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An integrated TOPSIS and fuzzy logic model for evaluating the rationality of sloping land use types in Bac Kan province

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Abstract:

This article employs an integrated model of fuzzy logic and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to evaluate the rationality of sloping land use types in Bac Kan province, encompassing planted forests and cropland. Soil samples were collected from 30 locations in Ba Be, Bac Kan, and Na Ri districts on January 12-13, 2024, to analyse soil quality components for the integrated model. The integrated model has been evaluated objectively and reliably based on the proposed set of criteria, addressing the limitations of consistency when determining the weight set and the permutation in the ranking results when used separately. Fifteen criteria are proposed to evaluate the rationality of sloping land use types in Bac Kan province, comprising 11 criteria for environmental values, two criteria for economic values, and two criteria for social values. Model results indicate that the most reasonable land use type for crops is intercropping cereal crops with *Glycine max*, while the most reasonable land use type for forestation is the mixed wood forest with shrubs or legumes. The rankings have been verified by their similarity with the opinions of numerous experts and authors studying sloping land in Vietnam. Thus, the model results can be utilised for planning purposes and to facilitate decision-making processes and tools in sustainable agriculture and forestry development in the sloping land of Bac Kan province.

Keywords: **criteria, fuzzy logic, rationality of slope land use, TOPSIS model.**

Classification numbers: **4.1, 5.3**

1. Introduction

Bac Kan is a highland mountainous province, with mountainous areas accounting for 80% of the natural area. The terrain is rugged and strongly divided, and flat land occupies a small area distributed into narrow strips, sandwiched between the strips of high mountains on both sides [1]. Most of the province's area has a steep slope of over 15 degrees, and people continue to cultivate, growing rice and other annual crops in areas with a slope of over 20 degrees. To date, there are five ecosystems in Bac Kan, including natural forests, planted forests, agricultural land, residential areas, and wetlands [2].

Land use type is a significant indicator of human activities that either contribute to land degradation or land improvement [3]. It affects soil quality and other components of land resources such as vegetation, water, and air [4-6]. Land suitability assessment is an essential step for land use planning and development [7]. Making optimal use of scarce resources in developing countries is a major challenge for sustainable crop production [8].

Sloping land is inherently susceptible to being washed away, degraded, and infertile [9]. Moreover, many types of land use on sloping land, with inappropriate techniques and disregard for improving soil fertility, cause soil degradation. Land management and the rational use of natural resources following environmental regulations are fundamental principles of sustainable development. A crucial aspect of the land use issue is whether the current land use is consistent with the characteristics of the land and whether it protects land quality to meet future land-use-oriented activities. Assessing the sustainability and efficiency of land use processes is necessary to provide reasonable land

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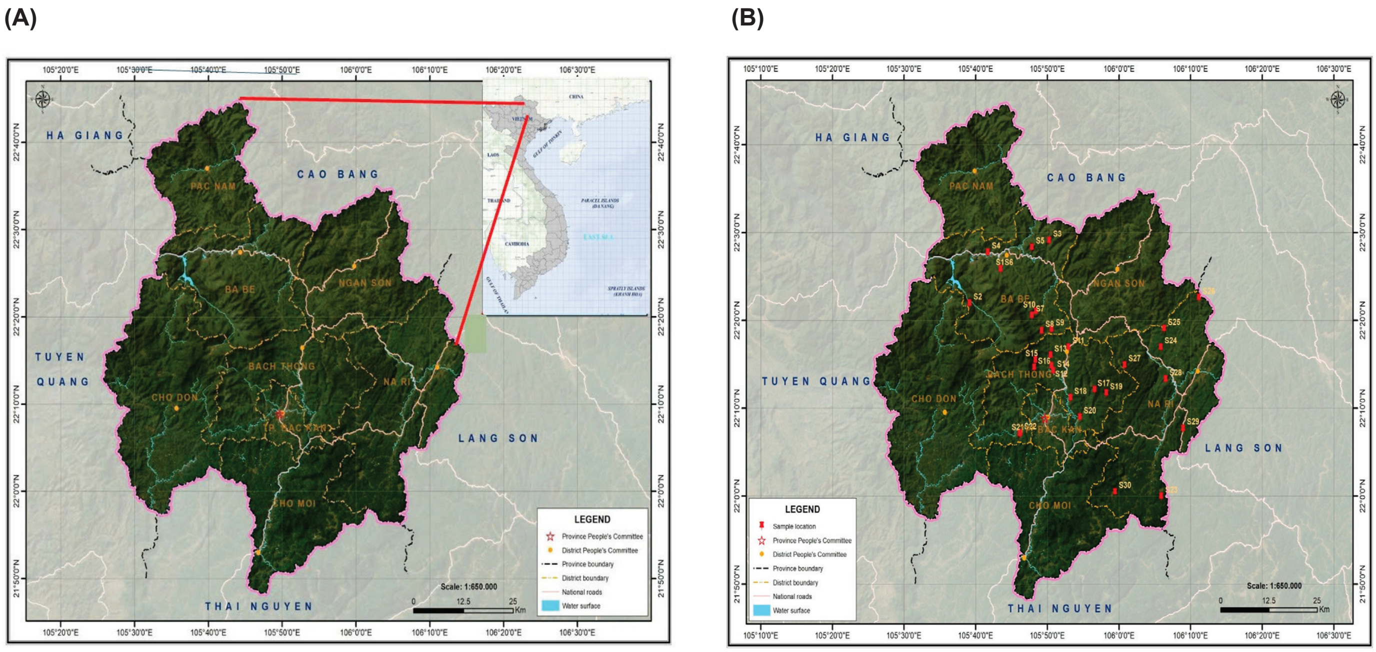

Fig. 1. Study areas and sample sites.

use directions because land is a precious and almost non-renewable resource. Traditional methods of assessing the rationality of land use types, such as monitoring changes in the quality of land use over the years, do not fully and accurately assess whether a type of land use is good or not, as this evaluation is based on many criteria related to the economic, social, and environmental fields [10].

This study employs an integrated model of multi-criteria analysis methods, TOPSIS and fuzzy logic, to evaluate the rationality of some sloping land use types in ecosystems of planted forests and agricultural land. The model uses a technique for order preference by similarity to the ideal situation to support selecting a reasonable solution. However, like other multi-criteria analysis methods, the subjective opinions of evaluators are not eliminated when applying TOPSIS. Therefore, the integrated fuzzy logic and TOPSIS model overcomes the inaccuracy caused by subjective data during the evaluation process.

The model allows the simultaneous use of many criteria to objectively evaluate the reasonableness of each type of land use in moving towards sustainable development, preventing soil erosion, limiting soil degradation, protecting soil fertility, and ensuring sustainable sloping land use. The ranking results assist managers, policymakers, and farmers in choosing appropriate land use models to effectively improve sustainable cropland and forest land development activities, thereby ensuring the protection of natural resources and the environment.

2. Materials and methodology

2.1. Study areas

A topographic survey and selection of study areas were conducted on January 12-13, 2024. The study area was located in three districts: Na Ri, Bach Thong, and Ba Be of Bac Kan province, with 9.08% of the total area dedicated to agriculture and 85.05% to forest land, encompassing natural forests, planted forests, and agricultural land. The chosen study areas represent typical ecological systems across seven districts within the province - planted forests and cropland. Fig. 1 displays the geographical location of Bac Kan province (A) and the soil sampling sites (B).

Figure 2 illustrates the four main types of forest land and cropland from which soil samples were taken in this study: a) monocrop (S1, S4, S10, S6, S13, S15, S20, S22), b) intercropping with two plant species (S5, S9, S12, S26, S27, S28), c) single-species forestation (S2, S11, S14, S18, S19, S23, S24, S25), and d) diverse plant species forestation (S3, S7, S8, S16, S17, S21, S29, S30).

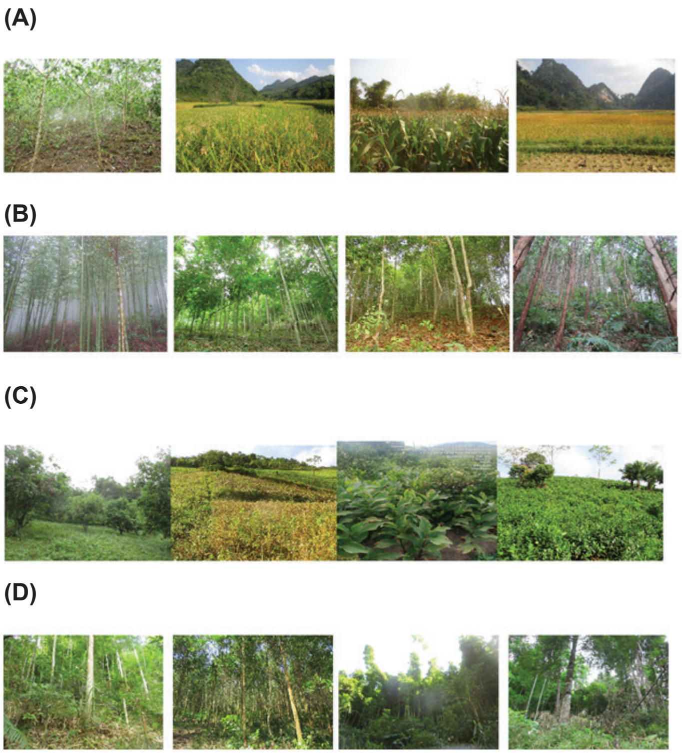

Fig. 2. Study subjects - 4 types of forest land and cropland. **(A)** Monoculture farming; **(B)** Single-species reforestation; **(C)** Intercropping with more than one plant; **(D)** Reforestation with diversity of plant species.

Soil samples were analysed for soil quality indicators, including bulk density, pH, cation exchange capacity (CEC), soil mechanical composition, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), and total potassium (TK). All analytical methods followed the technical guidelines for soil, water, and fertiliser analysis [11] and the laboratory of the Institute of Earth Sciences, Vietnam Academy of Science and Technology. Analysed soil quality data is used for the integrated TOPSIS and fuzzy logic model.

2.2. Methodology

2.2.1. Soil sampling and method of soil sample analysis for soil quality data

A topographic survey and selection of study areas were conducted in the spring of 2024. Four main land use types were selected for soil sampling. Subsequently, soil sampling was done on January 12-13, 2024. Soil samples were taken at 30 locations in the Bac Kan, Ba Be, and Na Ri districts. Each study site randomly collected soil samples at a depth of 0-20 cm. Square plots of size 30 cm x 30 m were set up at each corner of the square. One kilogram of soil was taken, mixed well, and from this mixed sample, one sample of topsoil and representative vegetation was taken to ensure the specificity of the area studied. Soil sampling locations are illustrated in Fig. 1B.

2.2.2. Integrated fuzzy logic - TOPSIS model method

TOPSIS is a multi-criteria decision-making method introduced by C.L. Hwang, et al. (1981) [12]. The principles of TOPSIS involve defining a positive ideal solution and a negative ideal solution. An option is considered best if it has the closest value to the positive ideal solution and is furthest from the negative ideal solution.

The fuzzy set theory was proposed by L.A. Zadeh (1965) [13]. The main idea of fuzzy logic is to capture the ambiguity in human thinking and express it using appropriate mathematical tools, based on reasoning about subjectivity and uncertainty.

The fuzzy-TOPSIS model evaluates and ranks objects by measuring the distance from the object to positive and negative ideal solutions, where fuzzy numbers are used to limit the uncertainty and subjectivity of the evaluator. The model, using analysed soil quality results and fuzzy-TOPSIS, to evaluate the rationality of main sloping land use types in Bac Kan province is carried out in the following steps. The step-by-step flow of the proposed method is briefly explained as follows.

Step 1: Determine criteria to evaluate reasonable land use types or sustainable land use types in terms of economics, society, and environment. The importance of the criteria and the reasonable level of land use types are expressed by weight. The weights for land use selection criteria are determined using fuzzy logic expressed as trapezoidal fuzzy numbers.

Step 2: In this study, there are m land uses in agriculture and forest land and n criteria for selecting land uses. Let x_{ij} be the score of i land use of j criterion. We have the following matrix $X = (x_{ij})m\times n$:

$$X = \begin{matrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{matrix} \quad (1)$$

Let J be the set of positive criteria for land use. Let J' be the set of negative criteria for land use.

Construct a standardised decision matrix. Selected standardised land use criteria so these criteria can be compared. The normalised scores are as follows:

$$r_{ij} = x_{ij}/(Sx2ij) \quad (2)$$

where $i = 1, ..., m$ is the criteria for selecting land use and $j = 1, ..., n$ is that for land uses.

Determine the weights for each criterion. The weights for selecting land use criteria are determined using fuzzy logic.

Step 3: Establish a decision matrix for ranking. Suppose we have a set of weights for each criterion w_j with $j=1,...n$. Multiply each column of the normalised decision matrix by the corresponding weight. The elements of the new matrix are:

$$v_{ij} = w_j r_{ij} \quad (3)$$

Step 4: Determine the most reasonable land use and the most unreasonable land use

Most reasonable land use (A^+):

$$A^+ = \{ v_1^* , ..., v_n^*\} \quad (4)$$

where $v_j^* = \{\max (v_{ij}) \text{ if } i \in J ; \min (v_{ij}) \text{ if } j \in J'\}$

Most unreasonable land use (A^-):

$$A^- = \{ v_1' , ..., v_n' \} \quad (5)$$

where $v' = \{\min (v_{ij}) \text{ if } j \in J; \max (v_{ij}) \text{ if } j \in J' \}$

Step 5: Calculate the relative difference measurements for each land use. The deviation from the most reasonable land use (S^+) is:

$$S_i^+ = [S (v_j^* - v_{ij})2] 1/2 , i = 1, ..., m \quad (6)$$

Similarly, the difference from the most unreasonable land use (S^-) is:

$$S_i^- = [S(v_j' - v_{ij})2]1/2, i=1,..., m \quad (7)$$

Step 6: Calculate the degree of close association with appropriate land use C_i^*

$$C_i^* = S_i^- / (S_i^+ + S_i^-), 0 < C_i^* < 1 \quad (8)$$

Choose the option Ci^* nearest to 1.

3. Results and discussion

3.1. Soil quality of land use types in Bac Kan province

Analysed results of soil samples collected from Bac Kan province show that the mechanical composition in crop soil samples is dominated by medium particles, while in forest soil samples, heavy mechanical composition is dominant. Acidity is one of the important factors that determine soil fertility. It affects the physical, chemical, and biological processes in the soil and significantly impacts the survival and growth of plants. Most plants prefer a neutral to slightly acidic soil reaction with a pH in the range of 6-7 [14]. The pH in soil samples collected from study locations ranges from 3.52 to 5.81. The acidic soil here is primarily due to the sloping soil and sandy soil structure, allowing alkaline earth ions to be easily washed away, causing the soil to become acidic.

Vietnam is in a tropical climate; high temperatures and relatively high humidity cause the organic matter mineralisation process to occur vigorously, so the organic matter content in soil is often poor, especially with prolonged cultivation without using organic fertilisers [15]. Comparing the organic matter content in this study to the results of other authors cultivating on sloping land, it is found that the organic matter content in Bac Kan's soil ranges from good to slightly poor [16, 17]. Organic matter is a unique component in almost any soil, being one of the most important indicators to evaluate soil fertility. Analysis results show that organic matter in crop soil ranges from 2.348 to 5.26%, with the lowest in *Zea mays* L. crop soil at 2.348%, higher in *Citrus reticulata* soil, *Oryza sativa* crop soil, and *Manihot esculenta* Craz crop soil, and the highest value in *Canna edulis* Ker intercropped *with Citrus reticulata* soil at 5.26%.

Organic matter in forest soil samples ranges from 2.348 to 8.175%. The highest organic matter value was from a mixed forest soil sample (S7) with a diversity of tree species formed from several forest layers, including high-story timber trees such as *Chukrasia tabularis, Fructus canarii,* and *Manglietia conifera*, which were left after forest exploitation five years ago, mid-story trees with dense shrubs, and a grass layer in the surface layer. Humidity in this area is generally quite high. In the remaining forest soil samples, high organic matter content is detected, ranging from 4.261 to 7.582%. Lower organic matter values are found in soil samples of mixed bamboo forests (S21, S29, S30) with mainly *Bambusaceae* family members such as *Chimonocalamus baviensis,* and a few groups of grass growing on the ground, such as *Arundo donax* L.

Cation exchange capacity (CEC) is the cation absorption capacity of the soil colloidal complex. CEC is greatly influenced by the content of clay minerals and organic matter present in the soil. The higher the CEC, the more beneficial it is for plant growth and development due to increased physicochemical absorption of soil nutrients. Analysis results show that average CEC values range from 13.2 to 18.8 meq/100 g in crop soil samples, while higher CEC values range from 16.2 to 21.3 meq/100 g in forest soil samples.

Nitrogen is important for plants during root development, budding, and determining harvest yield. Nitrogen from the soil is also easily lost and quite expensive to supply. The total N content in crop soil samples is mostly at an average level, ranging from 0.11 to 0.225%, with the highest in soil samples from intercropping *Zea mays* L. with *Glycine max* and the lowest in soil samples from monocropping *Zea mays* L. In forest soil samples, N content is high, ranging from 0.235 to 0.387%, with the highest in mixed *Manglietia conifera* and *Acacia auriculiformis-mangium* forests.

Total P content in soil samples ranges from poor to rich, ranging from 0.026 to 0.125% P_2O_5. Total P content is at an average to poor level in two-thirds of crop soil samples; one-third of the samples are at a rich level. Mixed forest soil samples are at a rich P level, while *Manglietia conifera* forests and mixed bamboo forests are at an average level. Available P content directly reflects the soil's ability to provide P for plants, as P is easily digestible in a form that can be directly absorbed by plants. Similar to total P content, total K content in crop soil samples is mainly at an average level. The easily digestible K content in different crop type ranges from 0.185 to 2.619%. The easily digestible K content in forest soil samples is also average, ranging from 0.287 to 1.375%.

Many studies have proven that land use types significantly influence soil quality, and there is a relationship between soil quality and soil sustainability. Understanding soil quality helps to detect problem areas, assess sustainable agricultural management, and provide early warning signs of adverse trends [18-20].

3.2. Using integrated fuzzy logic TOPSIS model for evaluating the rationality of sloping land use types in Bac Kan province

According to land suitability principles, limiting criteria should be selected for use in the assessment [7]. Applying methods for assessing the quality of sloping land and types of sloping land use from the Vietnam Soil Science Association and authors with many years of research on sloping land [15-17], criteria to evaluate the rationality of sloping land use types in Bac Kan province are proposed as follows: For environmental values, 11 criteria are selected, consisting of 9 criteria for soil quality protection and 2 criteria for ecological development. For ecological development, the score of enhanced biodiversity consists of the diversity of tree species and tree layers. For soil quality protection, the score for physical parameter criteria is estimated based on components of sand, clay, silt, and bulk density, while the score of chemical parameter content criteria is based on pH, EC, CEC, and organic matter, and the score of nutritional content criteria is based on nitrogen content, potassium content, and phosphorus content. All these criteria are scored according to the soil quality analysis results of soil samples taken from the evaluated land use type. The criteria have corresponding scores according to components compared with the classification table for each criterion of the Vietnam Soil Science Association [15].

For economic values, there are two criteria consisting of capital and profit [10]. The score for capital criteria is based on the suitable level of the invested capital with indigenous people, while the profit criteria are based on earned profit appropriate to the amount of spent capital and labour.

For social values, there are two criteria consisting of providing jobs for labourers and government policy application [10].

Applying the model in determining the weight of criteria: investigation, interviews with experts related to the fields of land, economy, society, and environment, results of estimating the weights of factors as in Table 1.

Table 1. Criteria for estimating rationality of land use type and its weight.

Criteria	pH	Organic matter	Bulk density	Mechanical component	Cation exchange capacity	Total nitrogen	Total phosphorus	Total potassium
Weight	0.02	0.1	0.01	0.1	0.01	0.1	0.1	0.1
Criteria	Jobs	Capital	Profit	Slope level	Biomass	Plant diversity	Government policy	
Weight	0.15	0.02	0.1	0.1	0.01	0.02	0.1	

Table 2. Land use types and the rank of land use rationality.

Land use types		Weighted sum	Land use rationality calculation	The rank of land use rationality
Crop land use types				
Monocrop	Monocrops each of food crops (*Canna edulis Ker.* (galangal), *Zea mays* L. (maize), *Manihot esculenta* Crantz (cassava), *Oryza sativa* (rice)...	6.28	0.4135	4
	Monocrops of *Glycine max* (soybean)	5.3	0.4273	2
Intercrop	Intercrops several other food crops with food crops *Glycine max*	7.65	0.8367	1
	Intercrops with *Citrus reticulata* and *Canna edulis* Ker.	6.89	0.4236	3
Forestation land use types				
One species forestation	*Manglietia conifera* forest, *Auriculiformis mangium forest, Pinus kesiya...*	5.54	0.5449	3
Mixed forestation	Mixed *Manglietia conifera Acacia* with *Auriculiformis mangium forest*	6.7	0.5502	2
	Mixed wood forest with legume shrubs	6.74	0.3754	1
	Mixed bamboo forest	6.43	0.3236	4

After applying fuzzy logic to determine the set of criteria and weights and applying TOPSIS to rank the rationality of land use types, the calculated results of the typical land use type rationality in Bac Kan province are presented in Table 2. The result from the integrated fuzzy logic and TOPSIS model shows that the most reasonable land use type for forestation is mixed wood forest with legume shrubs, while the most reasonable land use type for crops is intercropping *Zea mays* L. with *Glycine max*. The rankings have been verified by conducting actual surveys to interview experts and people. These results show similarities with the opinions of many authors who have studied crops and forestry on sloping land [1, 9, 16, 21, 22], especially sloping land in Vietnam [1, 16].

It was found that organic matter, high CEC, proper nitrogen content in the soil, high plant diversity, and proper government policy were the main positive factors for agricultural and forestry production in Bac Kan province. In contrast, the main limiting factors for agricultural and forestry production were the high slope and low pH of the soil. J. Seyedmohammadi, et al. (2019) [7] and M.N. Navidi, et al. (2022) [8] proved that rational land use types overcome limiting factors and enhance positive factors in their experiments. In Bac Kan forest, to increase biodiversity and the protection ability of forests, tree species suitable for each site condition are selected for planting, with priority given to large multi-purpose and native trees to enhance high economic efficiency. For protective forests, trees such as *Manglietia conifera*, *Auriculiformis mangium, Pinus kesiya, Illicium verum,* and *Cinnamomum cassia* are prioritised for planting. For productive forests, large and high economic value timber trees such as *Chukrasia tabularis, Canarium luzonicum,* and *Hopea odorata* are selected for planting [1]. In mixed wood forests with shrubs or grass, deep roots of timber trees will utilise nutrients in the soil layers to create large biomass that protects the soil, prevents erosion, and improves the soil in deeper layers, while shrubs serve as on-site covering material, reducing soil erosion and leaching at the surface layer. Additionally, legume shrubs can form a symbiotic relationship with nitrogen-fixing soil bacteria called rhizobia to convert N_2 into NH_3 that the plant can use [23, 24]. Legumes help timber trees grow healthier, achieve higher yields, and better withstand the effects of weather. M.A. Zöbisch, et al. (1995) [21] reported that the total amount of N, P, and K lost in eroded soils, as well as the amount dissolved in surface runoff, does not depend on the nutrient concentration of the eroded soil and water but on the total amount of runoff and soil erosion. Therefore, intercropping legumes with timber trees will be a good solution to help prevent erosion and leaching of nutrients on sloping land due to the legume's ability to reduce flow intensity during floods and storms.

Food crops *Glycine max* gives the best rationality in sloping land use due to not only ensuring the maintenance of food security but also improving soil quality and protecting the ecological environment by promoting high ecological diversity, so plant species support each other in many aspects. *Zea mays* L., *Manihot esculenta* Crantz, *Canna edulis* Ker., and *Oryza sativa* are four key traditional crops for food production in the sloping land of Bac Kan province which integrate the net benefits of natural and human systems interaction through managed agro-ecosystems [1]. *Glycine max* is grown worldwide as an important staple and commercial crop. *Glycine max* accounted for 56% of the production of the main world oilseed crops in 2011 with a total production of 251.5 million tons [23]. *Glycine max* with strong and thick root systems will improve the physical properties of the soil, reduce acidity, and increase the ability to hold organic carbon in the soil by breaking down solid soil layers, making the soil more porous and absorbing water. *Glycine max i*s a species of legume, therefore, *Glycine max* can also form a symbiotic relationship with nitrogen-fixing soil bacteria called rhizobia to improve soil quality [25]. Monocrops each crop or intercropping several food crops without *Glycine max* gets the lower rank of land use rationality due to the profit received being lower, the ability to improve land being lower, and the ability to keep soil from erosion also lower. Therefore, intercropping rows of legumes with main crops will be a good solution to help prevent erosion and leaching of nutrients on sloping land.

3.3. Proposing several types of cropland use and forestation land use that are highly effective in protecting the environment and bringing economic and social benefits

The results of the rationality assessment of land use demonstrate the successful application of the integrated fuzzy logic - TOPSIS model method in addressing complex issues in the context of cultivation priority planning management. The integration of this developed framework into the planning policies of cultivation priority in a developing country such as Vietnam is an effective tool for integrated regional land use planning that can help in better controlling soil, land, and environmental protection. Reasonable land use types are highly effective in protecting the environment and bringing economic and social benefits.

It is recommended that for cropland, intercropping cereal crops that are strong in Bac Kan, such as *Canna edulis* Ker., *Zea mays* L., together with *Glycine max*, can improve pH, increase nitrogen levels, protect soil, supply food and work, and guarantee food security based on the local ecosystem. For forest land, maintaining and enhancing plant diversity helps protect soil, protect forests, and increase the economic value of forests by intercropping valuable wood trees such as *Michelia tonkinensis* A., *Canarium album* Lour., *Chukrasia tabularis*, with *Auriculiformis mangium, Leucaena leucocephala, Acacia mangium*, which have a good ability to protect and enhance soil quality.

4. Conclusions

The integrated model of fuzzy logic and TOPSIS has been evaluated objectively and reliably based on the proposed set of criteria, overcoming the limitation of consistency when determining the weight set and the permutation in the ranking results when used separately. Model results prove that the most reasonable land use type for crops is intercropping food crops together with *Glycine max*, while the most reasonable land use type for forestation is mixed wood forest with legume shrubs. The rankings have been verified by conducting actual surveys to interview experts and people. Research results show similarities with the opinions of these individuals and many authors who have studied sloping land.

CRediT author statement

Vu Thi Phuong Thao: Idea, Analysis, Writing, Editing; Nguyen Duc Thanh: Data analysis; Nguyen Quoc Phi: Data analysis, Editing; Nguyen Thi Cuc, Nguyen Quang Minh: Data analysis.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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