Article

A Multicriteria Evaluation of Sustainable Riparian Revegetation with Local Fruit Trees around a Reservoir of a Hydroelectric Power Plant in Central Brazil

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Abstract: The construction of hydropower plants often requires the flooding of large land areas, causing considerable alterations in the natural environment. In the region surrounding the reservoir of the Corumbá IV hydroelectric plant, located in the Cerrado region of Central Brazil, two types of soil predominate, classified as Dystroferric Red Latosol and Dystroferric Haplic Cambisol. The plant owners have to restore the degraded biome after the flooding of the margins caused by the filling of the reservoir. An experiment was carried out with fifteen native species, selected for having ideal phytosociological properties. Nine of them showed a survivability considered satisfactory in a planting situation, with a view to large-scale planting. Assuming that the planting of native fruit trees can be a quick solution to the attraction and preservation of wildlife, it would therefore provide sustainable riparian revegetation around the reservoir. We adopted the SIMOS technique to rank the criteria based on four morphological features and a Fuzzy AHP model to rank the contributions of the nine fruit tree species to the sustainable restoration of part of the riparian vegetation cover around the reservoir. In practical terms, we concluded that the soil types did not have any influence on tree survival after two years of growth, but the native trees' morphological features varied among the species. These findings simplify the large-scale planting of seedlings that must be carried out by the operator in the riparian forest around the reservoir.

Keywords: revegetation; power plant reservoir; SIMOS; Fuzzy AHP; Brazilian Cerrado

1. Introduction

A hydropower plant provides clean and renewable energy, controls floods, and offers the most efficient and flexible means of storing large amounts of energy, with instant response to changes in electricity demand [1,2]. On the other hand, it modifies rivers and their ecosystems by fragmenting channels, changing river flows, and transforming watersheds. Perverse effects provoked by artificial reservoirs can be seen through the increase in the riverine population, water pollution by untreated sewage, deforestation, and water withdrawals for irrigation and municipal water supply [3–8]. The outcome is the disintegration of aquatic and terrestrial ecosystems. Among many upstream impacts, the water impoundment destroys the vegetation in and around the reservoir area, causes habitat fragmentation, and blocks the natural flow of nutrients [9]. Moreover, the flooding

and transformed regime during all stages of the project increase the concentration of pollutants and remove habitats for terrestrial wildlife [10]. Reforestation by planting trees in cleared sites bordering a reservoir, where the existing vegetation is in most cases restricted to pasture, is an important means to restore tree cover, although it is not a straightforward process [11]. The sustainability of reforestation projects [12–14], competition for land with farming and livestock grazing [15,16], and biodiversity [17] may affect the ability to attract wildlife and improve environmental quality.

After forest conversion to human land uses, there are four different modes of reforestation: (a) spontaneous natural regeneration, (b) assisted natural regeneration, (c) agroforestry, and (d) commercial tree planting [18]. Previous research on native seedlings for restoration of degraded environments was carried out in different contexts, mainly because of the wide diversity of biomes affected by the various stages of degradation worldwide. Among other issues, researchers have studied the growth, yield, and economic viability of different tree species [19–21], the influence of pedological factors [22,23], climatic factors [24], and the impact of biotic factors on water resources and other water-related issues [25,26], as well as the search for sustainable solutions to social and economic demands [27]. Seedlings of native species have been recommended because of their better resistance against local pests and adaptability to the climate and pedological conditions of the region [28–30]. Grossnickle and MacDonald [31] identified the attributes that are used to assess the quality of seedlings and how this is used in forest restoration programs; Bojórquez-Tapia et al. [32] used an integrated approach with GIS and MCDA to identify main land degradation drivers in a study area, and Holl and Brancalion [33] recommended community involvement and an adequate time scale for maintenance and monitoring to achieve the potential benefits of increasing tree cover.

Research aimed at the conservation and sustainability of nature using multiple criteria decision analysis (MCDA) has been classified into forest management and restoration; conservation prioritization and planning; protected area planning and management; and mapping of biodiversity according to wilderness and naturalness [34]. Regarding forest management and restoration, Martin et al. [35] assessed economic-environmental tradeoffs related to restoration strategies; Forsyth et al. [36] considered alternative water catchments; Harrison and Qureshi [37] calculated the preference weights of environmental, social, and economic objectives in ranking riparian revegetation options; and Aguirre-Salado et al. [38] adopted the Universal Soil Loss Equation and MCDA to identify physically degraded sites in need of feasible ecosystem restoration.

The Brazilian Cerrado is a tropical savanna biome consisting of different types of vegetation and physiognomies: (a) cerradão, an almost closed woodland with crown cover of 50% to 90%, made up of tall trees, typically found in most riparian forest formations along the banks of medium and large rivers; (b) cerrado sensu strictu, with more than 30% crown cover, having formations of shrubs and 3–8 m tall trees with twisted branches; (c) campo sujo ("dirty field"), with scattered shrubs and small trees and a large proportion of grasslands; and (d) campo limpo ("clean field"), consisting only of dry grasslands, without shrubs or trees [39]. The soil and climate characteristics of the Brazilian Cerrado biome are peculiar, marked by a high variety of soils and rainfall seasonality, with extremes. The wet season is concentrated between October and March, with annual average rainfall of 800 to 2000 mm. During the dry season, July and August have almost no rain and the relative air humidity reaches 10%. The temperature ranges from 18 °C to 28 °C. The climate is classified as Aw, or Equatorial Savannah, according to the Köppen system, with dry winter [40].

The Brazilian Forest Code determines that some areas, because of their importance to preserving the environment and water resources, are considered areas of permanent preservation, such as areas adjacent to rivers or natural or artificial reservoirs, springs, hilltops, and hillside properties with inclinations steeper than 45°. Artificial water reservoirs for energy generation or water supply must have permanent preservation areas located 100 m wide along their banks, measured from the limit determined by the maximum

water level in the reservoir. Suppression of vegetation in these areas can only occur in cases of public need or social interest, provided it is previously authorized by the proper environmental agencies. This measure created a riparian line of native trees along both borders of the majority of the Brazilian Cerrado rivers, but part of the remaining area was deforested. This biome is the second most important agricultural biome in Brazil, covering almost 200 million hectares. Half of this area has been replaced by cropland and pasture [41]. The biodiversity of the Brazilian Cerrado is high, with about 7000 species of plants, 199 species of mammals, and 837 species of birds, among others. The substitution of forest by crops is increasingly threatening this biodiversity [42]. To mitigate this problem when infrastructure projects such as hydropower plants are built, reforestation projects are required to mitigate the impacts on ecosystems. However, approximately 200–300 species per hectare are replaced by only a few species that show fast growth and high survival rate, such as eucalyptus, with negative consequences to the local fauna, endangering animal species [43]. In the study reported here, we analyzed the contribution of nine species of fruit trees of native to the Brazilian Cerrado biome in terms of their morphological features for revegetation around the reservoir of a hydroelectric plant, aiming at large-scale planting to restore the local biome.

2. Materials and Methods

The reservoir area of the Corumbá IV power plant, located in the Central region of Brazil, is delimited by the border between a permanent preservation area and the neighboring properties. It was formed by the impoundment of the Corumbá River, which flooded an extensive native riparian forest area and required rerouting the main highway in the area. The water partially or totally flooded the bordering properties. It forced some rural inhabitants to move to urban areas and transformed the surrounding landscape of the municipalities directly affected by the reservoir, among them Abadiânia and Alexânia (Figure 1). The municipality is the local administrative unit in Brazil. It is akin to a county, except that government is by a single mayor and municipal council. Municipalities range from lightly populated rural ones with one or two small towns to heavily populated urban ones that are part of greater metropolitan regions. During the construction period of the Corumbá IV power plant reservoir, illegal charcoal makers and cattle breeders extracted the vegetation in the region, eliminating virtually all its wildlife. The riparian forest disappeared and most of the vegetation remaining around the reservoir's borders was pasture, mainly consisting of *Brachiaria* sp. grass. Moreover, different forms of illegal fishing combined with wastewater discharge have decimated the fish population [44].
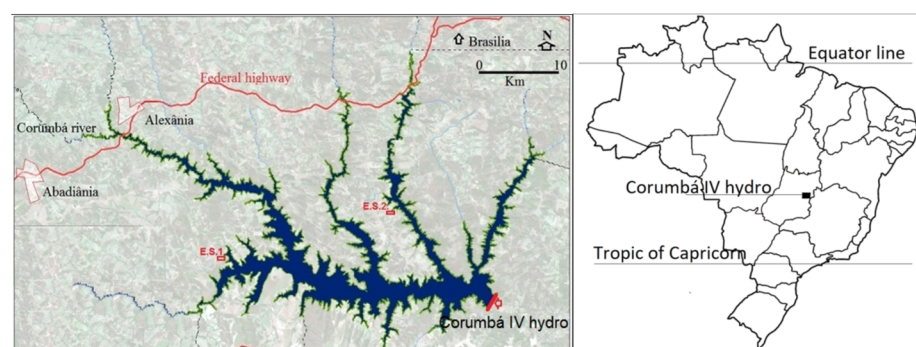
Figure 1. Corumbá IV reservoir (Brazil).

The state of Goias, where the reservoir is located, is characterized by public policies strongly oriented to agricultural production and livestock breeding. The inexistence of soil conservation techniques and the removal of gallery forests have contributed to the disappearance of entire species native to the Brazilian Cerrado. The few initiatives to restore the forests have been limited to the planting of high-performance exotic trees. Reforestation with exotic tree species in Brazil is mainly with species of Eucalyptus and

Pinus, widely used in South America [45–47]. Although they have fair resistance against environmental threats, insects, and microorganisms and provide satisfactory forest yield, they do not add value to ecosystems, mainly because they upset the balance between flora and fauna, favorably biased to the exotic trees [48]. First developed in Queensland, Australia [49], the framework species method involves the planting of indigenous trees that attract wild animals, which in turn are responsible for seed dispersal and germination, rapidly reestablishing the forest structure and revitalizing the ecosystem [20].

The experimental sites are identified as ES-1 and ES-2 (Figure 1), both located on the margins of the reservoir of the Corumbá IV hydroelectric power plant, located in central Brazil. They were in an advanced state of degradation caused by native tree deforestation, partial reforestation with exotic species like Eucalyptus, livestock grazing, and reservoir pollution due to indiscriminate discharge of untreated wastewater. The heterogeneity of soil between these sites was the primary factor for their choice among several location alternatives. The predominant types of soil in the study area are Dystroferric Red Latosol and Dystroferric Haplic Cambisol. Table 1 shows the granulometric and chemical compositions for the soils of the two experimental sites. The soil samples were analyzed for pH (0.01 M $CaCl_2$; 1:5 soil: solution), Al, Mg, K, P, Fe, and C according to procedures recommended by Silva [50]. The Ca^{2+}, Mg^{2+} and Al^{3+} were extracted using 1 mol L^{-1} KCl solution (Al^{3+} by tritation with 0.2 mol L^{-1} NAOH; Ca^{2+} and Mg^{2+} by atomic absortium spectrophotometry); and available K, P, and Fe were extracted with Mehlich-I. Concentration of K^+ was determined by flame spectrophotometry, P was determined by calorimetry using an UV-Vis spectrometer, and Fe was determined by atomic absortium spectrophotometry. The (H + Al) was extracted by calcium acetate pH 7.0 and determined by titration with 0.2 mol L^{-1} NAOH. Organic carbon was determined by Walkley-Black ($Na_2Cr_7O_7$ + H_2SO_4). Sum of base (SOB = Ca + Mg + K) and CEC ph 7.0 (CEC pH 7.0 = Ca + Mg + K + (H + Al)) were also determined. Organic matter was calculated considering the C content of 58%. Four samples were extracted, and the averages of the compositions were calculated for ES-1 and ES-2 sites. The granulometric composition is the determining factor for their differentiation, as they have relatively higher proportions of sand and silt, respectively. These soils are acidic with a pH approximately equal to 5 and have a low level of nutrients such as phosphorus, calcium, and sodium. The soil organic carbon (SOC), a critical indicator of soil health because it reflects the level of soil functionality associated with soil structure, hydraulic properties, and microbial activity, has a composition level considered medium, in both types of soils [51]. The sum of bases (SB) of the soil represents the sum of the exchangeable cation contents (SB = Ca^{2+} + Mg^{2+} + K^+), except for H^+ and Al^{3+}. Base saturation (V%) is an excellent indicator of the general conditions of soil fertility, being used even as a complement in soil nomenclature. Both soils at ES-1 and ES-2 sites are considered dystrophic, or poorly fertile, as they present V% less than 50%, in this case 20% and 18%, respectively. A low V% index means that there are small amounts of cations, such as Ca^{2+}, Mg^{2+}, and K^+, saturating the negative charges of the colloids and that most of them are being neutralized by H^+ and Al^{3+}. These dystrophic soils are poor in Ca^{2+}, Mg^{2+}, and K^+ and have a very high exchangeable aluminum content, with aluminum saturation (Al sat%) above 50%. They have also a high content of iron and aluminum, which cause clogging of particles and a reduction in soil permeability. High levels of iron prevent the fixation of phosphorus in the particles, whose content is poor in these soils, hindering root absorption and the energy source of adenosine triphosphate (ATP), essential for photosynthesis, cell division, and growth. Excess aluminum, in turn, hinders the regular absorption of water and nutrients by the deeper roots, causing superficial rooting and limiting the growth of trees [39]. The aluminum saturation of 61% and 62% for ES-1 and ES-2, respectively, confirms the high toxicity of both soils.

The accessibility of the sites and the commitment of the farmer to performing daily inspection were taken into consideration as well [52]. Experimental site ES-1 has a total area of 9379 m^2, which includes the firebreak perimeter and the access road. Its geographic coordinates for one vertex are S: 16°16′51.6″ and WO: 48°29′7.8″, and for the opposite

vertex are S: 16°16′55.0″ and WO: 48°29′4.4″. The soil classification is Dystroferric Red Latosol, here called Latosol, rich in iron, with a clayey structure [53]. Experimental site ES-2 has a total area of 9655 m^2, with firebreak and access road. Its geographic coordinates for one vertex are south: 16°12′55.7″ and west: 48°18′22.2″, and for the opposite vertex are S: 16°13′1.4″ and WO: 48°18′20.2″. The soil classification is Dystroferric Hapli Cambisol, here briefly called by Cambisol, with a light sandy loam structure [53].

Table 1. Soil granulometric and chemical composition.

	Granulometric Composition				Chemical Composition (cmolc/dm^3 = mE/100 mL)				
	Clay (%)	Sand (%)	Silt (%)	pH	SOB **	V%	CEC	SOC ***	SOM ****
ES-1	31.3	47.5	21.2	5.0	1.07	20	5.30	11.1	19.1
ES-2	29.4	60.0	10.6	4.8	0.90	18	5.14	13.1	22.4

	Chemical Composition (cmolc/dm^3 = mE/100 mL)							
	P *	Ca	Mg	K	Na	Fe *	Al	Al sat %
ES-1	1.1	0.4	0.4	0.18	0.02	299	1.7	61
ES-2	0.7	0.4	0.2	0.20	0.02	241	1.5	62

* Measured in mg/dm^3 = ppm; ** SOB: sum of bases; *** SOC: soil organic carbon in g/kg; **** SOM: soil organic matter in g/kg; V%: base saturation in percentage; P is P_2O_5 and Fe is Fe_2O_3.

2.1. Sampling Procedure

A phytosociological analysis considering the possible adaptation to the two types of soil initially identified 15 native fruit tree species as being viable [54]. All these fruits are juicy and sweet and make up part of the basic diet of many native species of birds and mammals. The protection of the two experimental sites against animal and human invasions was achieved with fences of barbed wire supported by autoclaved eucalyptus stakes erected along their perimeters. In order to evaluate the plants' ability to survive in the presence of *Brachiaria* sp., the grass was not removed, and the seedlings were planted in holes spaced three meters apart [55]. Finally, three organic elements were added: fertilizer made from chicken excrement, a compound of aquatic macrophytes applied on the crown of the plants, and a pesticide against ants. The fertilizer is plentiful and available without charge from local poultry farms and the aquatic macrophytes were harvested directly from the reservoir. A total of 1942 seedlings of the 15 species were planted in a randomized block design in the experimental sites ES-1 and ES-2, but since six species were excluded from the study, the remaining number of seedlings planted was reduced to 1248. However, two years after the seedlings were planted, six species were unable to adapt to the aggressive conditions of the soil and competition with *Brachiaria* sp. grass, having an average survival rate of only 8.6%, significantly different from the remaining group of nine species, with an average survival rate of 56% (*p*-value < 0.001). The nine species selected for the present study are listed in Table 2. The binomial name and the Brazilian common name of the six species not considered in the present study are: *Cheiloclinium cognatum* (Bacupari da Mata), *Anacardium humile St.Hilaire* (Cajuí), *Eugenia dysenterica* (Cagaita), *Brosimum gaudichaudii Tréc* (Mama Cadela), *Hancornia speciosa Gomes* (Mangaba) and *Caryocar brasiliense Cambess* (Pequi).

The first measurements were carried out two years after planting. The researchers responsible for site inspection, measurement, and reporting were a forest engineer, an agriculture technician, and one of the authors. The inspections were performed in sunny and dry weather. The dry season from May to September is particularly severe in Central Brazil. On the other hand, the wet season in the summer receives almost 50 times more than the average precipitation [56]. Although the planting in both experimental sites was done in the beginning of the wet season, the hot weather and intense rainstorms influenced the survival capacity of some species. Moreover, the presence of *Brachiaria* sp. grass covering the entire experimental sites posed additional challenges to the seedlings. This exotic African grass was introduced by farmers in the Brazilian Cerrado for pasture. Due to its high dispersion capacity for vegetative seedling reproduction, fast reproductive cycle, high photosynthesis

efficiency for nutrient usage, fast growth, resistance against livestock trampling, and fire tolerance, this grass has been a successful invader of natural ecosystems [57]. The competition between native plants and exotic grasses for soil nutrition resources changes the vegetation morphology. It also reduces the quantity and changes the composition of nutrients available for plant consumption, increasing plant vulnerability [58,59].

Table 2. Native fruit trees used in the experiment.

Abbreviation Identification	Binomial Name	Brazilian Common Name
PgS	*Psidium guineense* Swartz	Araçá Vermelho
SsAG	*Sterculia striata* A.St.-Hill & Gaudin	Chichá
IAW	*Ingá Alba* (Sw) Willd	Ingá
HsMH	*Hymenaea stigonocarpa* Mart. ex Hayne	Jatobá do Cerrado
GaLL	*Genipa americana* L.	Jenipapo
TsAR	*Talisia esculenta* (A.St.-Hill.) Radlk	Pitomba
AcLE	*Acrocomia aculeata* (Jacq.) Lodd. Ex Mart.	Macaúba
Byr	*Byrsonima verbascifolia* (L.) L.C.Rich	Murici
AaAR	*Alibertia edulis* (L.C.Rich) A.Riche ex DC.	Marmelada de Bezerro

2.2. Data Analysis

For the problem analyzed here, the comparison of the four morphological features—trees' percentage of survivors (SUR), average diameter at breast height (DBH), average total height (HEI), and average number of leaves per branch (LEA)—by means of the fuzzy analytic hierarchy process (FAHP) allowed the assignment of weights to them. Then, the comparison of the species measurements for each criterium resulted in the species performance metrics as shown in Figure 2. The analytic hierarchy process (AHP) is a MCDA method based on priority theory whose main characteristic is the decomposition of a problem into two elements, the criteria, and the alternatives. The criteria are compared to each other in terms of their relative importance to achieve a certain result and then the alternatives are compared to each other according to their performance in relation to each of the criteria. The main limitation of this method is that it is not able to reproduce inaccuracy and uncertainty [60,61]. Fuzzy AHP allows including a measure of inaccuracy in any step of the analysis. This measure is represented by α-cuts delimiting a fuzzy membership function (FMF), which defines a range over a set of possible values for the fuzzy variables. Thus, inaccuracy is incorporated into the assessment procedure, allowing a more coherent approach to the real world, thus influencing the conclusion. Chang [62] proposed a method for synthesizing the model solution and tested the respective algorithm to solve hierarchy problems associated with fuzzy logic.

The SIMOS elicitation method [63] was used to obtain comparison scores of the degree of importance between the criteria. An expert received four cards containing identification of the four criteria and twelve blank cards. He was asked to place the cards containing the criteria identifications in descending order of importance. Each blank card inserted between two criteria indicated the degree of importance of that criterion over the next one. The greater the number of blank cards, the greater the degree of importance, with the absence of cards meaning that the criteria are equally important. The cards with the criteria occupy a certain position, which divided by the total number of cards results in the normalized weight by the SIMOS procedure. To convert these weights into scores according to the Saaty procedure, the change to base eight plus one was used [64]. In this study, the cards' order represented the importance of the criteria that influence the survival of the species in the long run.

To apply the fuzzy AHP technique for the ranking of the tree species, we used the base eight plus one method, referring to the tree with the best performance. The result of the numerator or denominator, depending on the direction, must be rounded to the nearest integer. Therefore, the variable scores of relative survival rates are converted to the Saaty

scale. The advantage of this approach is that it meets the format requirement of the input data established by Saaty and Vargas [65] and the resulting matrix is transitive.
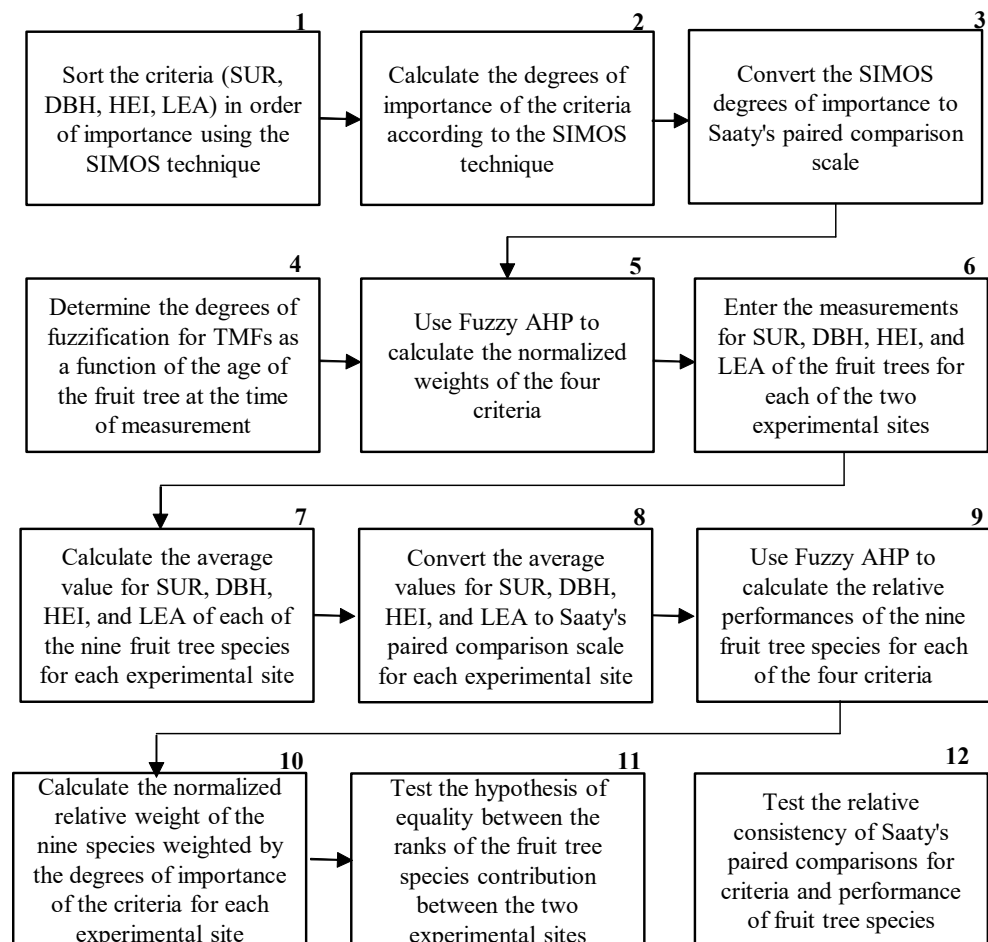
1	2	3
Sort the criteria (SUR, DBH, HEI, LEA) in order of importance using the SIMOS technique	Calculate the degrees of importance of the criteria according to the SIMOS technique	Convert the SIMOS degrees of importance to Saaty's paired comparison scale

4	5	6
Determine the degrees of fuzzification for TMFs as a function of the age of the fruit tree at the time of measurement	Use Fuzzy AHP to calculate the normalized weights of the four criteria	Enter the measurements for SUR, DBH, HEI, and LEA of the fruit trees for each of the two experimental sites

7	8	9
Calculate the average value for SUR, DBH, HEI, and LEA of each of the nine fruit tree species for each experimental site	Convert the average values for SUR, DBH, HEI, and LEA to Saaty's paired comparison scale for each experimental site	Use Fuzzy AHP to calculate the relative performances of the nine fruit tree species for each of the four criteria

10	11	12
Calculate the normalized relative weight of the nine species weighted by the degrees of importance of the criteria for each experimental site	Test the hypothesis of equality between the ranks of the fruit tree species contribution between the two experimental sites	Test the relative consistency of Saaty's paired comparisons for criteria and performance of fruit tree species

Figure 2. Flowchart of the proposed method.

3. Results

Two years after planting, the nine native trees' capacity to survive and their average traits measured—DBH, total height, and number of leaves—varied, as shown in Figure 3. Since these morphological features provide the best estimate of seedling performance after planting [66–68], we specified them as the criteria of the MCDA model to estimate the contributions of species to the sustainable restoration of the biome through new vegetation cover with fruit trees around the reservoir.

The assignment of scores aims to obtain the values of the criteria and the average values of measurements of seedling species so they can be processed by the FAHP algorithm. For this to be possible, we first converted the comparison among criteria values to a 4×4 matrix and the performance of the average values of measurements to a 9×9 matrix compatible with the Saaty scale [65], and then fuzzified them.
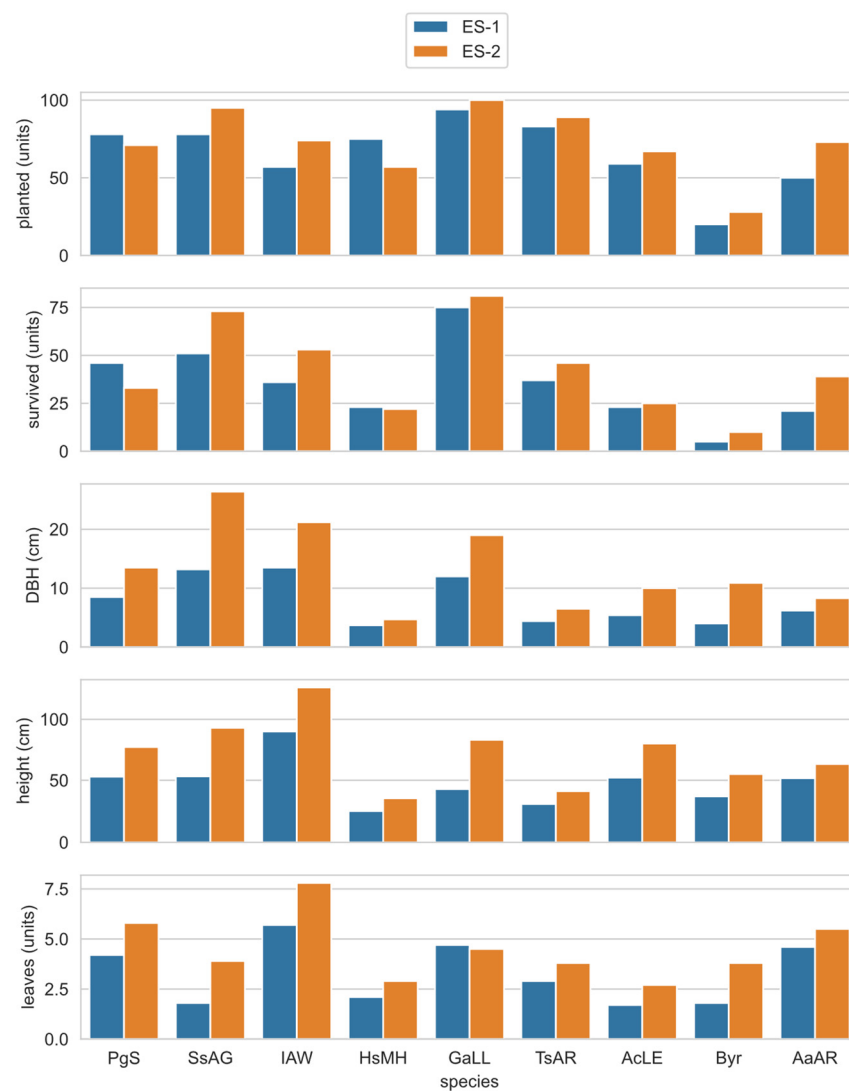
Figure 3. Measurements of seedlings planted after two years for each site.

3.1. Relative Importance among Criteria

The specialist chosen to give an opinion on the degree of relative importance among the four criteria is an agricultural engineer with 40 years of experience in the area of agricultural sciences. (The aim of identifying the fruit trees that would present the best performance for the revegetation of the surroundings of the reservoir led us to omit some representative variables for the environment, such as the stem CO_2 efflux, which contributes to the ecosystem respiration and carbon sequestration [63,69]). Using the SIMOS approach, he ordered the cards according to Figure 4. If a blank card was inserted between two criteria, it means that a displacement occurred in one position in the order of importance. The greater the number of blank cards between two criteria, the larger this displacement is, where just one blank card means "slightly more important", two blank cards mean "more important", and three blank cards means "much more important". The absence of a blank card between two criteria indicates a tie. The position value divided by the sum of criteria positions results in a basic or normalized score. Although the blank card occupies a position, no score is assigned to it since it is not a criterion.
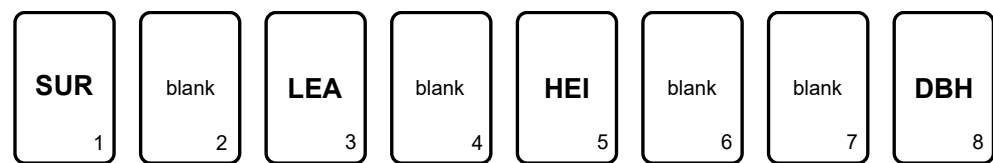
SUR, SURvivors; LEA, LEAves; HEI, HEIght; DBH, Diameter at Breast Height.

Figure 4. Relative comparison between criteria according to the SIMOS technique.

Thus, for any species, the percentage of survivors (SUR) was slightly more important than the average number of leaves per branch (LEA); which in turn was slightly more important than average total height (HEI); this being more important than average DBH. The expert gave the following explanation: "Two years after planting, the plants continue to seek stability in the formation of the regenerative forest (attempt to survive) in an abundant climate in the sun, with rains from October to April and drought from May to September. The soil continues to have *Brachiaria* sp. grass, which was introduced throughout the Cerrado. The percentage of surviving plants in relation to those planted after this period is the most important criterion, as it identifies the ability of these native plants to adapt to the two predominant types of soil surrounding the reservoir, which is highly representative throughout the entire length of the Biome. Very close in degree of importance is the average number of leaves of each species, because the leaves absorb intense local solar radiation through photosynthesis transform thermal energy into chemical energy, producing sugar, starch, and cellulose, which are essential for plant growth. The average height of each species is slightly less important than both of the previous criteria, but high values are essential for the plant to be able to compete favorably with *Brachiaria* sp. and the other species that make up the experiment, competing for space to access solar radiation. The DBH is the least important among these criteria, but significant values denote greater capacity of the wood in the transport of mineral salts and water collected from the soil by the roots." To obtain the matrix of paired comparisons shown in Table 2, we used base eight plus one according to the approach proposed by Ribas and Silva Rocha [64]. On the Saaty scale, whose domain ranges from 1/9 to 9, when comparing two elements, the unit value means equality, so to measure the comparative distance between such elements, it is necessary to subtract them and add one. On this same scale, the reverse situation is represented by the reciprocal of the value, so if the value 2 means that element A is slightly more important than B, the value 1/2 will mean that element B is slightly less important than A. In this way, reorganizing the matrix's differences between the four criteria in the new base will produce the input data organized in accordance with the Saaty pairwise comparison matrix, providing values suitable for calculating weights by the FAHP method. The advantage of this approach is that the resulting matrix of Table 3 is transitive.

Table 3. Matrix of paired comparisons among criteria.

	SUR	LEA	HEI	DBH
SUR	1	2	3	5
LEA	1/2	1	2	4
HEI	1/3	1/2	1	3
DBH	1/5	1/4	1/3	1

3.2. Comparison of Fruit Tree Species Relative to Each Other

To change the scale for a given species, it is necessary to multiply the species measure by eight and then divide it by the highest survival rate among all species. The result must be added to one and rounded to the nearest integer number. The matrix of paired comparisons was constructed in the same way as for the criteria of the previous step. Again, the resulting matrix was compatible with the Saaty scale and could be used as input for the FAHP method. For example, Table 4 shows the matrix of paired comparisons of seedlings

planted at the ES-1 site in relation to the survival criterion (SUR), being similar to the other criteria and the ES-2 site.

Table 4. ES-1 survival (SUR) rates converted to the Saaty pairwise comparison matrix.

	PGs	SsAG	IAW	HsMH	GaLL	TsAR	AcLE	BgT	AeAR
PGs	1	1/2	1	4	1/3	3	3	4	3
SsAG	2	1	2	5	1/2	4	4	5	4
IAW	1	1/2	1	4	1/3	3	3	4	3
HsMH	1/4	1/5	1/4	1	1/6	1/2	1/2	1	1/2
GaLL	3	2	3	6	1	5	5	6	5
TsAR	1/3	1/4	1/3	2	1/5	1	1	2	1
AcLE	1/3	1/4	1/3	2	1/5	1	1	2	1
BgT	1/4	1/5	1/4	1	1/6	1/2	1/2	1	1/2
AeAR	1/3	1/4	1/3	2	1/5	1	1	2	1

For the matrix of paired comparisons between criteria and for the performance matrices of the seedling species in relation to each of the criteria in both sites, the fuzzy values were calculated upward and downward by a triangular membership function. The criterion for establishing the fuzzification degree (δ), was based on the number of years elapsed between measuring the survival rate and planting the seedlings, equal to 3.0 for one to three years, 2.0 for four to five years, and 1.5 for a period greater than five years. Since the measurement at both sites took place two years after planting, the value set for δ was equal to 3.0.

In the next step, the values of the synthetic extensions were calculated according to the FAHP method and used to calculate the possibilities of dominance in the pairwise comparison among the nine species. The resulting entries in the paired comparison matrix and the δ value of 3.0 were input data for the FAHP, whose normalized degrees of importance for the four criteria are shown in Table 5.

Table 5. Normalized degrees of importance for morphological features.

SUR	LEA	HEI	DBH
0.285	0.270	0.248	0.197

3.3. Calculation of Performance of the Fruit Tree Survival Rates at Both Sites

Considering the convexity of the fuzzy set, the Min operator [70] was used to obtain the degrees of possibility. The performances obtained for the nine species relative to the four criteria were normalized to find their estimated contribution to revegetation, as shown in Figure 5 for the sites ES-1 and ES-2, respectively.

3.4. Consistency Analysis of the Pairwise Comparison Matrix

Inconsistency between the scores of the pairwise comparison matrix in Table 4 occurs when the procedure of changing the scale, rounding, and reorganizing the survival rates according to the Saaty table is not efficient, failing to guarantee the transitivity of the matrix of paired comparisons. To ensure that both matrices are transitive, Saaty proposed the calculation of the consistency index [71]. The consistency ratio (CR) is found by comparing the consistency index (CI) of the matrix of pairwise comparisons against the consistency index of a random-like matrix (RI), where RI is the random index table value according to the number of species. The optimal value for the criteria to be evaluated as consistent would be CR $\leq$ 0.1 [71]. For four criteria, the RI value is 0.8816 and for nine species, the RI value is 1.45. We checked the consistency of the survival rates converted to the Saaty pairwise comparison matrices. The results shown in Table 6 demonstrate that criteria ES-1 and ES-2 scores had CR values below 0.1, so all matrices were consistent and transitive.
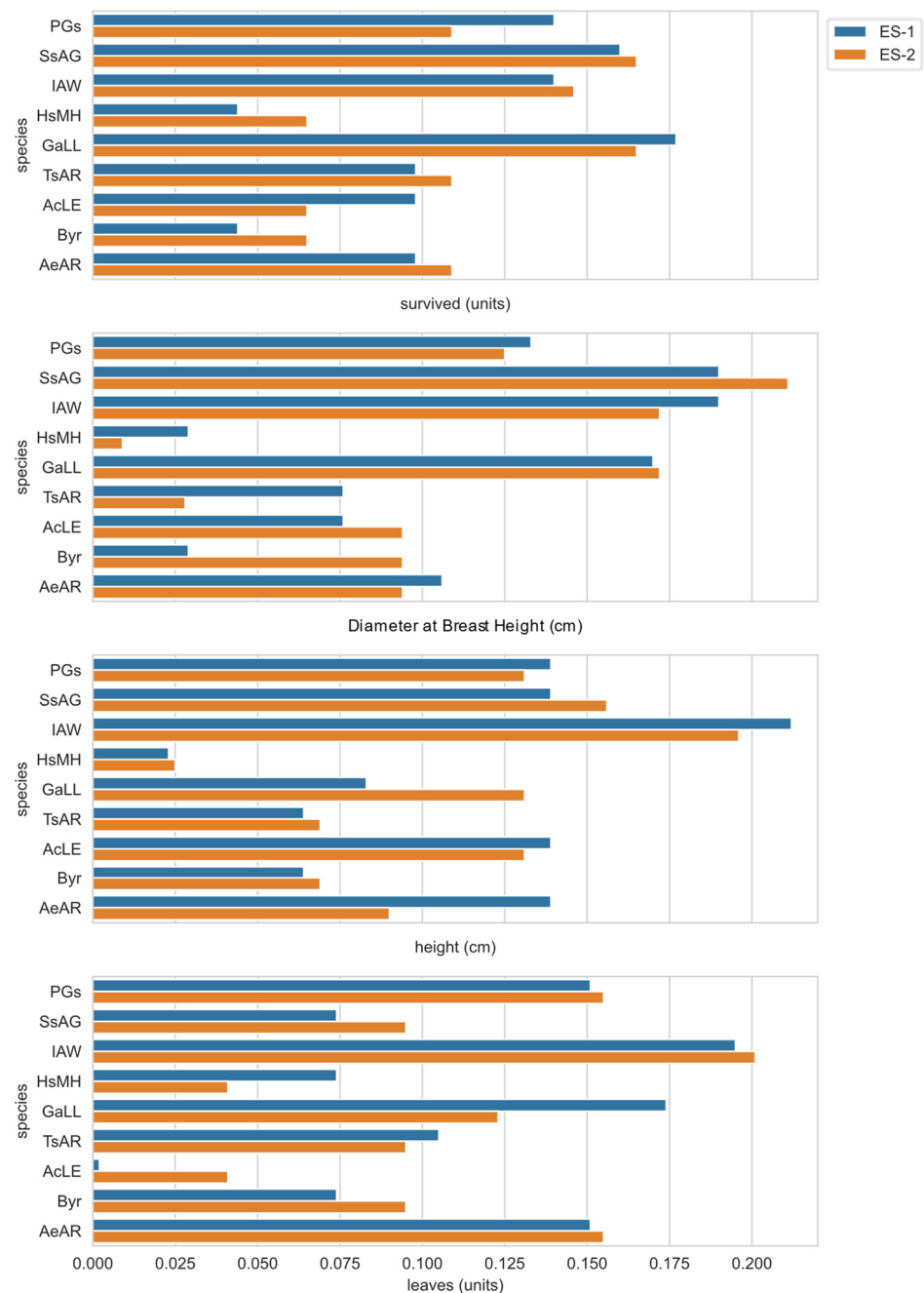
Figure 5. Species performance for each of the criteria.

Table 6. Consistency of the Saaty pairwise comparison matrices for ES-1 and ES-2.

	Criteria	ES-1				ES-2			
		SUR	**LEA**	**HEI**	**DBH**	**SUR**	**LEA**	**HEI**	**DBH**
CI		0.017	0.019	0.025	0.019	0.031	0.012	0.017	0.023	0.031
CR		0.019	0.013	0.017	0.013	0.021	0.008	0.012	0.016	0.022

4. Discussion

The intensity of solar radiation and rainfall are climatological factors that affect the survival of the seedlings. The dry season from May to September is particularly severe in the state of Goias. The average monthly precipitation in July is only 1.7 mm, with a standard deviation of 3.5 mm. On the other hand, the wet season in the summer receives 47 times

higher average precipitation, 882.6 mm. Although the planting in both experimental sites was done in the month of October, the hot weather with an average monthly temperature ranging from 30 °C to 32 °C and intense rainstorms influenced the survival capacity of some species.

As shown in Table 7, five species can be responsible for three-fourths of the revegetation of the reservoir margins if the results of this experiment are confirmed in large-scale planting. The production of Ingá (IAW), Chichá (SaAG), Jenipapo (GaLL), Araçá Vermelho (PgS), and Marmelada de Bezerro (AaAR) would not only serve for sustainable restoration of the biome, but also in some cases could produce an economic gain for the riverside population, since many of them are employed in the food industry.

The Pearson correlation value between the two columns of Table 7 of 0.9634 and the *p*-value close to zero demonstrated that the relative contributions of the nine species to the two types of soil had no significant differences. The same conclusion occurred with the Spearman rank correlations of the relative positions of the species, being equal to 0.90, with a *p*-value near zero. The vegetation and soil are intimately related, while the former protects the soil surface against water and wind erosion, induces the transfer of nutrients to the soil and provide surface soil enhancement [72], the latter is essential for the establishment of plant communities [73]. Because the proportion of surviving trees two years after planting was approximately equal between the two sites (53% for ES-1 and 58% for ES-2), we can state that the ability of the fruit trees to survive did not depend on the type of soil (between Latosol and Cambisol, the two predominant soils around the reservoir). Vegetation and soil are so closely related that it is hard to identify cause-and-effect relationships. For instance, vegetation can protect soil surface against erosion and influence the transfer of nutrients to the soil solution, especially iron and aluminum, adding organic components to the soil. The Latosol of ES-1 is highly weathered and has low natural fertility and a limited reserve of nutrients. It tends to have good physical but poor chemical properties relative to plant growth. The good physical properties are mainly due to high aggregate stability. Strong aggregate stability allows water and air to move through the soil readily and permits roots to penetrate with little resistance. The Cambisol of ES-2, on the other hand, is characterized by low natural fertility and high aluminum saturation. It has a high content of gravel and cobblestone [74]. The biome of ES-1 and ES-2 is classified according to its vegetation and physiognomies as "dirty field" and riverine forest. The latter aspect is ubiquitous throughout the Brazilian Cerrado biome, where nearly all water bodies are fringed by forests. This forest network is determined by the year-round high soil moisture, which despite the long dry season in the region, provides a suitable habitat for a large number of typical moist forest species. Soil moisture is one factor affecting plant performance, mostly restricted to soils that are well drained throughout the year, commonly causing pronounced physiognomic and floristic changes in the case of seasonally waterlogged grasslands. Where inter-fluvial lands are bordered by veredas (marshy grasslands), it is common to observe a decline in mean tree height and increased density of woody plants toward the land margin, where a distinct community of native tree species that are more resistant to soil saturation occurs. Another factor is the aluminum in the soil. The levels of this element are high in the dystrophic Brazilian Cerrado soils, making them extremely toxic to most cultivated plants. However, most native species are aluminum-tolerant, as would be expected. The tolerant species include a number of diverse unrelated families that accumulate aluminum in their tissues, particularly in leaves, but also in roots [39]. The roots of the trees, in turn, help to preserve the stability of the slopes on the banks of the reservoir, through hydro-mechanical reinforcement within the rooted zone. The combination of forest species with shrubs and grasses creates a dense mesh that prevents the formation of erosion and siltation along the reservoir [75,76] (Supplementary Materials).

Table 7. Weights of species contributions to the revegetation of sites.

Species	ES-1		ES-2	
PGs	0.141	3rd	0.1302	4th
SsAG	0.137	4th	0.1531	2nd
IAW	0.183	1st	0.1785	1st
HsMH	0.044	9th	0.0377	9th
GaLL	0.152	2nd	0.1465	3rd
TsAR	0.087	6th	0.0796	8th
AcLE	0.078	7th	0.0807	6th
Byr	0.054	8th	0.0799	7th
AeAR	0.124	5th	0.1139	5th

5. Conclusions

Two effects were specified as factors in the proposed model: (1) two experimental sites containing two different types of predominant soil; and (2) 1248 seedlings of nine fruit tree species, randomly dispersed in these two sites, measured by applying four criteria. The model also considered the combined effect involving the criterion weights and the species performance relative to the criteria.

The large-scale agricultural expansion in the state of Goias, stimulated by growing global food demand, has increased deforestation in areas with high potential for production of beef and soybeans. Another factor is paper demand, causing the expansion of planted forests. Currently, only a small part of the original biome remains, most of it located in protected areas such as along riverbanks and in headwater areas. The filling of the Corumbá IV reservoir inundated pasture and cropland and partially flooded riparian forest areas. The occurrence of the exotic invasive grass *Brachiaria* sp. in nearly the entire region, the hot temperature and generally dry weather, the concentration of aluminum in the soil, and the widespread presence of livestock are some of the technical difficulties found in the Brazilian Cerrado in Goias to reforestation with native trees. The natural regeneration of the environment is seriously affected by the presence of *Brachiaria* sp. Due to its aggressiveness and high competitiveness for solar radiation and soil nutrients, whenever an area is converted with this exotic grass for cattle grazing, it is difficult to revert to its original condition with native vegetation. Therefore, its presence in ES-1 and ES-2 sites is one of the main causes of the high mortality rate observed in most seedlings [77,78]. Urban expansion, spread of croplands, commercial tree plantation with Eucalyptus and Pinus, and higher cost of seedlings and maintenance of native trees are additional issues deterring municipal authorities and farmers from sustainable reforestation practices. The planting of native fruit trees scattered in large groves can contribute to the vegetative cycle (flowering, fruiting, ripening), offering wildlife habitats and wildlife corridors, thus increasing biodiversity by enabling aquatic and riparian animals to move along river systems, gradually reintegrating the fragmented landscapes. This action also acts as an erosion buffer and provides shaded areas for leisure activities by riverine communities.

This study showed that the contribution of tree species is independent of the two most common soil types. These findings simplify the decision for extensive plantation around reservoirs with seedlings of native tree species having better survivability. Regardless of biome, instead of replanting riparian forests with exotic trees, Brazilian hydropower companies should use seedlings of native fruit trees, thus providing a short-term solution for wildlife habitat and promoting faster local environmental recovery as a whole.

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