

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 uses an integrated model of fuzzy logic and technique for order of preference by similarity to ideal solution (TOPSIS) to evaluate the rationality of sloping land use types in Bac Kan province consisting of planted forests and cropland. Soil samples were taken at 30 locations in Ba Be, Bac Kan, and Na Ri districts on 12-13 January 2024 to analyze soil quality components to get soil quality data for an integrated model of TOPSIS and fuzzy logic. The integrated model 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. 15 criteria to evaluate the rationality of sloping land use types in Bac Kan province are proposed with 11 criteria for environmental values, 2 criteria for economic values, and 2 criteria for social values. Model results prove 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 similarity with the opinions of many experts and authors studying sloping land in Vietnam. Thus, the model results can be used 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 area 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, high mountains on both sides [1]. Most of the province's area with a steep slope of over 15° and people still cultivate, growing rice and other annual crops in areas with a slope of over 20°. Up to now, there are five ecosystems in Bac Kan, including natural forests, planted forests, agricultural land, residential areas, and wetlands [2].

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Land use type is one of the noticeable indicators 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]. Furthermore, many types of land use on sloping land with inappropriate techniques and disregard for improving soil fertility cause soil degradation. Land management and rational use of natural resources following environmental regulations are basic and important principles of sustainable development. One of the basic points 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 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 assess fully and accurately due to evaluating whether a type of land use is good or not is based on many criteria related to the economic, social, and environmental fields [10]. This study uses 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 evaluate the reasonableness of each type of land use in moving toward sustainable development objectively, preventing soil erosion, limiting soil degradation, protecting soil fertility, and ensuring sustainable sloping land use. The ranking results help managers, policymakers, and farmers choose appropriate land use models to effectively improve sustainable cropland and forest land development activities in the direction of good 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 in the spring of 12-13 January 2024. The study area was conducted 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 7 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).

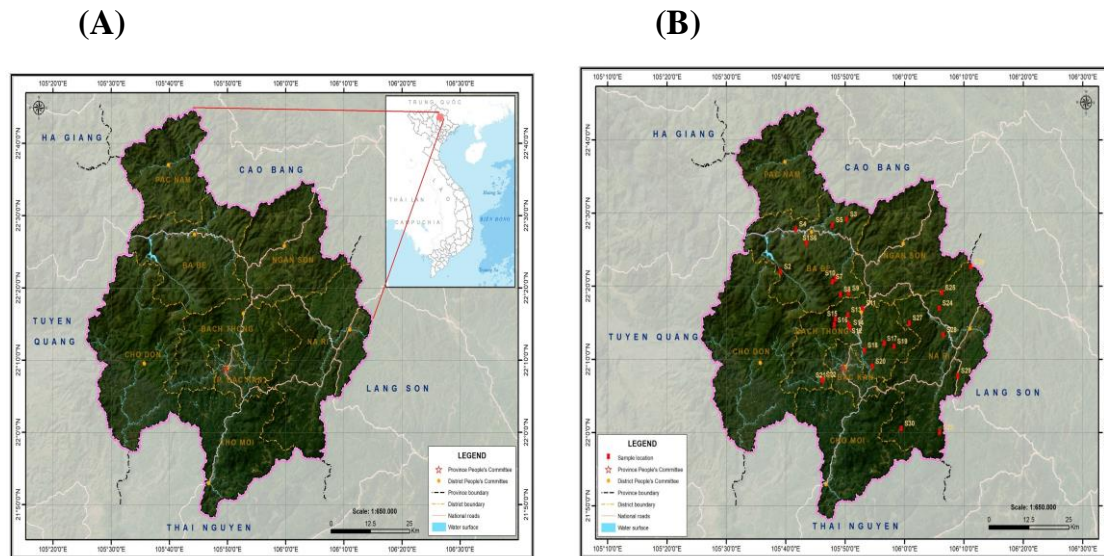


Fig. 1. Study areas and sample sites.

Figure 2 illustrates 4 main types of forest land and cropland which were taken soil samples in this study consisting of a) monocrop (S1, S4, S10, S6, S13, S15, S20, S22), b) Intercropping with 2 plant species (S5, S9, S12, S26, S27, S28), c) Single-species forestation (S2, S11, S14, S18, S19, S23, S24, S25), d) diverse of plant species forestation (S3, S7, S8, S16, S17, S21, S29, S30).

(A)



(B)



(C)



(D)



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 plat species.

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. 4 main land use types were selected for taking soil samples. Subsequently, soil sampling was done in 2024, 12-13th of January. 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 0-20 cm depth. Set up square plots of size 30 cm x 30 m, at each corner of the square, take 1 kg of soil, mix well, and from this mixed sample, take 1 sample of topsoil and representative vegetation to ensure the specificity of the area study. Soil sampling locations are illustrated in Fig. 1B.

Soil samples were analyzed soil quality indicators consist of 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 Fertilizer Analysis [11] and the laboratory of the Institute of Geography, Vietnam Academy of Science and Technology.

Analyzed soil quality data are used for the integrated TOPSIS and fuzzy logic model.

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 TOPSIS principles involve the definition of a positive ideal solution and a negative ideal solution. An option is best if this option has the closest value compared 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 based on 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 soil quality analyzed 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 also 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 matrix $X=(x_{ij})_{m \times n}$.

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

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

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

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

In which: $i=1, \dots, m$ is the criteria for selecting land use; $j = 1, \dots, n$ 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 $j=1 \dots n$. Multiply each column of the normalized 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^+):

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

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

Most unreasonable land use (A^-):

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

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

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

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

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

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

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 C_i^* nearest to 1.

3. Results and discussion

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

Analyzed results of soil samples collected from Bac Kan province show that mechanical composition in crop soil samples is dominated by the medium 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 has a great impact on 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 cause of the acidic soil here is mainly due to the sloping soil and sandy soil structure, so alkaline earth ions can easily be washed away, causing the soil to become acidic.

Vietnam is in a tropical climate, high temperatures and relatively high humidity cause the organic matter mineralization process to take place vigorously, so the organic matter content in soil is often poor, especially for long cultivation without using organic fertilizers [15].

Comparing the organic matter content in this study to the results of some other authors cultivating on sloping land, it is found that the organic matter content in Bac Kan's soil belongs to the type of soil from good to little 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%, lowest in *Zea mays* L. crop soil at 2,348%, higher in *Citrus reticulata* soil, *Oryza sativa* crop soil, *Manihot esculenta* Craz. crop soil while the highest value in *Canna edulis* Ker intercropping with *Citrus reticulata* soil sample 5,26%.

Organic matter in forest soil samples is in the range of 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 with high story consisting of timber trees such as *Chukrasia Tabularis*, *Fructus canarii*, *manglietia conifera*... were left after forest exploitations 5 years ago, midstory trees with dense shrubs and grass layer in the surface layer. Humidity in this area is generally quite high. With remaining forest soil samples, high organic matter content is detected ranging from 4,261 to 7,582%. The lower organic matter values are in soil samples of mixed bamboo forests (S21, S29, S30) with mainly Bambusaceae family such as *Chimonoc alamus baviensis*, a few groups of grass growing on the ground, *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. At the same time, 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 in the range of 13,2-18,8 ldl/100 g of crop soil samples are detected while higher CEC values in the range of 16,2-21,3 ldl/100 g of forest soil samples are detected.

Nitrogen is important for plants during the stages of root development, budding and determining harvest yield. N 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% N, highest at soil sample from intercropping *Zea mays* L. with *Glycine max*, lowest at soil sample from mono-crop of *Zea mays* L. In forest soil samples, N content is at a high range of 0.235-0.387%, highest at mixed *Manglietia conifera* and *Acacia Auriculiformis Mangium* forest.

Total P content in soil samples ranged from poor to rich, ranging from 0.026-0.125% P_2O_5 . Total P content is at the average to poor level in 2/3 of crop soil samples; 1/3 of the samples are in rich level. Mixed forest soil samples are at a rich P level, and *Manglietia conifera* forests and mixed bamboo forests are at an average level. Available P content is an indicator that directly reflects the soil's ability to provide P for plants because 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 the average level. The easily digestible K content in the soil in different crop types ranges from 0.185-2.619%. The easily digestible K content in forest soil samples is also average, at a range of 0.287-1.375 %.

Many studies have proven land use types would significantly influence soil quality, and there is a relationship between soil quality and soil sustainability. Soil quality understanding 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 follow: 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, organic matter, and the score of nutritional content criteria based on nitrogen content, potassium content, phosphorus content criteria. 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 2 criteria consisting of capital and Thả profit [10]. The score for capital criteria is based on the suitable level of the invested capital with Indigenous people while the profit criteria based on earned profit is appropriate to the amount of spent capital and labor.

For social values, there are 2 criteria consisting of providing jobs for laborers 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	CEC	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	

After applying Fuzzy logic to determine the set of criteria and weights and applying TOPSIS to rank the rationality of land use types, calculated results of the typical land use type rationality in Bac Kan province are presented in Table 2. The result from the integrated model fuzzy logic and TOPSIS show 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].

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

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

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 rationality 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*, *Cinnamomum cassia*... are given priority for planting; For productive forests, large and high economic value timber trees such as *Chukrasia tabularis*, *Canarium luzonicum*, *Hopea odorata*... are selected for planting [1]. In mixed wood forests with shrubs or grass, deep roots of timber trees will utilize nutrients in the soil layers to create large biomass that protects the soil, prevents erosion, and improves the soil in deep layer while shrubs serve as on-site covering material, reducing soil erosion and leaching at the surface layer. Besides, 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, have 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.

In a similar way, intercrops four key traditional food crops in Bac Kan with 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* is 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. Propose several types of cropland use and forestation land use that are highly effective in protecting the environment and bringing economic and social benefits

The result in the rationality assessment of land use proves the successful application of the integrated Fuzzy logic - TOPSIS model method in dealing with complicated issues in the context of cultivation priority planning management. The integration of this developed framework in 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 conducting better control over 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, intercrop cereal crops that are strong in Bac Kan such as *Canna edulis* Ker, *Zea mays* L... together with *Glycine max* to 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 Mangiumm*, *Leucaena leucocephalam*, *Acacia mangium*... that have 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 the crop 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 persons and many authors who have studied sloping land.

CRedit author statement

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COMPETING INTERESTS

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

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