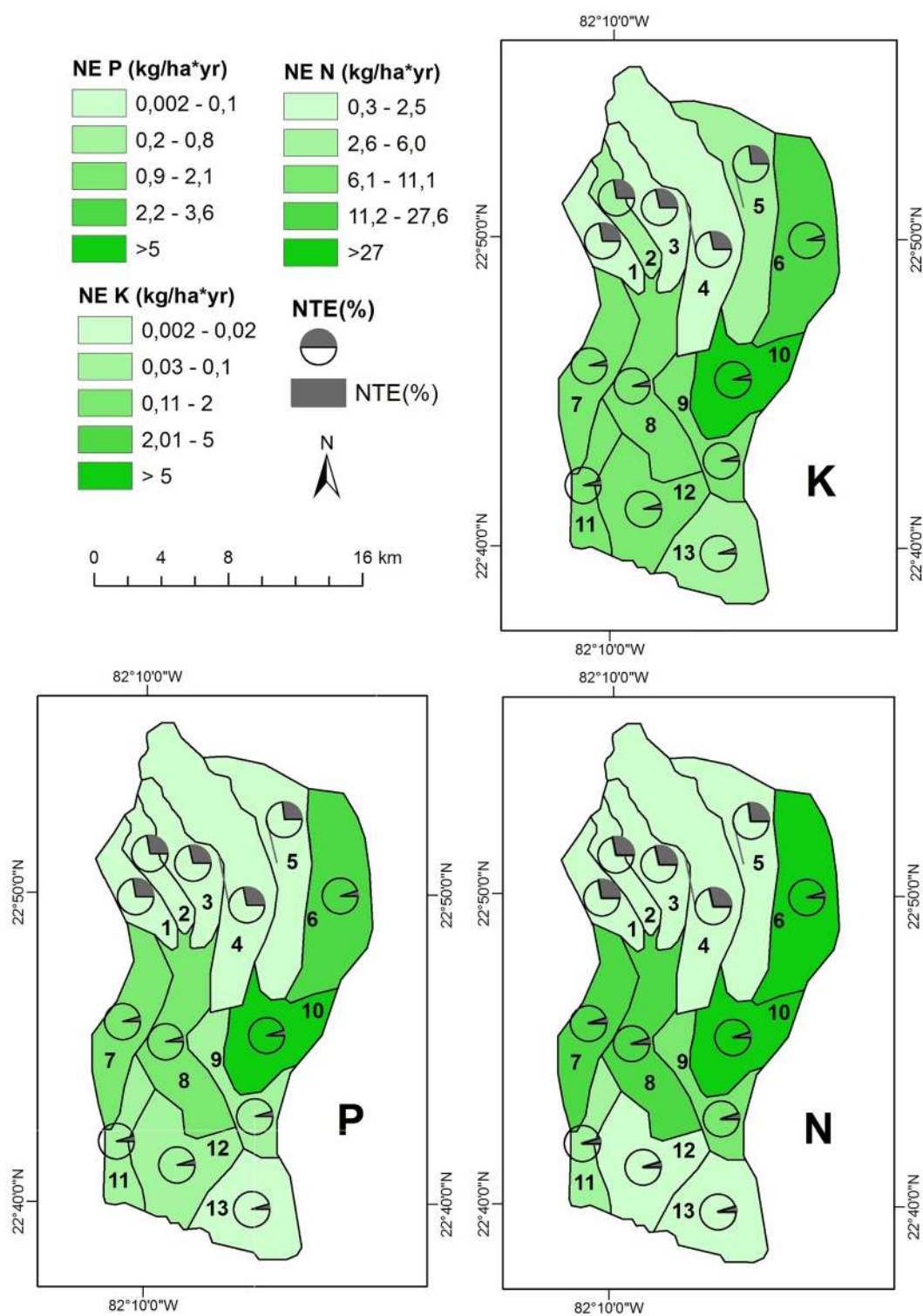


Fig. 8 Values of N, P, K exported from the La Teresa karst basin in the Southern Karst Plain Havana—Matanzas, Cuba [44]

$$E = R(11.9 + 8.7 \cdot \log_{10} I)$$

$$(1) \quad Q = R \exp(-R_c / \Theta R_o)$$

$$(2)$$

where E = Kinetic energy of rain [64] ($J m^{-2}$), I = Typical value of the rain intensity for tropical climates ($mm h^{-1}$).

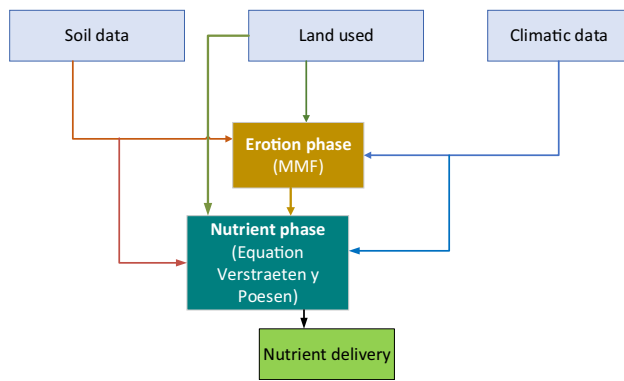


Fig. 9 Methodology for estimating nutrient fluxes to the sea in river basins with intermittent streams

$$R = 1000 \cdot MS \cdot BD \cdot RD (E_T/E_0)^{0.5} \quad (3)$$

$$R_0 = R/R_n \quad (4)$$

where Q = Volume of superficial flow (mm), R = Annual rainfall amount (mm), R_c = Critical value of moisture storage, R_0 = Average rain of the rainy days per year (mm day⁻¹), MS = Soil moisture (%), BD = Soil density (kg m⁻³), RD = Depth of rooting (m), E_T = Current Evapotranspiration, E_0 = Potential evapotranspiration.

In this phase, the dispersed soil splash rate (F) and the surface flow transport capacity (G) are evaluated using the following equations:

$$F = K(Ee^{-aA})^b \cdot 10^{-3} \quad (5)$$

where F = Particles mobilized by splash (kg m⁻²), K = Index of erodability, E = Kinetic energy of rain (J m⁻²), A = Interception factor due to rain (%)

Exponent values $a = 0.05$; $b = 1$

$$G = CQ^d \text{sen} S \cdot 10^{-3} \quad (6)$$

where G = Surface flow transport capacity (kg m⁻²), C = Vegetation factor, Q = Volume of superficial flow (mm), S = Slope (degrees), Values of exponent: $d = 2.0$.

The final prediction of the soil loss is made by comparing the values obtained of G and F . The lowest of them is taken as annual soil loss rate.

For the estimation of nutrient losses, the assumption was that the basin discharges by a single sector into the sea. Equation (7) with slight modifications (8) was used to estimate the effects of the amount of nutrients and sediments coming from the upper part of the basin through 13 small sub-basins that were mapped (Fig. 3).

$$NE = \sum_{i=1}^n \frac{SV_i \cdot dBD_i \cdot NC_i}{10 \cdot n \cdot A \cdot NTE} \quad (7)$$

$$NE_i = \frac{((\sum_{i=1}^n SV_i \cdot dBD_i \cdot NC_i) + (SV_{i-1} \cdot dBD_{i-1} \cdot NC_{i-1}))}{10 \cdot n \cdot A \cdot NTE} \quad (8)$$

$$SV_{i-1} = SV_{\text{upperbasin}} * NTE_{\text{upperbasin}} \quad (9)$$

$$NC_{i-1} = \frac{NE_{i-1} \cdot 10^6}{d \cdot \rho} \quad (10)$$

where NE : Nutrient exportation (kg ha⁻¹ yr⁻¹), SV : Volume of sediment moved (m³ yr⁻¹), dBD_i : Density of soil in sample i (Mg m⁻³), NC_i : Nutrient content associated with the sediment in the sample i (ppm), NTE : Efficiency of the nutrient trap in the basin (%), A : Basin area (ha), SV_{i-1} : Amount of sediment from the upper basin (t), NC_{i-1} : Amount of the nutrient from the upper basin (ppm), d : Depth of soil (m), ρ : Density of soil (mg·kg⁻¹), dBD_{i-1} : Soil density of the upper basin (Mg m⁻³), NE_{i-1} : Exporting nutrients from the upper basin (kg ha⁻¹ yr⁻¹).

3 Results

3.1 Pastures

Land used for pasture occupies 21% of the basin area, mainly located in the upper portion of the basin. The average soil nitrogen fixation concentration in the different treatments was within the range of 1.07–1070 ppm with a standard deviation of ± 2.23 –141 ppm, with a maximum fixation of 1619 ppm (Fig. 10).

Significant differences were found in all treatments in the Conover-Iman test (Fig. 10). The export to the Gulf of Batabanó ranged between 0.9623 and 0.9624 kg ha⁻¹ yr⁻¹, with the maximum value coinciding with the treatment of 500 kg ha⁻¹ at 40% of the area under legume management and less than 90 kg ha⁻¹ at 10% (Figs. 11, 12).

3.2 Crops

The land used for cultivation occupies 27% of the surface of the basin, mainly located in the middle portion of the basin. The average soil nitrogen fixation concentration in the different treatments was within the range of 0.3–1017 ppm with a standard deviation of ± 0.85 –69 ppm, with a maximum fixation of 1301 ppm (Fig. 13).

Significant differences were found in all treatments in the Conover-Iman test (Fig. 13). Export to the gulf ranged between 0.962379 and 0.962474 kg ha⁻¹ yr⁻¹,

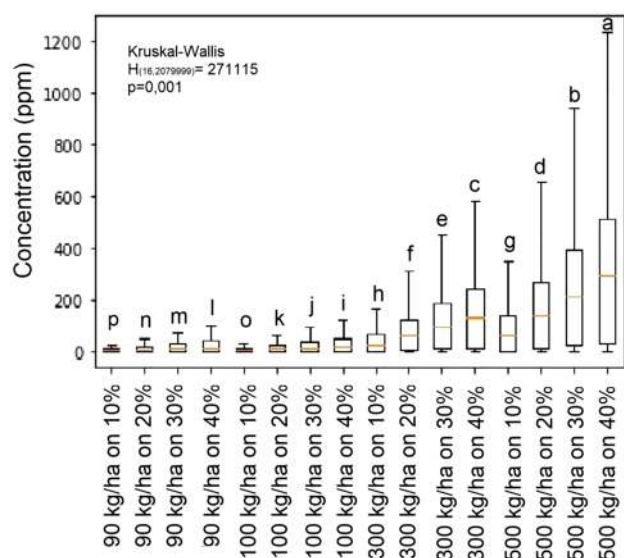


Fig. 10 N_2 fixation in pastures in each of the treatments

with the maximum value coinciding with the treatment of 125 kg ha^{-1} at 40% of the area under legume management and less than 30 kg ha^{-1} at 10% (Figs. 14, 15).

The dynamics of nutrient export when combining the spatial configurations of pasture and temporary crops in which higher export is achieved is shown in Fig. 16. The average difference between using 40% and 100% of the area is $0.0003 \text{ kg ha}^{-1} \text{ yr}^{-1}$ of N under the maximum capture rate reported in the literature.

3.3 Costs and revenues

Land, in terms of agriculture, turns out to be the most significant single asset. Soil degradation is a relevant

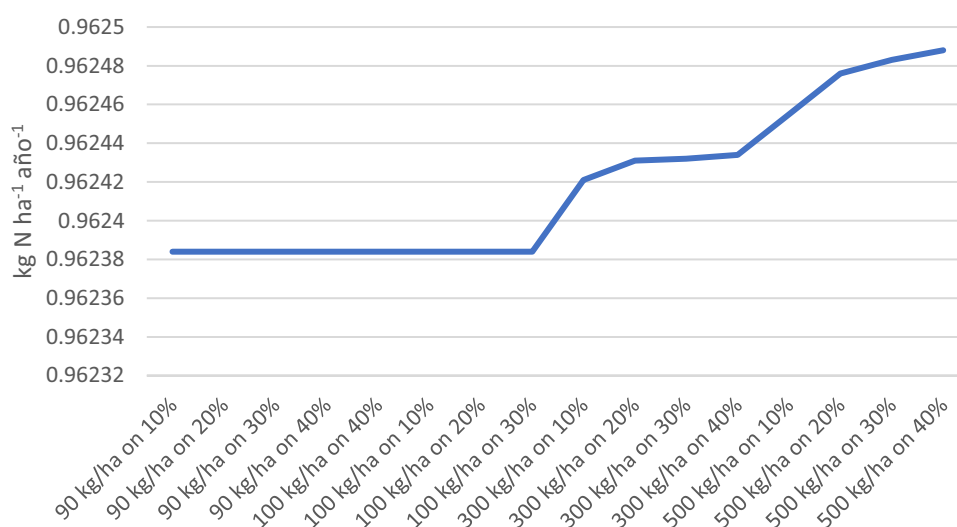
phenomenon in agricultural activity; therefore, it is necessary to take it into account. The negative effects of degraded soil on the economy are more severe in countries that strongly depend on agriculture [65, 66] and there is no doubt that the agricultural sector is one of the most significant in the Cuban economic activity [67].

For a correct estimate of its devaluation, it is necessary to consider the number of ways in which the phenomenon of degradation can be found. Bearing in mind that, it is common for more than one of these degradation variants to subsist in the same geographical area, these can be: excessive extraction of nutrients, saturation of salts, contamination with chemical products, soil erosion, vegetation degradation, logging of forests for farmland, water use, etc.. This process causes a decrease in the productive land capacity, decreasing potential yields. This decrease must be reflected by accounting in the financial statements [68].

Due to the complexity of estimating the depreciation of the soil resource, this research only offers an approximation of the costs produced by the export of nutrients caused by water erosion of the soils of the basin and inputs produced by the use of legume management. In estimating these costs, the value of fertilizers in the market was used (Table 3) and the spatial configurations that produced the highest export value (Figs. 12, 15).

The highest nutrient loss costs were found in sub-basin number 6 (Supplemental material III) between the range of $44\text{--}60 \text{ USD ha}^{-1} \text{ yr}^{-1}$ in pastures and $44\text{--}62 \text{ USD ha}^{-1} \text{ yr}^{-1}$ in crops. The income rates in each of the treatments, both in crops and pastures, vary according to the spatial configuration. These incomes have zero values in the sub-basins where these land uses are not present, mainly those found in the lower zone of La Teresa (Figs. 3, 5B).

Fig. 11 Maximum export of nutrients to the Gulf of Batabanó for each of the treatments



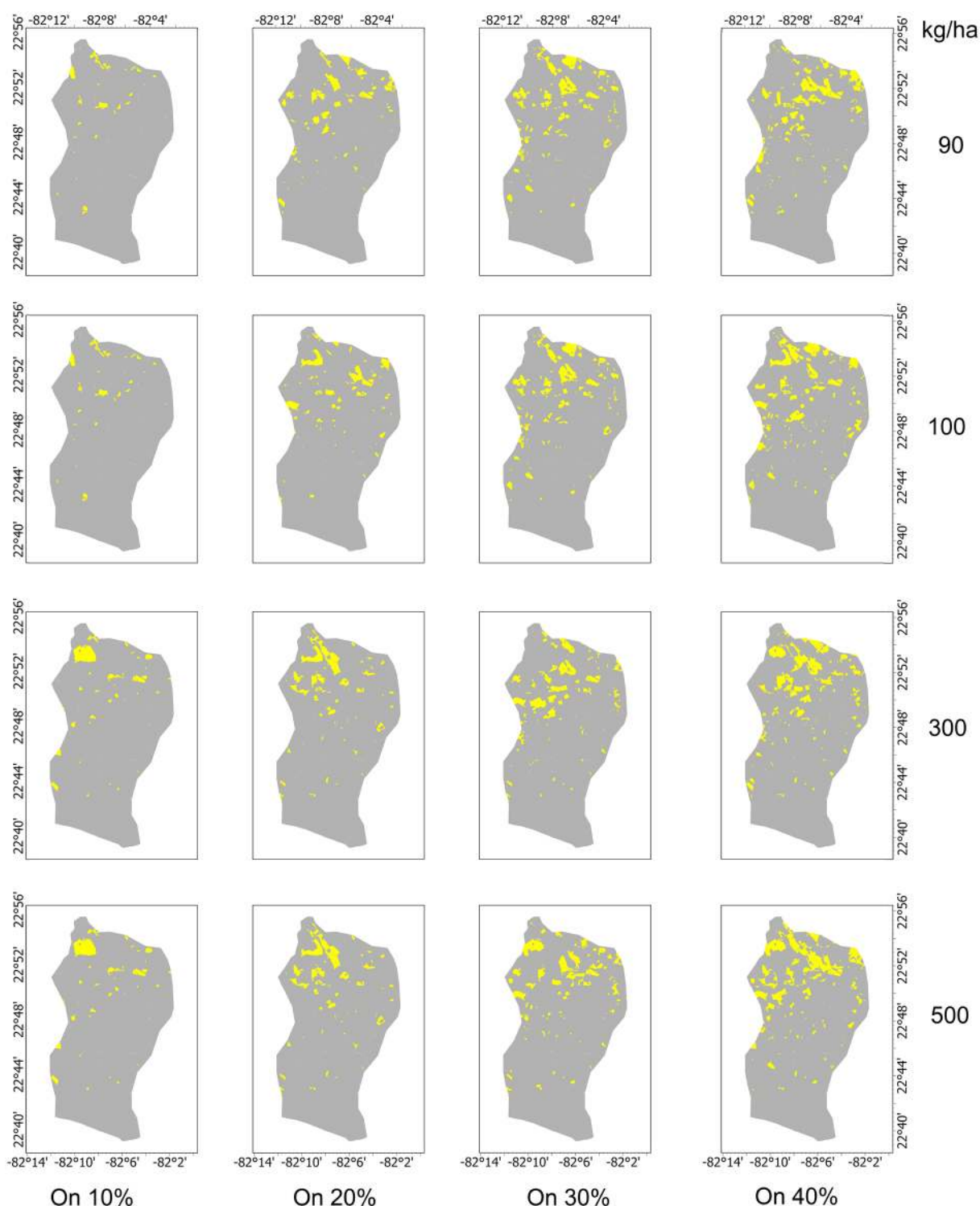


Fig. 12 Spatial distribution of the treatments in pastures with the highest export of nutrients to the Gulf of Batabanó

The general annual capital flow balance shows that the pasture treatments are more profitable than the crop treatments (Table 4), only taking into account the input and output of N, leaving out of the analysis the value of beans

in the national and international market. The pasture treatments had a positive balance of $22 \text{ USD ha}^{-1} \text{ yr}^{-1}$, which was less than the crop treatment of $55 \text{ USD ha}^{-1} \text{ yr}^{-1}$; but the latter, used more area at higher rates.

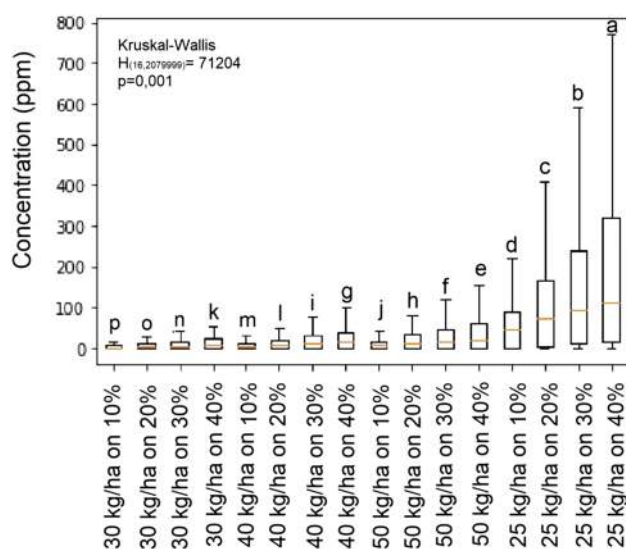
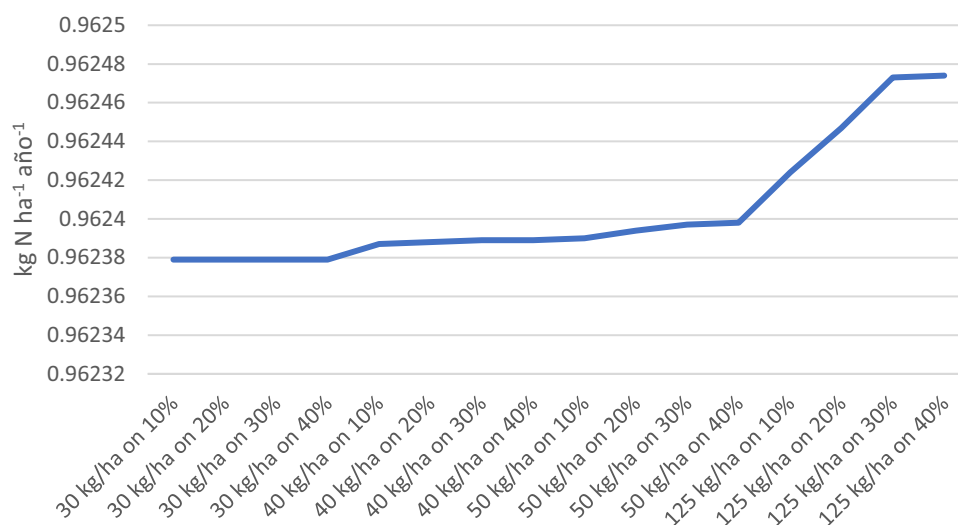


Fig. 13 N_2 fixation in the crops in each of the treatments

To see these costs in situ would be to go against the systemic model of nature whereby everything that is lost in one place ends up redeposited in another. In this case, what is lost by erosion in the middle and upper basin fertilizes the lower basin; and what escapes from the basin, in general, reaches the sea where it is used by marine biota as an external nutrient input. Therefore, proper accounting becomes complicated when nature only understands cycles and not losses. But these approaches serve to address the problem from another reference system, much more appropriate when estimating the economic benefits of implementing ecological measures [70].

Fig. 14 Maximum nutrients export to the gulf for each of the treatments



4 Discussion

4.1 Nitrogen fixation in soils of the La Teresa basin

A distinctive feature of legumes is their ability to develop root nodules and fix N_2 in symbiosis with compatible *Rhizobium*, which brings about increased nutrient properties of soils [71]. The data show that all legume treatments are effective in increasing soil fertility in the basin, being higher as the rate of legume fixation increases.

However, these rates do not progress linearly over time. Specialized research shows that as more nitrogen becomes available in soils, these rates begin to decrease, since nutrient uptake directly from the soil is thermodynamically more feasible than from the symbiont [72–74]. There is evidence that legumes use more photosynthates for N assimilation if the N comes from N_2 fixation compared to soil N uptake [75–79]. Increasing any form of N in the soil or nutrient solution reduces root nodule numbers and N_2 fixation rates [80, 81].

Nitrogen-fixing bacteria are equipped with an enzyme complex called nitrogenase. Nitrogenase is a protein enzyme, composed of two metalloproteins: ferroprotein and molybdoferroprotein. This enzyme catalyzes the primary nitrogen fixation reaction, in other words, the transformation of nitrogen present in the atmosphere into ammonia. The nitrogenase enzyme complex is irreversibly inactivated in the presence of oxygen [82].

The supply of oxygen (O_2) to the interior of the nodule is a key factor in the regulation of nodule activity [83]. This regulation can be either by excess, which could jeopardize the destruction of nitrogenase, or by defect, preventing the production of ATP necessary for fixation [84]. This problem presented by legumes is not a major limitation if

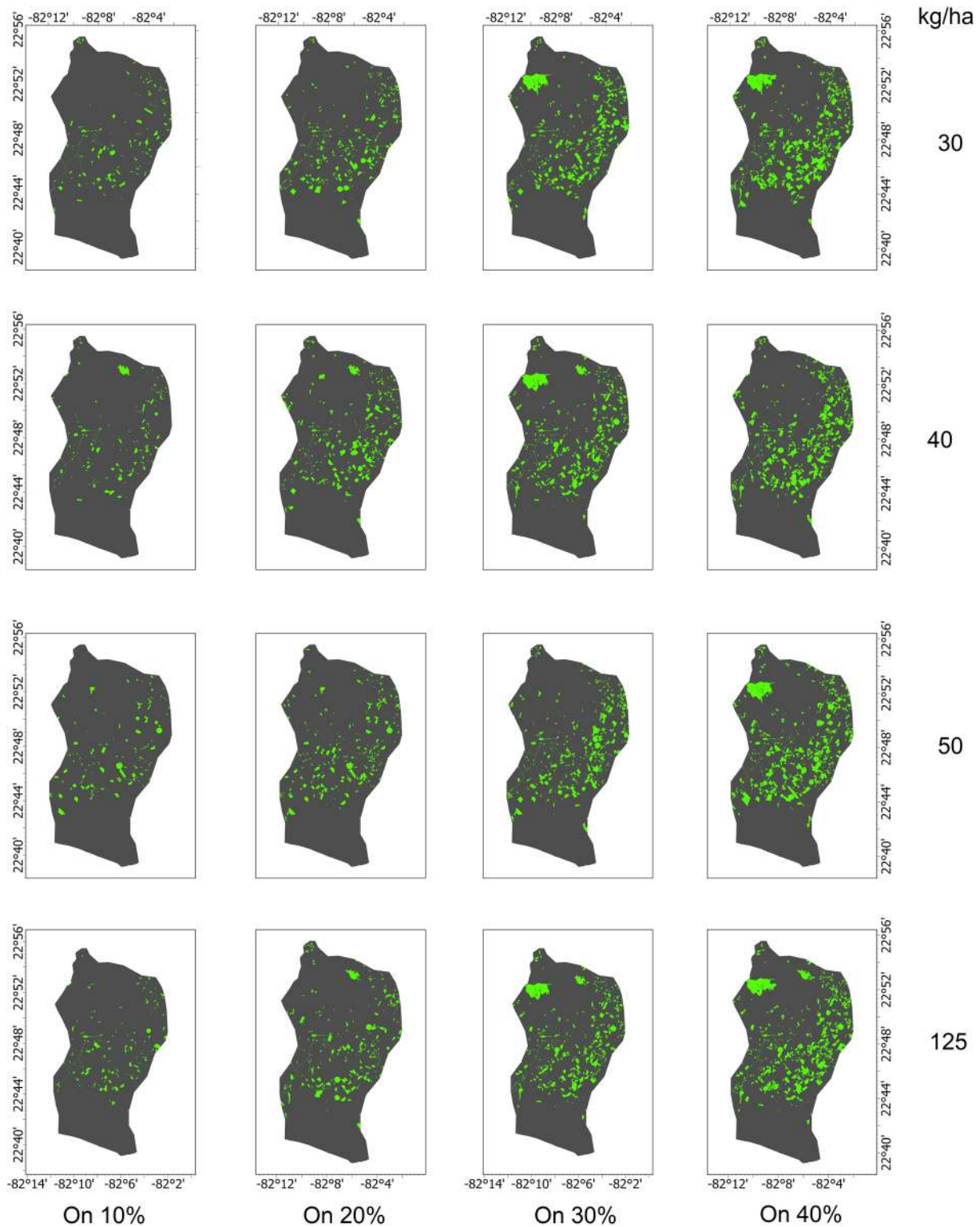


Fig. 15 Spatial distribution of the treatments in crops with the highest nutrients export to the Gulf of Batabanó

the soils of the basin are seen at a group level due to their mechanical characteristics. These well-drained soils have

an adequate aeration balance and a loamy clay texture, avoiding excessive pores.

Fig. 16 Maximum nutrient export from the La Teresa basin as a result of the treatments

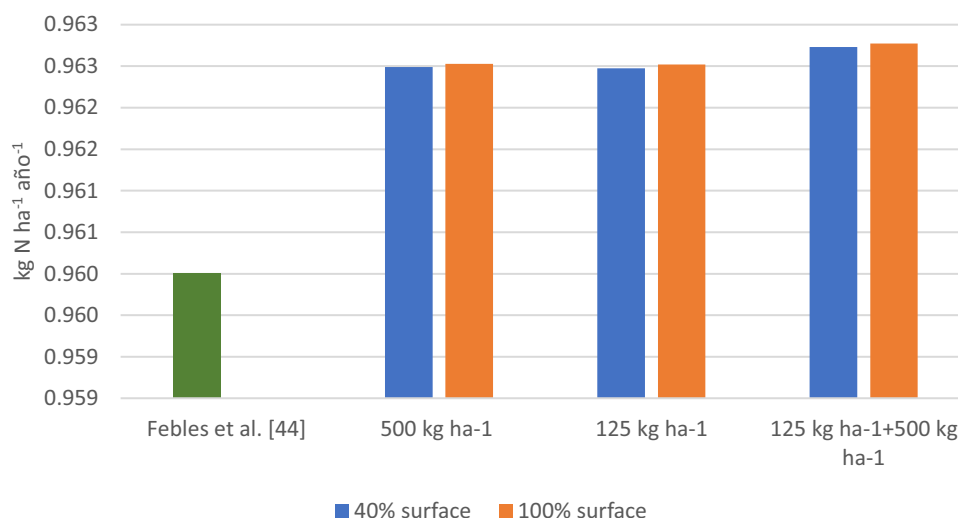


Table 3 Value of fertilizers on the international market

Type of fertilizer	1t de urea (CH ₄ N ₂ O)	1t of phospho-rite Ca ₃ (PO ₄) ₂	1t of potassium chloride (KCL)	Sources
Element mass (kg)	466.434	199.72	524	Indexmundi [69]
Average price in 5 years (USD)	264	97.5	265	

These optimum states may vary from sector to sector, due to the characteristics of management and crops that have been used, with density being the main indicator of loss of pore space.

The soils of the basin currently do not present any P limitation, but a continued use of this management under high N fixation rates can cause a decrease in this element, causing imbalances in long-term biogeochemical cycles. A study by Graham and Vance [85], showed that P deficiency constitutes a limitation for N₂ fixation in legumes, particularly in soils with low P availability, which has been associated with slow plant growth and a decrease in N₂ fixation [86, 87]. In another study by Robson et al. [88] in soils with low P availability, legumes dependent on N₂ fixation, have responded positively to P fertilization and have shown a higher N content in shoots and roots.

4.2 Nitrogen export

The amount of nutrients that reach the sea in each of the different treatments in the ten thousand simulations, do not present high values. The difference between the use of 40% relative to 100% of the surface destined to pasture is 0.004% and 0.005% for crops. In the union of both treatments, the values rise quite conservatively by 0.28% for crop + pasture at 40% with respect to pasture or crops separately, and 0.29% for 100% of the area under such management (Fig. 16).

The non-increase in nutrient export values concerning the increase in nutrient concentration in soils due to N₂ fixation produced by legumes, is mainly because of the physical characteristics of the basin. The convex geomorphological layout influences the overall behavior of sediment transport, with sedimentation prevailing in the more depressed sections. The most notorious inflection point of this convexity is the flattening of the slope in the lower sector, which can be appreciated from 19 km away in Fig. 17, corresponding to point C on the map in Fig. 3.

The dynamics governing this particular spatial configuration is the fact that the horizontal component of gravity decreases along the less steep slopes, which decreases the runoff velocity and thus lengthens the runoff generation time [89, 90]. Therefore, the sub-basins of the lower part of La Teresa act as a geomorphological barrier for sediments on their way to the sea.

Figure 17 also shows the configuration exerted by the karstic environment of the basin in a series of "U" and "V" shaped karstic depressions that act as geomorphological barriers arranged transversally to the slopes, intercepting runoff, as well as soil erosion that transports nutrients [44, 91]. The mechanical composition of the soils is predominantly clayey (85%), which has a high degree of resistance to detachment by raindrops [92, 93]. Therefore, texture is another factor to take into account when analyzing the arrival of nutrients to the sea.

Table 4 Annual balance of nutrient loss and nutrient inputs in each of the watersheds under pasture and crop management

JSD ha ⁻¹ yr ⁻¹																			
Grass	90 kg ha ⁻¹ 90 kg ha ⁻¹ 90 kg ha ⁻¹ 100 kg ha ⁻¹ 100 kg ha ⁻¹ 100 kg ha ⁻¹ 100 kg ha ⁻¹ 100 kg ha ⁻¹ 100 kg ha ⁻¹ 100 kg ha ⁻¹	yr ⁻¹ on 10%	yr ⁻¹ on 20%	yr ⁻¹ on 30%	yr ⁻¹ on 40%	100 kg ha ⁻¹ yr ⁻¹ on 40%	300 kg ha ⁻¹ yr ⁻¹ on 10%	300 kg ha ⁻¹ yr ⁻¹ on 20%	300 kg ha ⁻¹ yr ⁻¹ on 30%	300 kg ha ⁻¹ yr ⁻¹ on 40%	500 kg ha ⁻¹ yr ⁻¹ on 10%	500 kg ha ⁻¹ yr ⁻¹ on 20%	500 kg ha ⁻¹ yr ⁻¹ on 30%	500 kg ha ⁻¹ yr ⁻¹ on 40%					
	Income	120	120	122	122	122	122	124	125	131	127	131	143	145					
	Loss	-80	-103	-144	-229	-89	-137	-176	-274	-297	-623	-959	-1221	-1888	-2578				
	Balance	-40	-19	22	107	-31	15	54	151	174	497	828	1146	1745	2433				
Crops	30 kg ha ⁻¹ 30 kg ha ⁻¹ 30 kg ha ⁻¹ 30 kg ha ⁻¹ 40 kg ha ⁻¹ 40 kg ha ⁻¹ 40 kg ha ⁻¹ 40 kg ha ⁻¹ 50 kg ha ⁻¹ 50 kg ha ⁻¹ 50 kg ha ⁻¹ 50 kg ha ⁻¹ 50 kg ha ⁻¹ 50 kg ha ⁻¹ 50 kg ha ⁻¹	yr ⁻¹ on 10%	yr ⁻¹ on 20%	yr ⁻¹ on 30%	yr ⁻¹ on 40%	40 kg ha ⁻¹ yr ⁻¹ on 10%	40 kg ha ⁻¹ yr ⁻¹ on 20%	40 kg ha ⁻¹ yr ⁻¹ on 30%	40 kg ha ⁻¹ yr ⁻¹ on 40%	50 kg ha ⁻¹ yr ⁻¹ on 30%	50 kg ha ⁻¹ yr ⁻¹ on 40%	125 kg ha ⁻¹ yr ⁻¹ on 10%	125 kg ha ⁻¹ yr ⁻¹ on 20%	125 kg ha ⁻¹ yr ⁻¹ on 30%	125 kg ha ⁻¹ yr ⁻¹ on 40%				
	Income	120	121	122	122	121	122	123	124	121	122	124	125	126	132	140	147		
	Loss	-38	-68	-109	-120	-68	-119	-178	-241	-65	-146	-268	-330	-495	-866	-1317	-1707		
	Balance	-82	-52	-12	-2	-53	-2	55	117	-56	24	144	205	369	734	1176	1560		

Another variable to consider that influences the dynamics of nutrient export from La Teresa basin is the spatial arrangement of the areas of use, with exports being greater as the distance to the coastline shortens. The results show that the difference across spatial configurations and between the two land uses, which achieve the highest export values, only differs in the sixth significant digit after zero (Fig. 16). Both uses cover similar areas (21% pasture and 27% temporary crops (Fig. 5B) and markedly different nutrient fixation rates 90—500 kg ha⁻¹ yr⁻¹ for pasture and 30–125 kg ha⁻¹ yr⁻¹ for crops. However, since the cropland area is mainly located in the middle sector of the basin, as opposed to the pasture area in the upper sector, it manages to maintain a similar level of exports since it requires less total geomorphic potential to reach the coastline (Fig. 5B).

4.3 Soil use management in the basin

Given the above, the basin management proposed in accordance with the topic of soil management with leguminous plants so that it does not exert more pressure on the oligotrophic ecosystems of the Gulf of Batabanó is as follows:

This research does not require the use of this agroecological practice to increase yields in cultivated areas; however, it strongly recommends its use in these regions. In the case of applying this management, it should be done under the economic risks of having less land available for the cultivation of other crops during one stage of the year. Being a recommended practice, it gives autonomy to farmers to design/redesign the strategy that best suits their harvest and crop calendars, being legume management one of the many strategies that can be followed by this sector.

This research does encourage legume management in pasture areas, if feasible to the greatest extent possible. First, this management is suggested because the use of *Leucaena leucocephala* does not require such demanding care as would be required by a legume whose destination is the agricultural market or self-consumption, in addition to the fact that its life cycle is longer. This management also showed a positive economic balance, under low fixation rates depending on its extension or moderate to high N_2 fixation rates regardless of its extension (Table 4). Besides, the use of this management in these regions and its location in the upper zone of La Teresa, provides an indirect fertilization of the lower zones of these regions where the area of temporary or permanent crops is mostly concentrated (Fig. 5B). This would not only benefit the livestock sector, but also the agricultural sector.

The forested areas near the coastline (Fig. 5B) should not be disturbed in order to increase the export of nutrients to

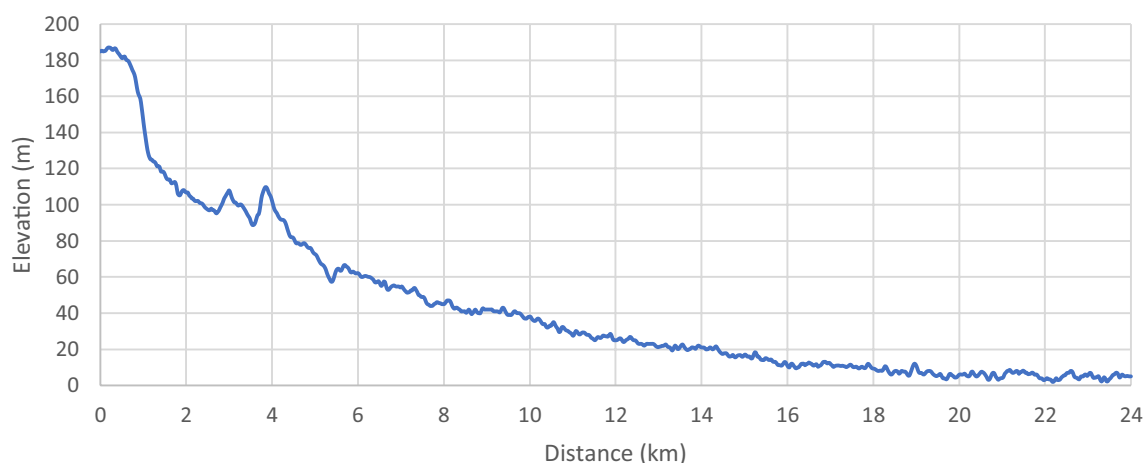


Fig. 17 North–South topographic profile of the La Teresa basin

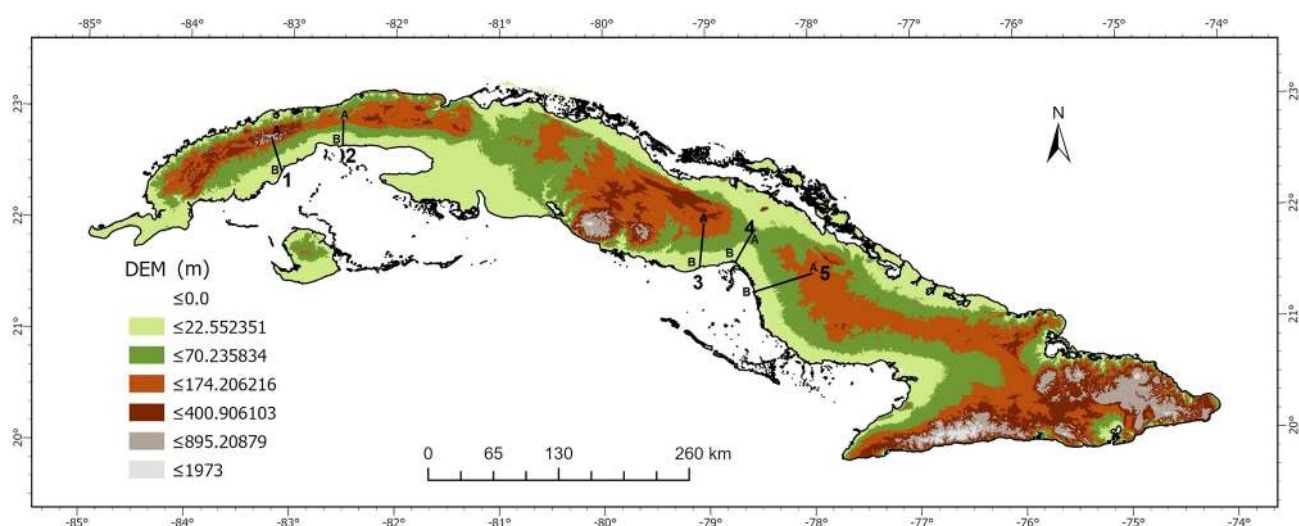


Fig. 18 Digital elevation model of Cuba [98]

the shelf. This is a natural barrier against extreme weather events by attenuating storm surges and windstorms [94]. This arboreal strip also protects from marine aerosol, which, according to Morcillo et al., [95] can have concentrations of 100 mg Cl m^{-2} at 1 km and 9 mg Cl m^{-2} at 5 km. Although, these data are subject to wind speed, obstacles, topography configuration and the concentration of sodium chloride in the seawater, an adverse effect on soils and infrastructures due to corrosion. Another advantage of this forest buffer is that they slow down or increase the shoreline as they retain sediment and stabilize the soil in the areas between high and low tide (intertidal zones) reducing erosion during storms and floods [96].

This study does not recommend a rate of N_2 fixation by the legume, because even the highest rates reported in agriculture do not achieve a notable export of nutrients. These fixation rates are not continuous over time for physiological reasons of the symbionts, and may vary from year to year and within the same year. This legume management is recommended to use as widely as possible in the basin.

4.4 Representativeness of this result to the rest of the southern zone of Cuba

Cuba is an island with a central watershed and a particular tilting where the northern zone rises, and the southern

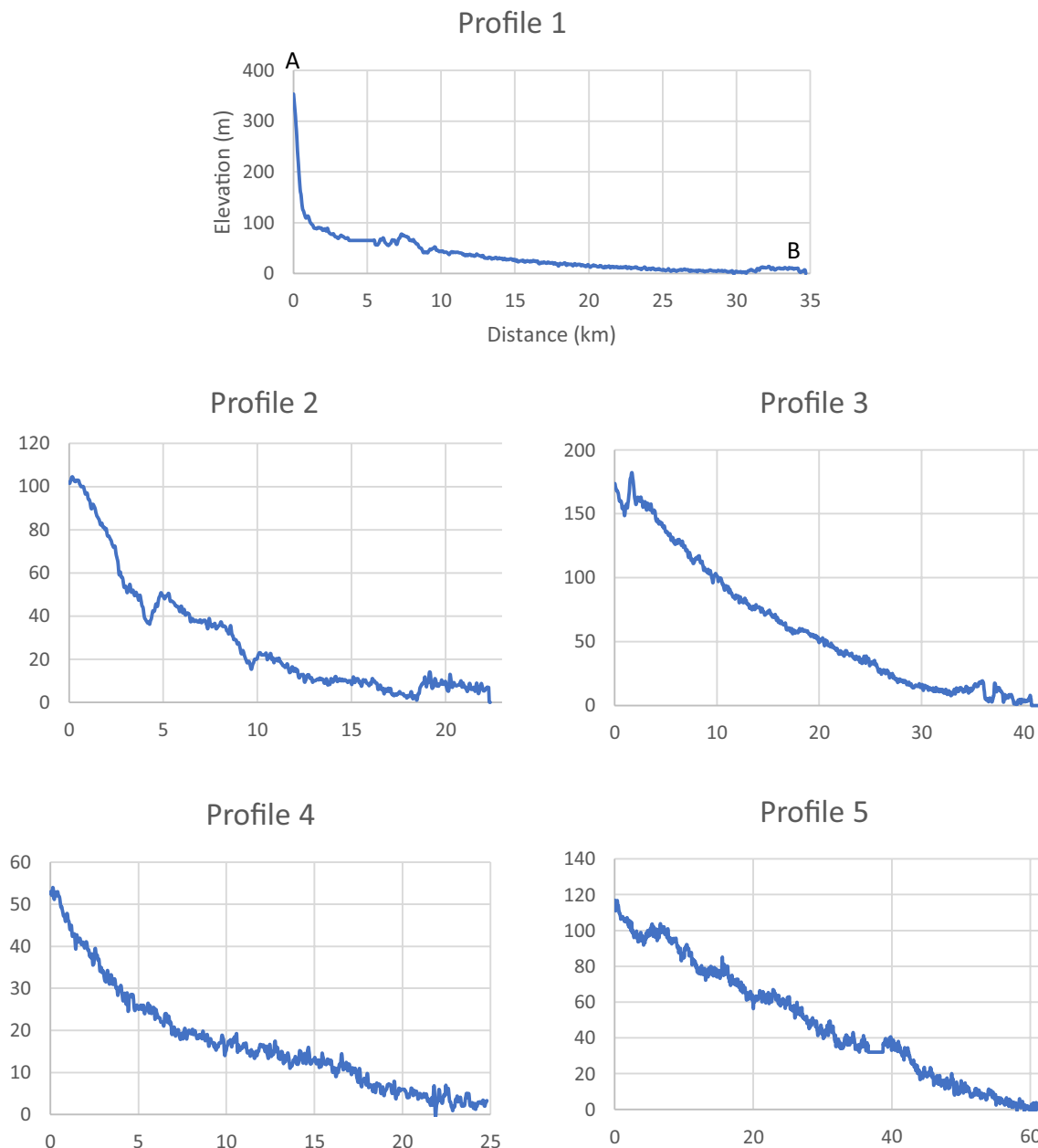


Fig. 19 Topographic profiles of different regions of southern Cuba. The profiles are represented in Fig. 18

zone submerges [97]. The geomorphology of this southern zone is mainly terraced (Fig. 18), with a slight convexity (Fig. 19), flattening several kilometers before reaching the coastline.

These topographic characteristics, being exposed to the same type of climate and a mainly karstic lithology, produce similar soil groups in these regions (Fig. 20). Therefore, it can be observed that around the Ana María and Batabanó Gulfs, there is a predominance of Ferralitic soils. In the upper part, near the watershed, there are Brown

soils or Fersialitic soils that have similar textural characteristics (silty).

The only area of these two gulfs that stands out for being quite dissimilar in this aspect, is the quartzite plain of Pinar del Río. Its texture is primarily sandy and possibly low in nutrients due to the little electric interaction that exists between its aggregates, in addition to the fact that an erosion much greater may occur than in the other sectors.

Therefore, it may not be surprising to extrapolate several of the results obtained in the La Teresa basin to almost

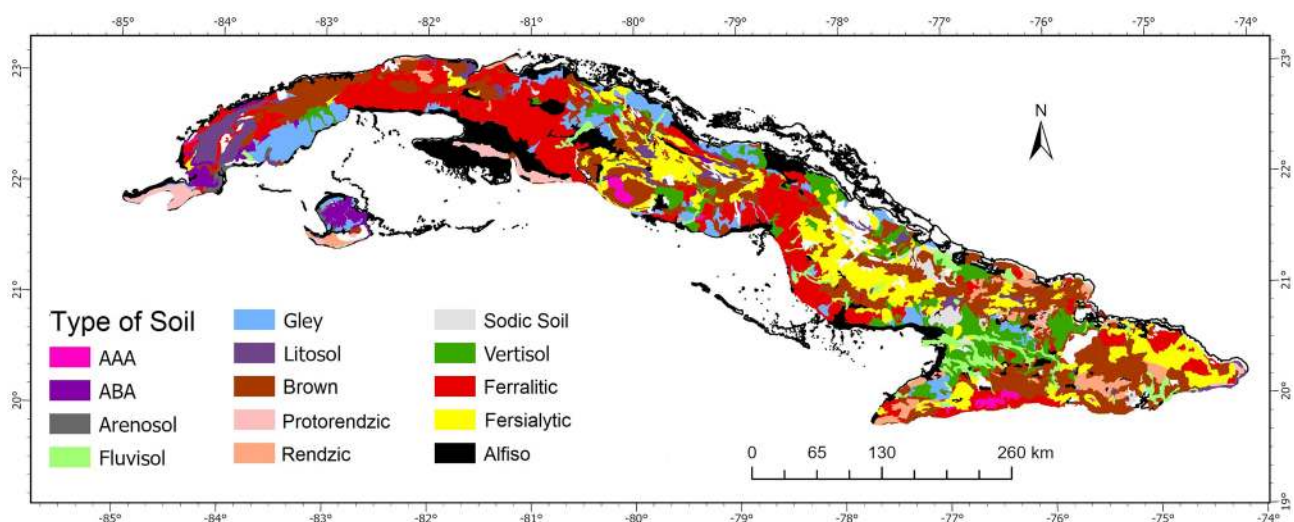


Fig. 20 Map of types of soil in Cuba [50]. AAA: Alitic High Clay Activity, ABA: Alitic Low Clay Activity

50% of the Gulf of Batabanó and a large part of the Gulf of Ana María. Mainly those of physical-geographical origin such as geomorphic potential, slope shape, dissection caused by karstic relief, and similarity in soil cover at the group level. Another aspect in which both areas are similar is that their shorelines are generally covered by a transition of mangrove forest with vegetation more in line with automorphic surface terrain. The exception to this rule is Dique Sur (South Dike) where the mangrove forest has deteriorated.

5 Conclusions

The soil management under legume management that maximizes gains and minimizes losses for both agricultural and marine ecosystems in the basin is in the areas used for pasture since the legume used does not require as demanding care as a legume for human consumption. This management also showed a positive economic balance at low fixation rates (from 55 to 1560 USD ha⁻¹ yr⁻¹ for crops and from 22 to 2400 USD ha⁻¹ yr⁻¹ for pasture). Its location in the highlands of La Teresa provides indirect fertilization of the lowlands. In agricultural regions, the use of this management is left to the personal discretion of the farmers because of the benefits in productivity and field yields. The maximum nutrient concentration in La Teresa by legume management was 1.07–1070 ± 2–141 ppm in pastures and 0.3–1017 ± 0.85–69 ppm in crops. The amount of nutrients that reached the Gulf of Batabanó in each of the different treatments did not show high values (0.9623–0.9624 kg ha⁻¹ yr⁻¹ for pastures; in the case of crops 0.962379–0.962474 kg ha⁻¹ yr⁻¹). Regarding

the spatial arrangement of the areas of use, it follows from the results that the shorter the distance to the coast, the higher the export. The main variable regulating this export is the geomorphic potential of a convex basin, with sedimentation predominating in the lower locations.

These results demonstrate that through legume management it is not possible to increase the export of the nutrient nitrogen to the oligotrophic waters of the Gulf of Batabanó without causing major modifications to the ecosystem. Therefore, the future scope of research should be the management of this fishing zone, adequate to these new conditions of low nutrient export values from land and damming.

Funding The authors did not receive support from any organization for the submitted work.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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