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Litter stock in different areas in the process of ecological restoration intercropped with eucalyptus in the Brazilian Atlantic Forest

Estoque de serapilheira em diferentes áreas em processo de restauração ecológica consorciadas com eucalipto na Mata Atlântica Brasileira

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RESUMO

O objetivo deste trabalho é quantificar e comparar a serapilheira acumulada em áreas em processo de restauração florestal as quais passaram por diferentes manejos. Os diferentes tipos de manejos para a restauração foram: regeneração natural após corte raso de plantio de eucalipto; plantio de espécies nativas após corte raso de plantio de eucalipto; plantio de espécies nativas após corte de 50% de plantio de eucalipto; e floresta secundária (referência). Foram alocadas de forma sistemática 10 parcelas permanentes de 25 x 25 m em cada área, totalizando 40 parcelas (2,5 ha). Posteriormente foi levantada a densidade absoluta de indivíduos arbóreos (ind. ha^{-1}). No centro de cada parcela foi coletada a serapilheira (0,25 x 0,25 x 0,05 m). A densidade do solo foi calculada para cada parcela nas profundidades de 0-5, 5-10 e 10-20. O índice de vegetação de diferença normalizada (NDVI) foi estimado por imagens espectrais obtidas por uma aeronave remotamente pilotada (ARP). Nuvens densas de pontos 3D também foram geradas a partir de fotogrametria aérea digital e os valores de abertura do dossel foram estimados para cada parcela. Em seguida foi calculada a matriz de correlação de Pearson entre os valores de serapilheira acumulada e as variáveis do ambiente abertura do dossel, densidade do solo e densidade absoluta de árvores. A serapilheira acumulada apresentou correlação positiva significativa com o NDVI. Os diferentes sistemas de restauração ecológica sejam consorciados com eucalipto ou somente com espécies florestais nativas não foram eficientes em promover um acumulo de serapilheira semelhante a uma floresta secundária. O eucalipto não competiu com espécies florestais nativas e proporcionou uma maior quantidade de serapilheira acumulada. O NDVI foi o parâmetro que mais se correlacionou com a serapilheira acumulada.

PALAVRAS-CHAVE: recuperação de áreas degradadas; ecologia florestal; solos florestais; NDVI; RPA.

ABSTRACT

The objective of this study was to quantify and compare the accumulated litter in areas undergoing forest restoration that underwent different management methods. The different types of management methods for restoration were: natural regeneration after clear-cutting of eucalyptus plantations; planting of native species after clear-cutting of eucalyptus plantations; planting of native species after 50% clear-cutting of eucalyptus plantations; and secondary forest (reference). Ten permanent plots of 25 x 25 m were systematically allocated in each area, totaling 40 plots (2.5 ha). Subsequently, the absolute density of tree individuals (ind. ha-1) was measured. Litter (0.25 x 0.25 x 0.05 m) was collected in the center of each plot. Soil density was calculated for each plot at depths of 0-5, 5-10 and 10-20. The normalized difference vegetation index (NDVI) was estimated from spectral images obtained by a remotely piloted aircraft (RPA). Dense 3D point clouds were also generated from digital aerial photogrammetry and canopy openness values were estimated for each plot. Then, the Pearson correlation matrix was calculated between the accumulated litter values and the environmental variables canopy openness, soil density and absolute tree density. The accumulated litter showed a significant positive correlation with NDVI. The different ecological restoration systems, whether intercropped with eucalyptus or only with native forest species, were not efficient in promoting litter accumulation similar to a secondary forest. Eucalyptus did not compete with native forest species and provided a greater amount of accumulated litter. NDVI was the parameter that most correlated with accumulated litter.

KEYWORDS: recovery of degraded areas; forest ecology; forest species; NDVI; RPA.

INTRODUCTION

In forest restoration, passive or active models can be used (ZANINNI et al. 2021). In the active successional model, the introduction of native seedlings requires silvicultural treatments and monitoring to ensure greater biodiversity (RODRIGUES et al. 2009). On the other hand, in the passive model, the focus is exclusively on natural regeneration, requiring only fencing and forest protection in some cases (ZAHAWI et al. 2014).

Although restoration methods aim to recreate conditions similar to those of the original ecosystem, ongoing Atlantic Forest restoration projects face numerous challenges due to insufficient diagnostics regarding area management and lack of monitoring (RODRIGUES et al. 2009). One of these gaps is the study of restorations of native species in consortium with eucalyptus.

In areas of mixed eucalyptus plantations with high diversity of native forest species in the Atlantic Forest, AMAZONAS et al. (2018) observed competition for resources such as water, light, and nutrients with eucalyptus, which slowed native species growth, although this was not sufficient to affect their survival or overtake native trees. Competition for water, light and nutrients mainly affects litter deposition and storage.

There are several indicators for evaluating and monitoring forest restoration, with one of the most important and most rapidly and accurately determined being the litter deposited on the soil surface, as litter is considered the primary form of organic matter and nutrient addition to forest soil. 1998). Litter, composed of plant and animal material, exhibits variations in soil deposition patterns influenced by climate, vegetation successional stage, soil fertility and compaction (VITOUSEK & SANFORD 1986), as well as canopy openness and tree density.

We hypothesize that eucalyptus may compete with native forest species for resources such as water, light, and nutrients in ecological restoration sites, potentially affecting litter stocks. In this context, this study aims to quantify and compare litter accumulation in areas undergoing forest restoration that have undergone different management approaches.

MATERIAL AND METHODS

Description of the study area

The study sites were located at Rio Fundo Farm in Itaporanga D'Ajuda and at the rural campus of the Federal University of Sergipe in São Cristóvão, both in Sergipe state, Brazil. The geographic coordinates of the study area of Fazenda Rio Fundo are 11º06'30” South latitude and 37º19'60” West longitude and of the Rural Campus of the Federal University of Sergipe, 10°55' South latitude and 37°11' West longitude.

The annual average temperature is 24.8°C, with minimum and maximum temperatures of 21.4°C and 28.2°C, respectively. The average annual precipitation is 1300 mm (FONTES 2010). The terrain consists predominantly of rolling hills. The original vegetation is semi-deciduous seasonal forest of the Atlantic Forest. The Atlantic Forest that occurs in the study region is a forest typology that includes semi-deciduous and deciduous species such as ingá (*Inga uruguensis Gancho. & Arn*.), amescla (*Protium heptaphyllum* (Aubl.) Marchand), embiruçu (*Pseudobombax grandiflorum* (Cav.) A. Robyns), embaúba (*Cecropia pachystachya* Trécul) and murici (*Byrsonima crassifolia* (L.) Kunth).

The region is dominated by livestock farming (FERNANDES et al. 2017). The predominant soil type in the study areas was classified as a sandy loam Ultisol with moderate A horizon (FONTES 2010).

Description of successional models of forest restoration

The Rio Fundo Farm, located in Itaporanga d'Ajuda, Sergipe, encompasses 1,563.44 hectares and is owned by a pulp and paper manufacturing company. The main activity at Fazenda Rio Fundo is the planting of eucalyptus for firewood production. In 2012, Rio Fundo Farm faced legal action from Brazilian authorities for clearing native vegetation to establish eucalyptus plantations. In 2013, farm managers implemented 38,63 ha of forest restoration (Figure 1).

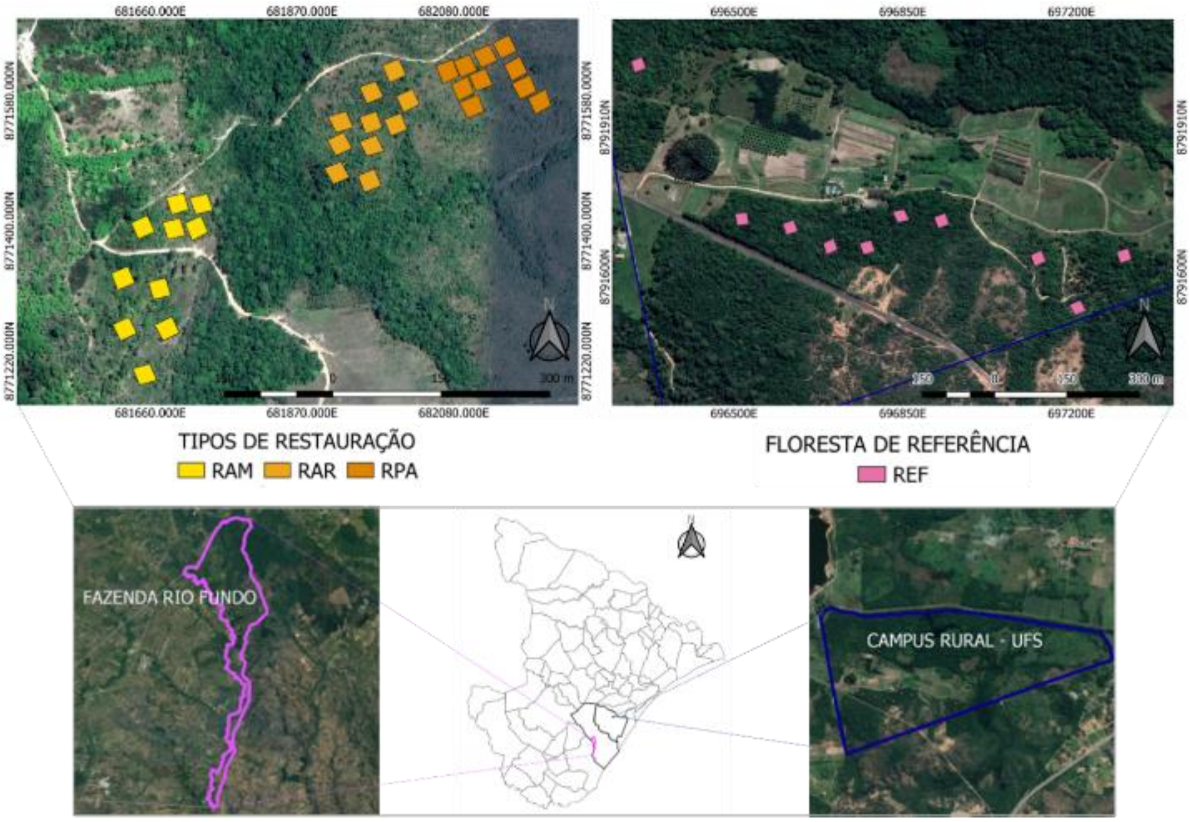

Figure 1. Map of location of plots allocated at Fazenda Rio Fundo, Itaporanga d'Ajuda and at the Rural Campus of the Federal University of Sergipe, São Cristóvão, Sergipe, Brazil.

In the first forest restoration area, all eucalyptus trees were removed, leaving the area completely deforested. Subsequently, 30 native tree species were planted at 4 x 4 m spacing. This treatment was called Active Restoration (RAM).

The following species were planted: *Anadenanthera colubrina, Centrolorobium robustum, Eritroxyllum deciduum, Swartizia apetala, Himatanthus bracteatus, Strypnodendron pulcherrinum, Eschweilera ovata, Cupania vernalis, Cupania oblongfolia, Cecropia pachystachya, Eriotheca pubencens, Inga laurina, Inga marginata, Inga vera, Miconia cinnamomifollia, Guapira opposita, Didymopanax morototonii, Erythrina velutina, Byrsonima sericea, Myrcia selloi, Guazuma ulmifolia, Tapirira guianensis, Vismia brasiliensis, Himatanthus bracteatus, Apeiba tibourbou, Tibouchina granulosa, Mimosa caesalpinifolia, Sapindus saponaria, Curatella americana, Samanea tubulosa, Pterodum emarginatus and Aegiphila klotzchiana.*

In the second forest restoration area, 30 native tree species were planted following selective eucalyptus thinning (approximately 50%), with seedlings established in the gaps created by eucalyptus removal. This process was called active restoration intercropped with eucalyptus (RAR).

In the third forest restoration area, clear-cutting of eucalyptus (100% thinning) was performed, but native tree species were not planted, allowing natural regeneration to occur, which is termed passive forest restoration (PFR).

An efficient forest ecosystem restoration is evaluated by comparing the degree of similarity between the restored site and a relatively undisturbed reference site. Thus, we considered a fourth area as a control or reference area for the study. This area is located in the region and consists of a secondary forest fragment in early successional stage, aged twenty years. This land was formerly used for grazing. This area was called secondary forest (REF). Data collection was carried out in the four areas. The reference site data were used to assess recovery levels and performance across the three restoration treatments.

Survey of field indicators

10 permanent plots (25 m x 25 m) were systematically established in each area, totaling 40 plots (2.5 ha), with equal spacing between them (Figure 1).

In the center of each plot, a 1 m × 1 m (1.0 m^2) wooden frame was placed, and all non-decomposed organic material (leaves, twigs, fruits, and flowers) within it was collected. Subsequently, the samples were packed in paper bags and transported to the Forest Ecology Laboratory (FEL) at the Federal University of Sergipe (UFS), where they were oven-dried at 70 °C for 48 h and their dry matter mass was measured using an analytical balance.

The amount of accumulated litter found on the wooden template (1.0 m^{-2}) was estimated in tons ha^{-1} and the averages obtained in the different ecological restorations were compared with the secondary forest using the Tukey test at 5%, with the aid of Past 4.0 software.

Tree individuals were quantified by counting trees and shrubs with diameter at breast height (DBH = 1.30 m above ground) ≥ 15 cm within the plots. Subsequently, the absolute density of tree individuals (ind. ha^{-1}) was calculated.

In each treatment, 1 undeformed sample was collected using a volumetric ring in each plot at the depths of 0-5, 5-10 and 10-20 cm to determine soil density (SD). The collected material was oven-dried at 105°C for 72 h and weighed using a precision balance (0.01 g). Soil bulk density (Mg m^{-3}) was calculated using the dry mass of each sample (g) and the known volume of each core (cm^{-3}).

RPA data collection

High spatial resolution (~0.04 m) RGB aerial photos were taken during an overflight by a 1” CMOS sensor (20 megapixels) attached to a DJI Phantom 4 PRO multi-rotor platform Remotely Piloted Aircraft (RPA) (SZ DJI Technology Co., Ltd., Shenzhen, China). The images were collected during the forest inventory, in good conditions, with sunny weather and wind speed below 10 ms^{-1}. The flight altitude was set to 120 meters above ground level and 75% frontal and 70% lateral overlap. During the same flight, aerial images in the near-infrared (NIR - 850 nm) and red (R - 660 nm) bands were acquired using a Mapir Survey 3W camera (Peau Productions, Inc, San Diego, CA, USA) mounted on the UAV. Surface reflectance values for NIR and red bands were derived using an empirical method (SMITH & MILTON, 1999) based on a calibration panel and Mapir Camera Control software (https://www.mapir.camera/en-gb/collections/software).

The images acquired by the cameras on board the RPA were processed in the Agisoft Metashape Professional Edition 1.1.0 software (AGISOFT, 2023). During the photo alignment process, 20 ground control points were used along with 10 checkpoints. All points were collected with the Trimble RTK R6 GNSS receiver (www.trimble.com). At the end of processing, the RMSE values for the checkpoints were 0.04 m (horizontal) and 0.11 m (vertical). Image alignment was performed with high accuracy using reference pair selection, with 40,000 key points and 4,000 tie points. For the construction of dense point clouds, medium quality and mild filtering mode settings were applied. The Digital Terrain Model (DTM) was generated from the 3D point cloud. Finally, the 3D point cloud was exported in file format (“.las”) and the MDT in raster format (“.tif”) with a spatial resolution of 0.50 m.

Canopy gaps were determined using normalized point clouds (ground-filtered point clouds) segmented by plot and analyzed with the getforestsgap function in R (R Core Team, 2024) using the ForestgapR package (SILVA et al., 2019). We defined canopy gaps as areas with vegetation height below 2 m and a minimum size of 2 m^2. Canopy openness refers to the percentage of forest canopy unoccupied by crown components, while canopy cover represents the percentage of crown components occupying the forest canopy (MARTINS 2012). The Normalized Difference Vegetation Index (NDVI = (NIR-V)/(NIR+V)) was calculated from the surface reflectance values.

Statistical analysis

To assess litter relationships, Pearson correlation matrices were calculated between accumulated litter, canopy openness, UAV-derived NDVI, soil bulk density, and absolute tree density. A 5% Tukey test was also performed between the different treatments for each parameter evaluated.

RESULTS

Soil bulk density was significantly higher in forest restoration areas compared to secondary forest at 0-5 cm depth. At the 5-10 cm depth, soil bulk density did not differ significantly among the studied areas. At 10-20 cm depth, RAM, RAR, and REF showed significantly higher soil bulk density compared to RPA (Table 1).

Table 1. Soil density of forest restoration areas (RAM, RAR and RPA) and secondary forest (REF).

Attribute	Depth	RAM	RAR	RPA	REF
Soil density (Mg m^{-3})	0-5 cm	1.31b	1.43a	1.33b	1.22c
	5-10 cm	1.50a	1.46a	1.42a	1.53a
	10-20 cm	1.55a	1.50a	1.21b	1.50a

Averages followed by the same letter, in each column, do not differ statistically (Tukey, p > 0.05).

The litter stock of REF was significantly higher than the other areas. It should be noted that this same pattern was observed for absolute tree density, with REF being significantly higher than the other areas (Table 2).

The NDVI in REF was significantly higher than RAR, RPA and RAM. Canopy openness was significantly higher in RPA and significantly lower in REF (Table 3).

Table 2. Accumulated litter and absolute density of trees in forest restoration areas (RAM, RAR and RPA) and secondary forest (REF).

Attribute	RAM	RAR	RPA	REF
Accumulated litter (ton. ha^{-1})	2.80c	4.99b	3.93b	8.45a
Absolute density (ind. ha^{-1})	501c	765b	519c	1263a

Averages followed by the same letter, in each column, do not differ statistically (Tukey, p > 0.05).

Table 3. Attributes obtained from the UAV in forest restoration and secondary forest areas.

Attribute	RAM	RAR	RPA	REF
NDVI	0.36c	0.39b	0.39b	0.59a
Canopy opening (%)	10.44b	9.83b	15,16a	1.66c

Averages followed by the same letter, in each column, do not differ statistically (Tukey, p > 0.05).

Accumulated litter showed a significant negative correlation (P< 0.05) with canopy openness for RAM and REF (Table 4). There was also a significant positive correlation (P<0.05) between accumulated litter and NDVI in all areas (Table 4). Only RAR presents a significant positive correlation (P<0.05) between accumulated litter and soil density (Table 4). RPA showed a significant positive correlation (P< 0.05) between litter accumulation and absolute tree density (Table 4).

Table 4. Accumulated litter and absolute density of trees in forest restoration and secondary forest areas.

Attribute	RAM	RAR	RPA	REF
	Accumulated litter			
Canopy opening	-0,88*	0,65	-0,41	-0,87*
NDVI	0,97*	0,88*	0,95*	0,98*
Soil density	-0,18	0,78*	0,17	0,15
Absolute density	0,18	0,20	0,68*	-0,11

Averages followed by the same letter, in each column, do not differ statistically (Tukey, p > 0.05).

DISCUSSION

Neither native species restoration nor mixed-species plantations with eucalyptus achieved soil bulk density values comparable to secondary forest in the uppermost soil layer (0-5 cm). Although RAR showed higher accumulated litter among ecological restorations, potentially indicating higher soil carbon content, it exhibited the highest soil bulk density at 0-5 cm depth. A greater amount of soil organic matter reduces soil density (BERTOLINI et al. 2019), but this was not observed in RAR.

In RPA at 10-20 cm depth, the lower soil bulk density may be attributed to reduced soil disturbance compared to other restoration methods, along with a more developed eucalyptus root system, which promotes greater rhizodeposition of organic matter.

The accumulated litter biomass and absolute tree density indicate that, even after a decade of ecological restoration, these areas have not yet reached values comparable to those of a 20-year-old early secondary forest. According to DINIZ et al. (2015) recent studies indicate that secondary forests tend to have higher litter stocks, primarily due to greater tree density compared to areas undergoing ecological restoration.

Active ecological restoration with planting of native species (RAM) and accumulated litter was significantly inferior to ecological restorations intercropped with eucalyptus. Thus, intercropping native species with eucalyptus can enhance litter accumulation compared to active restoration using native species alone.

None of the ecological restorations present NDVI similar to secondary forest. The REF treatment was the only one to achieve an NDVI value above 0.5, which is considered optimal. The presence of eucalyptus in RPA and RAR may have optimized the use of resources such as water, light, and nutrients, resulting in higher NDVI values and litter stocks compared to RAM, which contains only native forest species. Different vegetation indices can be used to study and evaluate vegetation. The NDVI has been successfully employed to classify global vegetation distribution, assess ecological and environmental variability, estimate phytomass and litter production, photosynthetically active radiation, and crop productivity (GAMARRA et al. 2016).

After 10 years, passive restoration (RPA) relying on natural regeneration did not achieve canopy closure comparable to RAM and RAR restoration methods or secondary forest (REF). The eucalyptus consortium with native species did not provide greater canopy closure compared to native forest species plantations and secondary forest.

Ecological restoration sites with higher canopy openness showed lower litter stocks compared to the reference ecosystem. This indicates that greater canopy openness represents lower litter stock. In a study by CORREIA et al. (2016) observed a correlation between canopy openness and accumulated litter in ecological restoration sites in the Atlantic Forest of Espírito Santo, where denser canopies resulted in higher litter deposition compared to more open canopies.

Only REF and RAM show a significant negative correlation between canopy openness and accumulated litter. These areas contain only native species with a closed canopy, without eucalyptus individuals, potentially facilitating enhanced ecological succession. Despite the significant negative correlation between canopy openness and litter accumulation in RAM, this area showed lower values for both parameters.

NDVI showed the strongest correlation across all areas, thus representing the most reliable indicator for accumulated litter. NDVI enables the characterization of vegetation biophysical parameters, such as phytomass and vegetation density, with values normalized between -1 and +1 (PONZONI & SHIMABUKURO 2007, GAMARRA et al. 2016), with the value zero referring to non-vegetated pixels. These values represent an indirect measure of the phytomass including the litter under the soil, indicating values of matter and energy present in the sampled area (GAMARRA et al. 2016).

The positive correlation between soil bulk density and accumulated litter in RAR indicates litter accumulation persists even in highly compacted soils. It should be noted that only the 0-5 cm depth showed a significant correlation between soil bulk density and accumulated litter in RAR. Conforme CORREIA et al. (2016), when an ecological restoration area was previously occupied by eucalyptus plantations and subjected to soil compaction during timber harvesting operations, it may exhibit higher levels of soil compaction, even after 10 years of restoration.

The RPA was the only area to show a significant positive correlation between absolute tree density and accumulated litter. This demonstrates that since RPA consists of 91% eucalyptus in its floristic composition (JOSÉ, 2023), the density of trees of this species is a determining factor in the deposition and accumulation of litter on the soil. The low absolute density of trees in RPA also contributes to a greater correlation with the accumulation of litter.

The eucalyptus litter on the forest floor exhibits greater accumulation due to its slower decomposition rate compared to native species, attributed to its distinct chemical composition (lignin and polyphenols), which affects decomposition rates and leads to litter accumulation (O'CONNELL & SANKARAN 1997, AERTS & CHAPIN 2000). Depending on the climate and soil, eucalyptus hinders the decomposition process, favoring the accumulation of litter, due to its own leaf structure influencing the activity of litter decomposers (VALADÃO et al. 2019).

CONCLUSION

The different ecological restoration systems, whether combined with eucalyptus or solely with native forest species, were not effective in promoting litter accumulation comparable to that of a secondary forest.

The eucalyptus did not compete with native forest species and provided a greater amount of accumulated litter.

The NDVI was the parameter most correlated with the accumulated litter.

REFERENCES

AERTS R & CHAPIN FS. 2000. The mineral nutrition of wild plants revisited: a re-evaluation of processes and patterns. In: Advances in ecological research. Cambridge: Academic Press. p.1-67.

AGISOFT. 2023. Agisoft Metashape User Manual: Professional Edition, version 2.0. LLC Agisoft: St. Petersburg, Russia.

AMAZONAS NT et al. 2018. High diversity mixed plantations of Eucalyptus and native trees: An interface between production and restoration for the tropics. Forest Ecology and Management 417: 247-256.

BERTOLINI IC et al. 2019. Propriedades físicas de solo em Floresta Ombrófila Mista sob processo de restauração passiva. Scientia Forestalis 47: 696-707.

CORREIA GGS et al. 2016. Estoque de serapilheira em floresta em restauração e em Floresta Atlântica de tabuleiro no Sudeste Brasileiro. Revista Árvore 40: 13-20.

DINIZ AR et al. 2015. Biomassa, estoques de carbono e de nutrientes em estádios sucessionais da Floresta Atlântica, RJ. Revista Brasileira de Ciências Agrarias 10: 443-451.

FERNANDES MRM et al. 2017. Ecologia da Paisagem de uma Bacia Hidrográfica dos Tabuleiros Costeiros do Brasil. Floresta e Ambiente 24: 1-9.

FONTES JAC. 2010. Caracterização geoambiental da sub-bacia do rio Fundo. Dissertação de Mestrado (Meio Ambiente e Desenvolvimento, São Cristovão: UFS. 120p.

GAMARRA R et al. 2016. Uso do NDVI na análise da estrutura da vegetação e efetividade da proteção de unidade de conservação no cerrado. Revista Ra'e Ga Espaço Geográfico em Análise 37: 307-332.

JOSÉ MB. 2023. Viabilidade econômica e ecológica dos modelos sucessionais de restauração florestal nos serviços ambientais na mata atlântica brasileira. Dissertação de Mestrado (Meio Ambiente e Desenvolvimento), São Cristovão: UFS. 77p.

MARTINS SV. 2012. Ecologia de florestas tropicais do Brasil. 2.ed. Viçosa: Editora UFV. 371p.

O'CONNELL AM & SANKARAN KV. 1997. Organic matter accretion, decomposition and mineralisation. In: NAMBIAR EKS & BROWN AG. (Ed.) Management of soil, nutrients and water in tropical plantations forests. Canberra: ACIAR Australia/CSIRO. p 443-480.

PONZONI FJ & SHIMABUKURO YE. 2007. Sensoriamento Remoto no Estudo da Vegetação. São José dos Campos-: INPE-Editora Parêntese. 280p.

R Core Team. 2024. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Áustria. <https://www.R-project.org/>.

RODRIGUES RR et al. 2009. On the restoration of high diversity forests: 30 years of experience in the Brazilian Atlantic Forest. Biological conservation 142: 1242-1251.

SILVA CA et al. 2019. ForestGapR: An R Package for Airborne Laser Scanning-derived Tropical Forest Gaps Analysis. Methods Ecology and Evolution. 10: 1347-1356.

SMITH GM & MILTON EJ. 1999. The use of the empirical line method to calibrate remotely sensed data to reflectance. International Journal of Remote Sensing 20: 2653–2662.

POGGIANI F et al. 1998. Indicadores de sustentabilidade das plantações florestais. Série Técnica IPEF 12: 33-44.

VALADÃO MBX et al. 2019. Litterfall, litter layer and leaf decomposition in Eucalyptus stands on Cerrado soils. Scientia Forestalis 122: 256-264.

VITOUSEK PM & SANFORD RL. 1986. Nutrient cycling in moist tropical forest. Annual Review of Ecology and Systematics 17: 137-167.

ZAHAWI RA et al. 2014. Hidden costs of passive restoration. Restoration Ecology 22: 284-287.

ZANINNI AM et al. 2021. The effect of ecological restoration methods on carbon stocks in the Brazilian Atlantic Forest. Forest Ecology and Management 481: 118-138.