UNIVERSIDADE FEDERAL DE OURO PRETO
INSTITUTE OF EXACT AND BIOLOGICAL SCIENCES
DEPARTMENT OF BIODIVERSITY, EVOLUTION
AND ENVIRONMENT

MUHSIN HASSAN KAFINGA

Reforestation of riparian fragments and it's influence on the forest structure and carbon sequestration. A case study of Brazilian Cerrado at Hydroelectric Power Plant (UHE) of Volta Grande, in the municipality of Conceição das Alagoas in Minas Gerais, Brazil.

Ouro Preto - MG
March 01, 2023

UNIVERSIDADE FEDERAL DE OURO PRETO
INSTITUTE OF EXACT AND BIOLOGICAL SCIENCES
DEPARTMENT OF BIODIVERSITY, EVOLUTION
AND ENVIRONMENT

TOPIC: "Reforestation of riparian fragments and its influence on the forest structure and carbon sequestration". A case study of Brazilian Cerrado at Hydroelectric Power Plant (UHE) of Volta Grande, in the municipality of Conceição das Alagoas in Minas Gerais, Brazil.

Master's dissertation presented to the Federal University of Ouro Preto as part of the requirements for the Postgraduate Program in Ecology of Tropical Biomes.

Author: Muhsin Hassan Kafinga
Advisor: Profa. Dra. Yasmine Antonini
Co-advisor: Profa. Dra. Alessandra Rodrigues Kozovits
Co-advisor: Profa. Dra. Maria Cristina T.B. Messias

Ouro Preto
March 01, 2023

SISBIN - SISTEMA DE BIBLIOTECAS E INFORMAÇÃO

K11r Kafinga, Muhsin Hassan.
Reforestation of riparian fragments and its influence on the forest structure and carbon sequestration. [manuscrito] / Muhsin Hassan Kafinga. - 2023.
84 f.: il.: color., gráf., tab., mapa. (Série: n/a)

Orientadora: Profa. Dra. Yasmine Antonini.
Coorientadores: Profa. Dra. Alessandra Kozovits Rodrigues, Profa. Dra. Maria Cristina Teixeira B Messias.
Dissertação (Mestrado Acadêmico). Universidade Federal de Ouro Preto. Departamento de Biodiversidade, Evolução e Meio Ambiente. Programa de Pós-Graduação em Ecologia de Biomas Tropicais.
Área de Concentração: Evolução e Funcionamento de Ecossistemas.
ISBN: n/a.
ISSN: n/a.

1. Carbon stocks. 2. Litter. 3. Forest structure. I. Antonini, Yasmine. II. Rodrigues, Alessandra Kozovits. III. Teixeira B Messias, Maria Cristina. IV. Universidade Federal de Ouro Preto. V. Título.

CDU 574

Bibliotecário(a) Responsável: Luciana De Oliveira - CRB 2630

MINISTÉRIO DA EDUCAÇÃO
UNIVERSIDADE FEDERAL DE OURO PRETO
REITORIA
INSTITUTO DE CIENCIAS EXATAS E BIOLOGICAS
PROGRAMA DE POS-GRADUACAO EM ECOLOGIA DE BIOMAS TROPICAIS

FOLHA DE APROVAÇÃO

Muhsin Hassan Kafinga

Reforestation of Riparian Fragments and its Influence on the Forest Structure and Carbon Sequestration

Dissertação apresentada ao Programa de Pós-graduação em Ecologia de Biomas Tropicais da Universidade Federal de Ouro Preto como requisito parcial para obtenção do título de Mestre em Ecologia de Biomas Tropicais

Aprovada em 01 de março de 2023

Membros da banca

Dra. Yasmine Antonini Itabaiana - Orientadora - Universidade Federal de Ouro Preto
Dr. Carlos Victor Mendonça Filho - Universidade Federal do Vale do Jequitinhonha e Mucuri
Dr. Alexandre de Siqueira Pinto - Universidade Federal de Minas Gerais

Profa. Dra. Yasmine Antonini Itabaiana, orientadora do trabalho, aprovou a versão final e autorizou seu depósito no Repositório Institucional da UFOP em XX/XX/XXXX

R. Diogo de Vasconcelos, 122, - Bairro Pilar Ouro Preto/MG, CEP 35402-163
Telefone: (31)3559-1747 - www.ufop.br

AKNOWLEDGEMENTS

I wish to extend my sincere gratitude to Almighty ALLAH (S.W.T) who has given me the ability to write this project. I wish to acknowledge this project to my parents for their overwhelming and uncountable support I received from them, their encouragement and love I received to overcome this important stage in my life. and I pray to Almighty ALLAH (S.W.T) to reward them with Jannatul Firdausi, ameen.

To my seven (7) brothers, for their advice and show of love and constant support to me in all I achieved in my life.

To my loving wife, for the sacrifices she made to me. The constant caring, love, support, encouragement and prayers she has shown to me all the time. May Almighty Allah reward her abundantly, ameen.

To Yasmine, who coordinated the project, her support, guidance and her ability to enable the success of several dissertations under her supervision and mentorship.

To Alessandra Kozovits and Maria Cristina, their precise guidance and learning during my stay in Brazil will not go unnoticed.

To all my teachers and staff in UFOP, thank you so much for the support and love for me.

To the DRI team and my teacher-turned Brother Almiro Ebani, for their efforts in making life easier for me during my stay in Brazil

To FARA/TetFund and KUST Wudil Memorandum of Understanding, for finding me worthy of a scholarship for my masters degree program study in Ouro Preto, Brazil

To my able Mentor and Father Professor Aminu Umar Fagge, for his unconditional mentorship, support, love and many advices given to me throughout our stay.

Lastly, to all my friends and to everyone who somehow participated in another important stage of my life.

TABLE OF CONTENTS (SUMMARY)

INDEX

ABSTRACT

In recent decades, the role played by planted forests in carbon sequestration has been an essential ecosystem service for maintaining the quality of life on the planet. In this study we compared the carbon stocks in soil, litter and aboveground tree biomass in four riparian reforested strips in the surroundings of the State Hydroelectric Power Plant (UHE) of Volta Grande at Minas Gerais, Brazil. The objectives are 1) to evaluate if and how much these new riparian stripes were able to change C stocks in comparison with baseline of neighboring sugarcane with reference areas and 2) to determine if the forest structure of restored strips of riparian forest, of the Volta Grande Reservoir, will change in terms of age and width since restoration. For this we asked the hypothesis that 1) older and narrower strips will present higher C stocks than younger and larger ones and 2) the structure of the vegetation will be different regarding age and size of the riparian stripes. The planted forest strips ranged from 30 to 100 m wide and 10 to 20 years old. Despite this, no significant differences ($p < 0.5$) were found in C stocks among areas. Carbon stock in trees was 86tMgC.ha^{-1}on average. Litter carbon stocks varied from 4.15 to 6.59 MgC.ha^{-1}and in the soil (0-30 cm), the values were about 31 MgC.ha^{-1}. Litter carbon stock was only significantly higher in narrower strips at ($p<0.1$) probably due to an edge effect. The new riparian reforested areas increased C stocks by 40% in the first decade compared to the baseline of the agricultural surrounding environments. This result corroborates other studies and encourages the restoration of riparian zones as an efficient and rapid mechanism for C sequestration, in addition to countless other ecosystem services.

The work was carried out in four actively restored sites and one passively restored riparian stripes, around the Volta Grande Hydroelectric Reservoir (UHE-Volta Grande). We found that the five studied areas different regarding the structure of the restored riparian stripes while the PCA axes explained 63% of the variation with 26.48% in axes one and 37.11 in axes two are influenced by the age and width of the riparian strips. Based on the result obtained, the forest structure of the riparian stripes influenced the response variables at different rates and also the forest structures are influenced by the age and width of the riparian strips.

Riparian buffer restorations are used as management tools to produce favorable water quality impacts, moreover among the many benefits riparian buffers may provide, their application as instruments for water quality restoration rests on a relatively firm foundation of research.

GENERAL INTRODUCTION

Restoration is an assisted recovery process of an ecosystem that has been degraded, damaged or destroyed (Wikipedia, 2022). Restoration of degraded landscapes can contribute to improving ecological integrity, which will provide many additional benefits to biodiversity and human well-being (IUCN, 2016). As a result, 56 countries have pledged to restore 168.4 million ha of deforested and degraded land through the Bonn Challenge, which will sequester an estimated 15.7 Gt CO_2 and generate $48.4 billion USD in economic activity (IUCN, 2018). Primary productivity, biomass, and soil carbon inputs are positively associated with warm, wet climates, and are limited in warm, dry climates, while warm temperatures are also associated with higher rates of decomposition and reduced soil carbon storage (Naiman et al., 2010; Sutfin et al., 2016).

Restoration projects that support economic development and creation of sustainable livelihoods protect biodiversity, because unemployment is often associated with forest degradation and overexploitation (Cao et al., 2017). Thus, restoration is likely to often be a very effective method to mitigate the impacts of human activity on both biodiversity (Qin et al., 2016), and to recover degraded ecosystems (Srivastava &Giri, 2020).

Land use and land cover shape both above ground and soil carbon stock (Laganière et al., 2010). Riparian forest restoration can provide a huge amount of carbon storage benefit, in both the biomass and soil. The extent of this accumulation depends on the environmental features (soil, climate, degradation level) and restoration design (Laganière et al., 2010).

Riparian forests and floodplain areas have been referred to as important carbon sinks, and thus are crucial systems to mitigate the effects of climate change and to provide a regulation ecosystem service. Some of the ecosystem services provided by the riparian forest restoration include carbon sequestration, improvement of ecological integrity, conservation of biodiversity and also improvement of human well-being. Litter produced by the trees helps in nutrient cycling into the soil. Also, another factor which is very important is the bio-indicators which help in screening the health of natural ecosystem in the environment. Carbon uptake by forests reduces the rate at which carbon accumulates in the atmosphere and thus reduces the rate at which climate change occurs. Riparian ecosystems around the world have been severely degraded by anthropogenic activity including altered flows from dams, leaves, and water diversions, and conversion of riparian forests to urban and agricultural development (Nilsson & Berggren, 2000; Perry et al., 2012; Zedler& Kercher, 2005). These activities have resulted in the loss of ecological integrity and numerous ecosystem services.

Forests are the most important part when it comes to carbon dioxide sequestration from the atmosphere sequestering much better carbon in an annual basis than other land-use. Carbon stocks are broadly described as live tree biomass or deadwood (Antonini et al. 2016).

Reforestation of disturbed areas can enhance numerous carbon (C)-based ecosystem services and functions. These include, among other ecosystem services, mitigation of atmospheric CO_2 and climate change by sequestering C into woody biomass where it can be stored for long timescales. Thus, efficacy of carbon sequestration and their contribution on different reforestation system are reviewed in the first chapter.

There has been a widespread interest in quantifying carbon storage as a useful and monetizable co-benefit of riparian restoration, which could contribute to funding that would help increase the pace and scale of riparian forest restoration (Daigneault et al., 2017; Matzek, Puleston, & Gunn, 2015), and in turn, help reach global forest landscape restoration goals (IUCN, 2018).

Native tree plantations were shown to be more effective in accumulating aboveground and soil carbon stocks than natural forest re-growth during the first 50 years, but their higher implementation (tree plantations: US$2,788 vs. natural forest regrowth: US$1,250) and land opportunity (tree plantations: US$324 per year vs. natural forest regrowth: US$106 per year; Molin et al, 2018) costs make them less cost-effective for carbon farming. It is important to note that some researches usually assessed high-diversity plantations of native tree species rather than monoculture tree plantations, to which natural forest re-growth has often been compared (Lewis et al, 2019). In addition, tree plantations were fertilized, weeded, and planted at a regular spacing, which produces an efficient occupation of the deforested area by trees and enhance their growth, resulting in a higher accumulation of biomass per unit area (Brancalion, Meli, et al., 2019). It was reported by (Mora et al. 2018) that variations in soil properties among study plots may have obscured the relationship between soil carbon stocks and restored forest age at landscape level. By providing estimates of average carbon stocks in riparian forest biomass and soil, and demonstrating the rapid rate at which riparian forests can sequester carbon, our results suggest that investing in riparian forest restoration can be a valuable global strategy for contributing to urgent climate change mitigation goals as well as long-term biodiversity conservation and ecosystem services.

Carbon markets first emerged in response to the 1994 Kyoto Protocol (UNFCCC, 2008) which was adopted in December 1997, and began to be enforced in February 2005. The Kyoto Protocol spells out the international need to reduce greenhouse gas (GHG) emissions, namely decrease carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydro fluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6) (UNFCCC, 2021).

Despite the issues with the Kyoto Protocol, which primarily focused on emissions reductions and did not address land-use changes, it put carbon markets on the global stage (The Nature Conservancy, 2018).

The Nature Conservancy outlines in their 2018 report international soil carbon sequestration projects and their potential market value. Markets are shifting thanks to technological advances that allow for soil carbon monitoring in the agricultural sector. Previously, the Kyoto Protocol excluded land-uses changes from the international carbon trading possibly due to the difficulties of measuring carbon on the landscape (The Nature Conservancy, 2018).

Recently, riparian areas have been identified as areas where large-scale carbon sequestration and storage occurs (Doetterl *et al*, 2016; Dybala *et al*, 2019; Maraseni& Mitchell, 2016; Matzek *et al*, 2018).

Besides carbon stock, riparian forests can provide other ecosystem functions. Forest structure usually refers to the way in which the attributes of trees are distributed within a forest ecosystem. Trees are usually long-lived, with different strategies to propagate, grow and die. The production and dispersal of seeds and the associated processes of germination, seedling establishment and survival are important factors of plant population dynamics and structuring. Trees compete for essential resources, and tree growth and mortality are also important structuring processes. In a forest ecosystem, diversity does, however, not only refer to species richness, but to a range of phenomena that determine the heterogeneity within a community of trees, including the diversity of tree sizes. Tree growth and the interactions between trees depend, to a large degree, on the structure of the forest (Harper, 1997).

Structure and diversity are important features which characterize a forest ecosystem. Complex spatial structures are more difficult to describe than simple ones based on frequency distributions. Greater inhomogeneity of species and size within close-range neighborhoods indicates greater structural diversity. The evaluation of forest structure thus informs us about the distribution of tree attributes, including the spatial distribution of tree species and their dimensions, crown lengths and leaf areas. The structure of a forest is the result of natural processes and human disturbance. Important natural processes are species-specific tree growth, mortality and recruitment and natural disturbances such as fire, wind or snow damage. In addition, human disturbance in the form of clearfellings, plantings or selective tree removal has a major structuring effect. The condition of the majority of forest ecosystems today is the result of human use (Kareiva et al, 2007).

The degradation or invasion of natural ecosystems often results in the formation of so-called novel ecosystems with new species combinations and the potential for change in ecosystem functioning. These ecosystems are the result of deliberate or inadvertent human activity. As more of the Earth's land surface becomes transformed by human use, novel ecosystems are increasing in importance. Natural ecosystems are disappearing or are being modified by human use. Thus, forest structure is not only the outcome of natural processes, but is determined to a considerable extent by silviculture (Hobbs et al, 2006).

Forest landscapes are an essential part of development and climate change action, contributing to the livelihoods of 1.3 billion people as well as the health of our planet. But forests are under threat. The demand to use land for agriculture drives deforestation. Transportation, energy infrastructure, mining and wood-based energy also affect forest cover. More than 100 countries have recognized the need for stronger forest protection and have included actions related to land-use change and forests in their Nationally Determined Contributions (NDCs). Enhanced efforts to preserve forests and restore degraded lands can help address an expected global gap in emission reductions. Trees growing in crop fields help to reduce soil erosion, and can serve as sources of fertilizer, while reducing water and heat stress affecting crops. Trees can also increase households' food security by providing food and fodder when crops become unavailable, and increase people's coping capacity by providing assets that can be harvested in times of need (World Bank, 2017).

Forests are more biologically diverse than any other land-based ecosystem. Conserving and sustainably using our forests protects more than two-thirds of all land-based animal and plant species. Biodiversity underpins the health and vitality of forests and is the basis for a wide range of ecosystem services necessary for people's livelihoods and well-being. Biodiversity of degraded forests can often be successfully restored if the factors that lead to forest degradation can be effectively controlled. More than 1.6 billion people depend on forests for their livelihoods; forests are home to an estimated 300 million people around the world. Forest biodiversity is being lost at an alarming rate: up to 100 animal and plant species are lost every day in tropical forests (FAO, 2010). Forests are amazingly rich in biodiversity. It is estimated that two thirds of all land-based species live in forests, or depend on them for their survival. Presently, around 1.75 million species of plants, animals and fungi are known to science.

However, it is estimated that there could be up to 100 million species, most of them in tropical rainforests. Forest biodiversity sustains human well-being through a multitude of ecosystem services (FAO, 2010).

Forest management is the deliberate application of a system of management into the conservation, nurturing, harvesting and renewal of forest resources. It is essential for providing sustainable flow of forest resources to industry or other consumers. Without management, forest resources will be completely depleted. WRI (2000) reposed that forests must be regulated by a management plan, but procedures and regulation of these plans remained undefined.

Riparian buffer restorations are used as management tools to produce favorable water quality impacts, moreover among the many benefits riparian buffers may provide, their application as instruments for water quality restoration rests on a relatively firm foundation of research.

The idea to restore the riparian forest in the banks of Volta Grande Reservoir comes into being in the year 1990 due to an agreement between Federal University of Lavras and Hydro-electric Energy Company in Minas Gerais, Brazil (CEMIG). Some of the challenges encountered include seed production and acquisition, participation of land owners in restoring the riparian forest and also fire and cattle grazing. But most of the problems were arrested by the help of the laboratories in CEMIG, organization of lectures and press conference to the land owners. It was reported earlier that most of the problems face by the riparian forest in the riparian forest of the Volta Grande reservoir includes high agricultural activity, and also the human and livestock activity (JR Silveira, 2016).

As this area used to be occupied by Agricultural and livestock activities and also having a sugarcane plantation initially. We used the sugarcane area to serve as the baseline or the land use of our research. Sugarcane plantation helps these areas to increase or accumulate at a faster rate more carbon in the soil.

In this way, the goal of this dissertation was to evaluate and to compare the Carbon stock and structure of reforested riparian areas with different ages and planted under different widths.

So, in Chapter 1; we compared the carbon stocks in a chronosequence of reforested areas with different planting strips widths, added to a sugarcane plantation and a reference area. We hypothesized that;

a) Carbon stocks (tree biomass, litter and in soil) are influenced by different restored riparian forest ages and width

b) Carbon stocks is higher in reforested patches than in sugarcane plantation

And in Chapter 2; we evaluated if the forest structure of these reforestations changed along the time (reforestation age) and under the different width. We hypothesized that;

a. Older and wider reforestation areas will present higher tree richness, tree abundance, tree density and above ground biomass as well as higher tree richness.

REFERENCES

1. Antonini Y& Martins R (2016): Can pollination syndromes indicate ecological restoration success in tropical forests? Restoration Ecology, 24(3), 373-380.
2. Brancalion PHS, Meli P, Tymus JRC, Lenti FEB, Benini M, Silva APM, Holl KD (2019): What makes ecosystem restoration expensive? A systematic cost assessment of projects in Brazil. Biological Conservation, 240, 108274. https://doi.org/10.1016/j.biocon.2019. 108274
3. Cao S, Shang D, Yue H, & Ma H (2017): A win-win strategy for ecological restoration and biodiversity conservation in Southern China. *Environmental Research Letters*, *12*.
4. Daigneault AJ, Eppink FV, & Lee WG (2017): A national riparian restoration programme in New Zealand: Is it value for money? *Journal of Environmental Management*, *187*, 166–177. https://doi.org/10.1016/j.jenvman.2016.11.013
5. Doetterl S, Berhe AA, Nadeu E, Wang Z, Sommer M, & Fiener P (2016): Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth-Science Reviews*, *154*, 102□122. https://doi.org/10.1016/j.earscirev.2015.12.005
6. Dybala KE, Clipperton N, Gardali T, Golet GH, Kelsey R, Lorenzato S, Yarris GS (2017): Population and habitat objectives for avian conservation in California's Central Valley riparian ecosystems. *San Francisco Estuary and Watershed Science*, *15*(1), 5. https://doi.org/10.15447/sfews.2017v15iss1art5
7. Dybala KE, Matzek V, Gardali T, & Seavy NE (2019): Carbon sequestration in riparian forests: A global synthesis and meta-analysis. *Global Change Biology*, *25*(1), 57□67. https://doi.org/10.1111/gcb.14475

8. FAO 2010: Global Forest Resource Assessment 2010 (FAO 2010): www.fao.org/forestry/fra/en
9. Harper JL (1977): Population biology of plants. Academic, London
10. Hobbs RJ, Arico S, Aronson J, Baron JS, Bridgewater P, Cramer VA, Epstein PR, Ewel JJ, Klink CA, Lugo AE, Norton D, Ojima D, Richardson DM, Sanderson EW, Valladares F, Vil`a M, Zamora R, Zobel M (2006): Novel ecosystems: theoretical and management aspects of the new ecological world order. Global Ecol Bio geogr 15:1–7
11. International Union for the Conservation of Nature (IUCN) (2016): *Restoration of forest ecosystems and landscapes as contribution to the Aichi Biodiversity Targets*. Gland, Switzerland: IUCN. Retrieved from https://portals.iucn.org/library/sites/library/files/documents/2016-078.pdf.
12. International Union for the Conservation of Nature (IUCN) (2018): Bonn Challenge. Retrieved from http://www.bonnchallenge.org/. October 1, 2018.
13. IPCC Intergovernmental Panel on Climate Change (2000): *Summary for policymakers: Land use, land-use change, and forestry: A special report of the Intergovernmental Panel on Climate Change*. Washington, DC: Intergovernmental Panel on Climate Change. Retrieved from: https://www.ipcc.ch/pdf/special-reports/spm/srl-en.pdf
14. JR Silveira, Barlow J, Lennox GD, Ferreira J, Berenguer E, Lees AC, Nally RM, Thomson JR, Ferraz SF, Louzada J, Oliveira VH, Parry L (2016): Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. Nature. Jul; 535(7610):144-7.
15. Kareiva P, Watts S, McDonald R & Boucher T (2007): Domesticated nature shaping landscapes and ecosystems for human welfare. Science 316(5833):1866–1869

16. Laganière J, Angers DA, & Paré D (2010): Carbon accumulation in agricultural soils after afforestation: A meta-analysis. *Global Change Biology*, *16*(1), 439–453. https://doi.org/10.1111/j.1365-2486.2009. 01930.x
17. Lewis SL, Wheeler CE, Mitchard ETA, & Koch A (2019): Restoring natural forests is the best way to remove atmospheric carbon. Nature, 568, 5–28. https://doi.org/10.1038/d41586-019-01026-8
18. Maraseni TN & Mitchell C (2016): An assessment of carbon sequestration potential of riparian zone of condamine catchment in Queensland, Australia. *Land Use Policy*, *54*, 139□ 146. https://doi.org/10.1016/j.landusepol.2016.02.013
19. Matzek V, Stella JC, & Ropion P (2018): Development of a carbon calculator tool for riparian forest restoration. *Applied Vegetation Science*. https://doi.org/10.1111/avsc.12400.
20. Molin PG, Chazdon R, Ferraz SFB, & Brancalion PHS (2018): A landscape approach for cost-effective large-scale forest restoration: Journal of Applied Ecology, 55(6), 2767–2778. https://doi.org/10.1111/1365-2664.13263
21. Mora F, Jaramillo VJ, Bhaskar R, Gavito M, Siddique I, Byrnes JEK & Balvanera P (2018): Carbon accumulation in neo-tropical dry secondary forests: The roles of Forest age and tree dominance and diversity. Ecosystems, 21(3), 536–550. https://doi.org/10.1007/s10021-017-0168-2
22. Naiman RJ, Decamps H & McClain ME (2010) *Riparia: Ecology, conservation, and management of streamside communities*. Burlington, MA: Academic Press.

23. Nilsson C& Berggren K (2000): Alterations of riparian ecosystems caused by river regulation. *Bioscience*, *50*(9), 783–792. https://doi.org/10.1641/00063568(2000)050[0783:AORECB]2.0.CO;2

24. Perry LG, Andersen DC, Reynolds LV, Nelson SM & Shafroth PB (2012): Vulnerability of riparian ecosystems to elevated CO2 and climate change in arid and semiarid western North America. *Global Change Biology*, *18*, 821–842. https://doi.org/10.1111/j.1365-2486.2011.02588.x

25. Puleston C, Matzek V and Gunn J (2015): Can carbon credits fund riparian forest restoration? *Restoration Ecology*, *23*(1), pp.7-14.

26. Qin H, Wang Y, Zhang F, Chen J, Zhang G & Dong G (2016): Application of species, phylogenetic and functional diversity to the evaluation on the effects of ecological restoration on biodiversity. *Ecological Informatics*, *32*, 53–62. https://doi. org/10.1016/j.ecoinf.2016.01.004. Reductions for the future: State of the voluntary carbon markets 2019. Retrieved from file:///C:/Users/Pedro/Downloads/20191205-FT-EM-SOVCM-2019-Report MarketOverview-web.pdf

27. Srivastava P & Giri N (2020): Restoration of forest in a changing climate. *Climate Change and Environmental Sustainability*, *8*(2), 261–266. https://doi.org/10.5958/ 2320-642X.2020.00028.9

28. Sutfin NA, Wohl EE, & Dwire KA (2016): Banking carbon: A review of organic carbon storage and physical factors influencing retention in floodplains and riparian ecosystems. *Earth Surface Processes and Landforms*, *41*(1), 38–60. https://doi.org/10.1002/esp.3857.

29. World Bank. World development report (2017): Governance and the law. The World Bank; 2017 Jan 23.

30. World Resources Institute (2000) World Resources 2000-2001: People and ecosystems: The fraying web of life. Report Series. 41p. [http://pubs.wri.org/pubs_pdf.cfm?PubID=3027]

31. Zedler JB, Kercher S (2005): Wetland resources: status, trends, ecosystem services, and restorability. Annual Rev. Environmental Resources. Nov 21; 30:39-74.

CHAPTER 1

NEW RIPARIAN FOREST FRAGMENTS INCREASE CARBON STOCKS BASELINE

Authors: Kafinga M.H[1,5], Martins I[1], Antonini Y[2], Messias MCTB[2],Pinto AS[3], Leite MGP[4], Kozovits AR[2*].

1- Post-Graduate program in Ecology of Tropical Biomes, Federal University of Ouro Preto, 2-Department of Biodiversity, Evolution and Environment, Federal University of Ouro Preto, 3- Department of Ecology, Federal University of Sergipe, 4- Department of Geology, Federal University of Ouro Preto, 5- Department of Forestry and Wildlife, Kano University of Science and Technology, Wudil, Nigeria.

***Corresponding author: kozovits@ufop.edu.br**

ABSTRACT

In recent decades, the role played by planted forests in carbon sequestration and storage has been recognized as an essential ecosystem service for maintaining the quality of life on the planet. Although it is already known that restoration of riparian forests potentially accelerates C sequestration compared to upland plantations, the models still deal with many uncertainties, a reflection of the insufficient database, especially in the tropics. In this study we compared the carbon stocks in soil, litter and aboveground tree biomass in four riparian reforested strips in the surroundings of the State Hydroelectric Power Plant (UHE) of Volta Grande in Minas Gerais, Brazil. The planted forest strips ranged from 30 to 100 m wide and 10 to 20 years old. Despite this, no significant differences ($p < 0.5$) were found in C stocks among areas. Carbon stock in trees was 86tMgC.ha^{-1}on average. Litter carbon stocks varied from 4.15 to 6.59 MgC.ha^{-1}and in the soil (0-30 cm), the values were about 31 MgC.ha^{-1}. Litter carbon stock was only significantly higher in narrower strips at ($p<0.1$) probably due to an edge effect. Our results suggest that factors such as the management and protection of the reforested area, use of the area for recreational activities and the surrounding landscape seem to exert a strong influence on the quality of the reforested fragments, adding variability to the sampled data, what may overcome the effects of age and width of planting strips on the C sequestration. Regardless, the reforested areas in the new riparian zones created on the banks of the dam increased C stocks by 40% in the first decade compared to the baseline of the agricultural surrounding environments. This result corroborates other studies and encourages the restoration of riparian zones as an efficient and rapid mechanism for C sequestration, in addition to countless other ecosystem services.

Key words: C stocks, forest plantation, effect of surrounding matrix, litter

1. INTRODUCTION

Global efforts to mitigate climate change seem to be generating positive results since the annual rate of increase in greenhouse gas emissions (GGE) fell from an average of 2.1% between 2000 and 2009 to 1.3% between 2010 and 2019. However, the increase of about 59 giga-tons of CO_2-equivalent in that last decade and projections for the near future demonstrate that the worldwide national climate commitments may be not feasible or even sufficient to guarantee the level required for the 1.5°C threshold by 2030, as established by the Paris Agreement (IPCC 2022).

Regarding strategies involving ecosystem-based adaptation measures, there is room for improving ecological restoration methods for the purpose of sequestering carbon in trees and soils, especially in tropical developing countries. Accurate information on how much and how quickly carbon can be stored in both vegetation and soil under different managements and environmental conditions, cost-effectiveness ratios and adaptation to climate change scenarios are more than ever highly demanded (Koch & Kaplan 2022, Zanini et al. 2021, Brancalion et al. 2020, Philipson et al. 2020, Dybala et al. 2018) to reduce the uncertainties of the models and increasing confidence in resulting patterns. All that needs must be reflected in a significant increase in research funding in this sector, which may not occur on the scale required in socially and economically vulnerable countries (IPCC 2022, WRI Brasil, 2022).

Among several vegetation types under restoration, riparian forests have been identified as the ecosystems with the greatest potential for increasing carbon sequestration in the short-term (Brancalion et al. 2020, Matzek et al. 2020). Dybala et al. (2018) found that the establishment of riparian forest may more than triple the carbon stock baseline of unforested soils. Moreover, actively planting substantially speeds up the biomass carbon accumulation in the first ten years through at least two times faster growth rates than those of naturally regenerating riparian forests. Despite occupying only 1% of the global area, if entirely covered by forests, with the expansion of restoration activities, it could represent 3 to 7% of the current global C stock in vegetation, helping countries move closer and faster to C reduction targets desired for the next decades (Dybala et al. 2018). Such estimates, however, still carry a great degree of uncertainty due to the small database available, especially for some ecosystems, and discrepancies in the methods of data collection and interpretation for both unmanaged primary and natural or planted secondary forests (Gundersen et al. 2021, Lewis et al. 2019, Dybala et al. 2018, Luyssaert et al. 2008). Regionally, the effects of forest restoration on C stocks are expected to vary widely in response to the complex interplay of factors that affect C sequestration such as climate, inundation regimes, initial soil conditions, types of management and protection of areas, biodiversity, age and size of fragments, surrounding landscapes features (Koch & Kaplan 2022, Zanini et al. 2021, Brancalion et al. 2020, Matzek et al. 2020, Dybala et al. 2018, Robinson et al. 2015, Holl & Aide 2011, Wilson et al. 2011). Research approaches that try to encompass part of this complexity demand more time and amount of financial resources, which partly explains the low percentage of studies that present data on carbon sequestration in soil and vegetation in restored forests, especially in countries with high diversity of environmental conditions and that are economically more vulnerable (Guerra et al. 2020, Dybala et al. 2018, Ruiz-Jaen& Aide 2005). Indeed, financial constraints can be an obstacle to filling knowledge gaps and promoting practices that accelerate forest restoration in developing countries (IPCC 2022, Philipson et al. 2020, Brancalion et al. 2020). The cost-effectiveness relationship involved in active and passive restoration projects is a relevant point that needs further maturation and must be evaluated on a case-by-case basis (Philipson et al. 2020, Brancalion et al. 2020). When considering the short-term benefits, such as the potential for rapid accumulation of C, and the long-term ones, such as the conservation of biodiversity and restoration of valuable ecosystem services for the human societies, the installation cost of planted riparian forests might be offset (Philipson et al. 2020, Brancalion et al. 2020, Dybala et al. 2018).

- The installation of riparian forests in topographical zones originally occupied by another type of vegetation, an action forced by the creation of hydroelectric reservoirs, offers an interesting opportunity to study. Around the Volta Grande hydroelectric dam, Brazil, the planting of discontinuous forest strips with 30 and 100m wide and 10 to 20 year-old on areas that were cultivated with sugar cane has shown to be very effective for creating structural and functional heterogeneity, allowing the recolonization of invertebrate and vertebrate fauna, native plant species recruitment, increasing complexity of biotic interactions, soil erosion control and an option for leisure for local populations (Antonini et al. 2022, Londe et al. 2021, Silva et al. 2021, Londe et al. 2020, Araújo et al. 2018, Corrêa et al. 2017). Increased availability of light to plants along edges allows more plants to be supported (greater diversity) and increases productivity. The region is located in the Cerrado biome, a hotspot highly fragmented mainly by agro-pastoral activities. The objective of this chapter was to evaluate if and how much of those new riparian forest were already able to change C stocks in comparison with the baseline of neighboring sugarcane areas with reference areas and how the age and width of the planting strips affect such performance. We hypothesize that (1) older and narrower fragments (with greater edge effect) will present higher C stocks than the younger and larger ones and that (2) even the very young reforested areas (10 years-old) will already be able to increase carbon stocks in the soil in relation to the levels of the surrounding sugarcane areas. Our results may confirm that the planting of riparian forests can play a relevant role in accelerating carbon sequestration, helping the country towards compliance with the signed agreements.

2 MATERIALS AND METHODS

2.1 Study Area

The study was carried out in an area of remaining riparian forest around the Volta Grande Hydroelectric Power Plant (UHE) located on the Grande river near the MG427 km 40 Highway, between the municipalities of Conceição das Alagoas (Minas Gerais state) and Miguelópolis (São Paulo state) (Figure 1).

Figure 1: Location of UHE Volta Grande. Image: use and occupation represented by a 6 km buffer around the reservoir. Highlight for the location of the study areas (Noboro, Santa Barbara, Figueira and Delta).

The climate of the region is classified by Köppen as Kwa, with an average annual temperature between 22°C and 24°C. The average annual precipitation over the last 20 years encompassing the study period is close to 1500 mm, with a well-defined dry season, comprising the months from April to September and a rainy season from October to March (Figure 2).

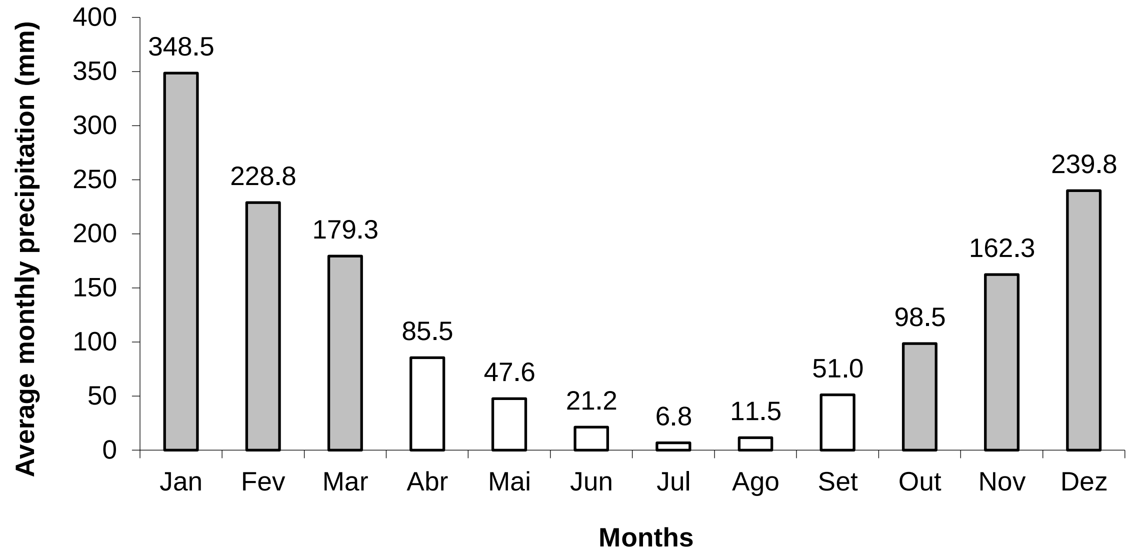


Figure 2: Average monthly rainfall in the years 1994-2014 of the study area. Source: UHE Porto Colombia (Furnas Centrais Elétricas S/A). Gray bars represent the rainy season and white bars the dry season.

The predominant soil type in the region is eutrophic purple latosols (Filardi et al, 2007; Ferreira, 2009). Most of the original riparian vegetation was lost by flooding events or removal promoted by the construction of the reservoir. After the construction of the reservoir, a process of recovery through the planting of seedlings of the new riparian areas began in the year 1991. There was no sugarcane plantation during seedling plantings but initially the area was used to be a sugarcane plantation. The area consists of Agricultural and livestock activities aimed, among other objectives, to reduce erosion. For the present study four reforestation areas were selected. These areas had different ages and widths (Table 1, Figure 1).

Table1: Characteristics of the studied riparian forest areas located around the Volta Grande HPP. Age and width of the planted fragments, location in relation to the reservoir, management after planting, main land use of surroundings and inside the fragment (Forest protection), geographic co-ordinates. Use and occupation maps and further details on reforestation is founded in Antonini & Martins (2016)

Site	Age of planting (years)	Width (m)	Location	Forest Management	Forest protection	Landscape Matrix	Coordinates (UTM)
Santa Bárbara	10	30	Reservoir shore	No managment after planting	Protected	Sugarcane	22K - 798082 / 7775015
Delta	10	100	Reservoir shore	No manegement after planting	Forest trails, shore fishing spots	Presence of huts on the shore, and houses in the upland Sugarcane	23K - 208838 / 7787209
Noboro	20	30	Reservoir shore	Weed control and seedling replanting	Protected	Rubber tree and sugarcane	22K - 800294 / 7768027
Figueira	20	100	A lake separates the forest from the shore	No magement after planting	Protected	Sugarcane	23K - 205429 / 7786874

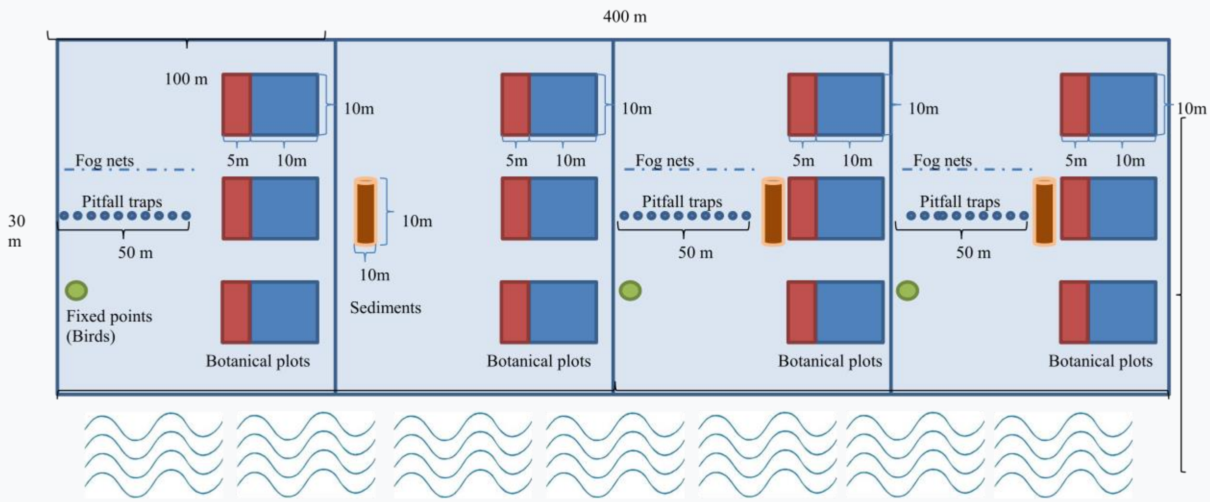
Among the reforestation areas, two fragments had a width of 30 m (Noboro and Santa Barbara), while the other two had a width of 100 m (Figueira and Delta) and at the beginning of this study the areas had planting ages of 10 and 20 years. The planting of trees in the fragments followed the availability of seedlings in the nurseries of the HPP at the time (1994 to 2004), with around 35 species being planted in each area, from seeds obtained in nearby forest remnants. The seedlings, which were approximately 10 months old at the time of planting, were installed along the banks of the reservoir (in the case of Delta, a lake separates the banks of the reservoir, where fishing huts for recreational use are installed, and the forested fragment) with a spacing of 3×2m (Martins and Antonini, 2016).

The forest fragment in Delta is the only one where trails can be seen within it. The trails connect upland residences, the lake, and the huts on the banks of the reservoir. In the other forested fragments, the free movements of people were, in general, not observed. Noboro has the highest level of forest protection, as the fragment is separated from agricultural areas and upland roads by commercial rubber plantations. Noboro also seems to be the only area whose landowners claim to have weeded grasses and planted seedlings of native species and exotic fruit trees in the first years after reforestation.

In 2014, the species with the highest stem diameter at breast height (DBH) found in these areas were: *Clitoria fairchildiana, Anadenanthera peregrina, Syzygium jambolanum, Acacia mangium, Parapeptadenia rigidis, Ficus sp, Guazumaulmifolia, Machaerium opacum, Acacia auriculiformis and Hymenaea stignocarpa* (Antonini& Martins 2016, restoration and forest conservation rillaries in reservoirs hydroelectric Part 1, Chapter 1).

2.2 Establishment of plots for sampling

In all study sites, four blocks perpendicular to the river were settled, within which three plots of 10 x 10 meters were demarcated (for phytosociology studies and litter collection), totaling 12 plots of 100m^2 per site. The plots were parallel and the distance between them varied from zero meters in the 30 m wide fragments to 15m in the 100 m wide fragments. For the collection of soil used in the determination of carbon content and apparent density, three plots of 1 x 10 meters were allocated from the 10 x 10 meters plot. These plots were isolated with four wooden stakes and ropes, preventing the entry of people, in order to avoid soil compaction.



Width	Age	Site
30 m	10 years	Santa Bárbara
	20 years	Noboro
100 m	10 years	Delta
	20 years	Figueira
400 m	+ 30years	Nativa

2.3. Carbon stocks in the tree biomass

All individuals within the plots with circumference at breast height (BAH) equal to or greater than 10 cm were measured. The height of the individuals was estimated with the aid of a pole graduated in meters and they were also identified at species level when possible. The inventoried tree species were classified by functional groups (pioneer, early secondary, late secondary and climatic) according to the methodology described by (Gandolfi et al, 1991 and Leitão Filho et al, 1993). The main characteristics for classification into succession groups were: growth, shade tolerance, life span, onset of fruiting, main dispersal syndromes and species occurrence as shown in Table 2).

Table 2: Percentage of successional groups in the different areas studied (Noboro, Santa Bárbara, Figueira and Delta) (Scolforo et al, 2008).

Classification	**Noboro**	**Santa Bárbara**	**Figuera**	**Delta**
Pioneer (%)	40,45	34,4	9,8	22,7
Pioneer tosecondary (%)	1,94	4,8	3,6	41,3
Secondary (%)	46,92	29,2	60,8	20,9
Secondarytoclimax (%)	0,97	5,8	0,0	9,3
Undetermined (%)	6,15	11,0	11,9	0,4
Dead (%)	1,94	7,6	9,3	5,3
Exotic (%)	1,62	7,2	4,6	0,0

The height and basal area data of the individuals sampled were used to estimate the carbon stock in the vegetation using allometric equations developed in a previous study carried out in the watersheds of the Grande and Piracicaba rivers (Scolforo et al., 2008):

$$Ln(BM) = -10.439791707 + 2.1182873001 \times Ln(DAP) + 0.8339834928 \times Ln(H)$$

Subsequently, the carbon stock in the biomass was estimated through the equation developed by the same author:

$$Ln(C) = -12.73390371 + 2.7305080487 \times Ln(DAP) + 0.5217505822 \times Ln(H)$$

Where: DAP is the diameter at 1.30 m from the ground (cm) and H is the stem height (m).

2.4 Soil Carbon Stock

To evaluate the carbon stock in the soil, undisturbed samples were collected, using an Uhland-type auger for collection, in plots of 1 x 10 meters, at depths of 0-5, 5-10, 10-20 and 20-30 cm, totaling three samples per profile for each area according to the methodology suggested by EMBRAPA (1997). The samples were analyzed at the Laboratory of Soil Analysis of the Federal University of Viçosa, to determine the density of the soil and the carbon content (Walkley-Black).

The calculation of soil carbon stock was estimated using the following expression:

$Cac = (C \times Ds \times e)/10$ Where;

Cac represents stored carbon (Mg ha-1); C indicates the C content (g kg-1) of the soil; Ds, the density of the soil (Mg m-3) and e is the thickness of the layer under analysis in cm (Freixo et al. 2002).

2.5 Litter Carbon Stock

Litter collections to estimate the carbon stock in this compartment were carried out in February-2015, when a square frame of 0.25 m^2 (0.50 x 0.50 cm) was randomly released in all the sample plots of 10m x 10m. All material contained within the square frame were collected and weighed firstly to gain fresh weight. A sub-sample (100 g) of the material was taken from each sample, identified and dried in a circulating oven (50°C, 72 hours) until constant weight and mass was gained and then re-weighed to gain the dry weight. The relationship between moisture content and the amount of carbon was then determined.

2.6 Statistical analysis

All statistical analysis were done using Generalized Linear Models (GLMs), SPSS software and post-hoc Tukey tests. Generalized linear models (GLMs) were constructed to compare the average carbon stock in the aboveground, litter and soil biomass of the studied treatments (Noboro, Santa Bárbara, Figueira and Delta).

We compare the restored areas also in relation to sugarcane plantation because sugarcane plantation was the pioneer vegetation before the dam was constructed and the forest was lost. Also, the sugarcane area serves as the baseline and thereby helps to accumulate carbon in the soil at a much faster rate. Due to the nature and the variability of data and the limitation of sample size, which is common in studies of ecosystem parameters under field conditions, the acceptance level (P) was 0.1. This statistical approach increases the power of the hypothesis tests and reduces the probability of making a type II error (Davidson & Hewitt 2014, Peterman 1990). It is also used to evaluate the effects of explanatory variables (fragment age and width, soil depth of plants presented in each sample unit) on the variation of carbon stocks in aerial biomass, litter and soil (response variables) between treatments. All statistical analysis was performed using R software (R Development Core Team, 2013).

3 Results

3.1 Carbon Stock in the Biomass

The average C stocks (± SD) in the aerial biomass found in Santa Bárbara, Delta, Noboro and Figueira were 79.3 (± 79.0), 83.2 (± 60.6), 109.3 (± 91.1) and 75.1 (± 80.0) $Mg.ha^{-1}$, respectively (Figure 3), however, there was no differences observed between the treatments. The values of stocks of C between plots of the same treatment showed great variation. The plot with the lowest stock of C in the aerial biomass was found in Santa Bárbara and Figueira (0.03 $Mg.ha^{-1}$) while the plot with the highest value was found in Noboro (294.0 $Mg.ha^{-1}$).

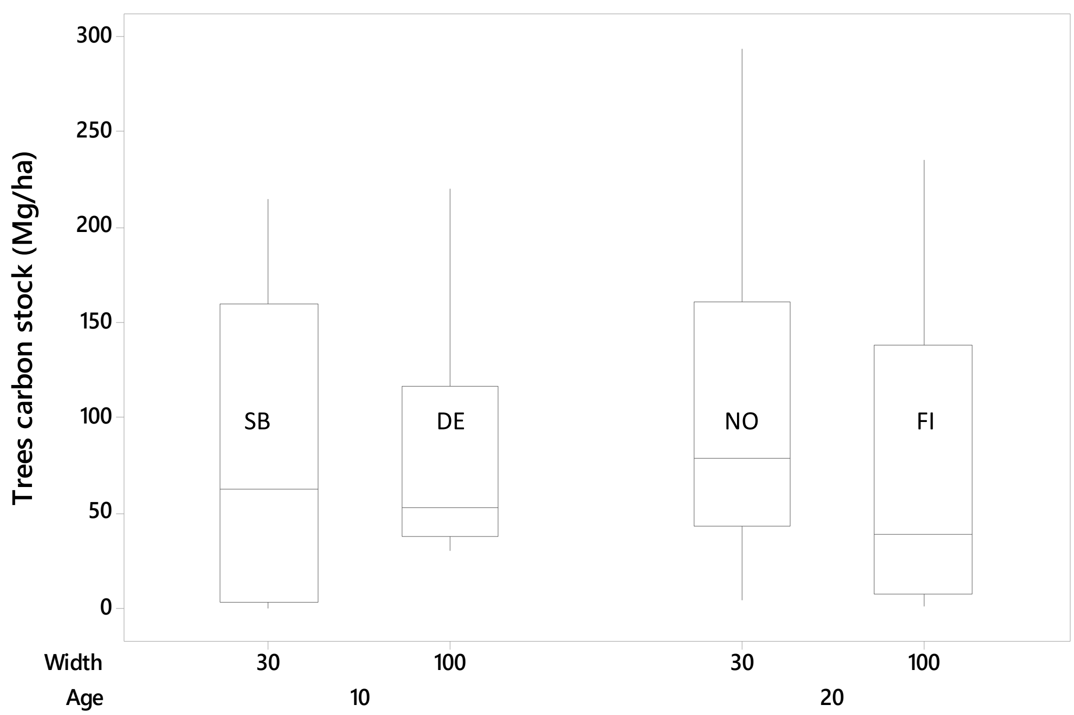
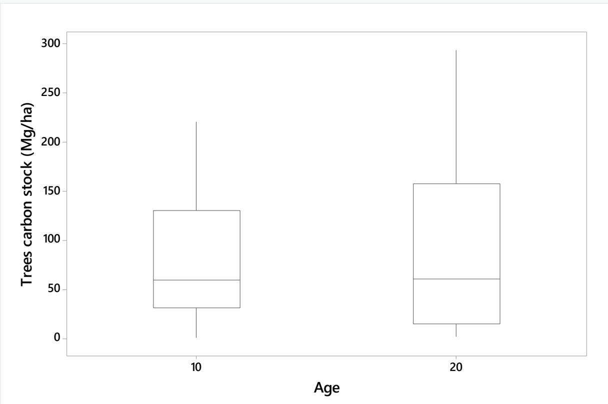


Figure 3: Carbon stocks ($Mg.ha^{-1}$) in tree biomass in the planted riparian areas (Santa Bárbara – SB, Delta – DE, Noboro – NO and Figueira – FI) which differ in age (10 and 20 years) and planting width (30 and 100m) around the Volta Grande State Hydroelectric Power Plant, Minas Gerais, Brazil. The solid lines within the box plots represent the median.

The variation of C stocks in the biomass was not significantly related to any of the parameters surveyed (age and width of the fragment).Tests of data grouped only by age or by forest fragment width also did not reveal significant differences in C stocks in the aerial biomass of the trees (Figure 4).The lines of the plots are very weak



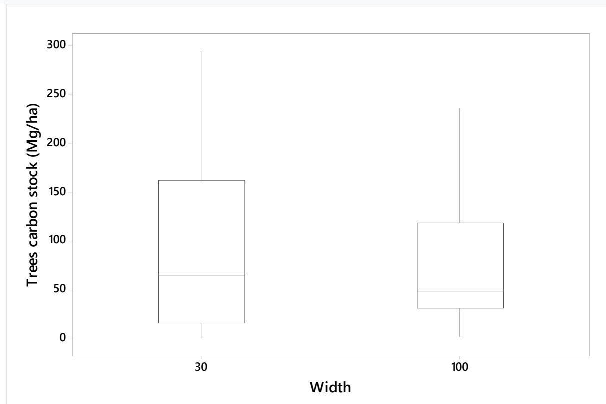


Figure 4: Carbon stocks ($Mg.ha^{-1}$) in tree biomass in the planted riparian areas which differ in age (graph on the left) or in planting width (on the right) around the Volta Grande State Hydroelectric Power Plant, Minas Gerais, Brazil. The solid lines within the box plots represent the median.

3.2 Litter Carbon Stock

The averages of carbon stocks in the litter varied between 3.4 and 11.0 Mg.ha^{-1}. Significant difference was found only between Delta and Santa Bárbara, with the highest value found in Noboro (Figure 5). When comparing C stocks in litter only by age or planting width, the narrowest forest fragments presented the highest stocks, and there was no significant effect of planting age (Figure 6).

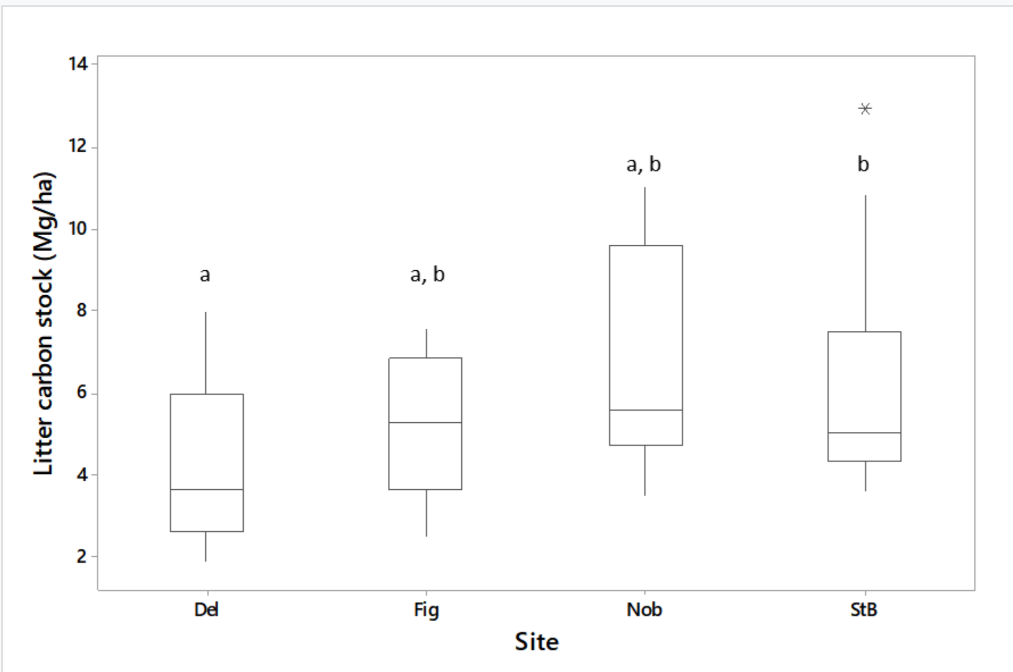


Figure 5: Litter carbon stocks (Mg. ha^{-1}) in four reforested areas (Delta – DE, Figueira – FI, Noboro – NO and Santa Bárbara – SB) around the Volta Grande State Hydroelectric Power Plant, Minas Gerais, Brazil. Different letters denote significant differences at the 0.10 level in the post-hoc Tukey tests.

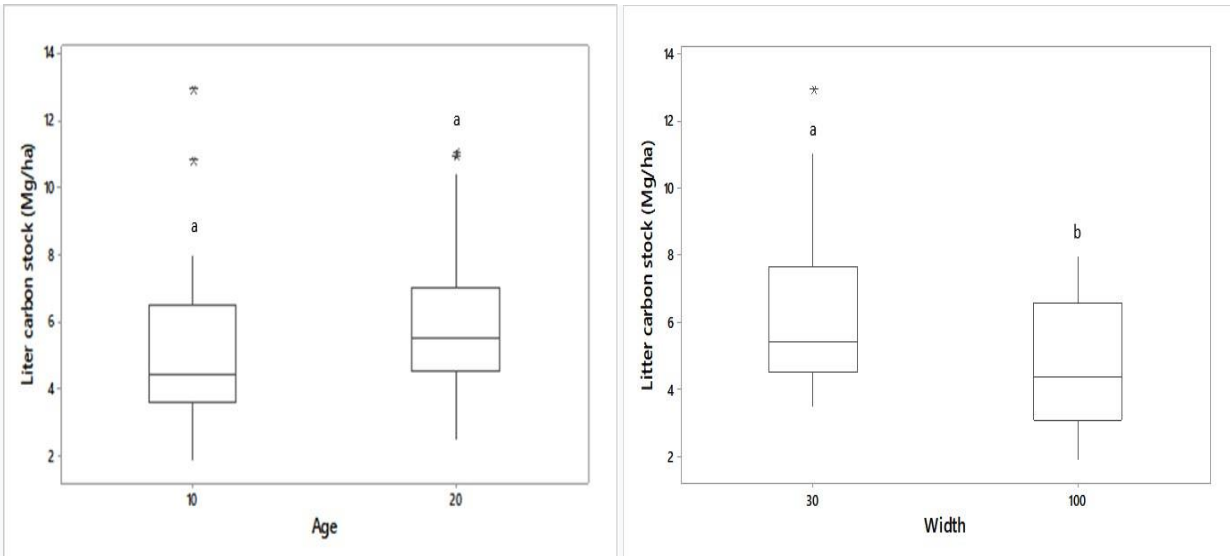


Figure 6: Litter Carbon Stock in relation to a) Fragment age (years); b) Fragment width (m) in four riparian forest fragments around the Volta Grande State Hydroelectric Power Plant, MG, Brazil. Different letters denote significant differences at the 0.10 level.

3.3 Soil Carbon Stock

The Soil carbon stock value at 0-30cm ranges from 26 $Mg.ha^{-1}$ to 32 $Mg.ha^{-1}$ at the studied sites. The general average of the values of the reforested fragments is about 40% higher than that found for the sugarcane areas (Figure 7).

The age and width of the reforestation strips did not cause, so far, significant differences in the stock of C in the soil (0-30 cm). However, in terms of carbon concentration (Total C) in this layer, higher values were measured in the older reforested fragments (Figure 8).

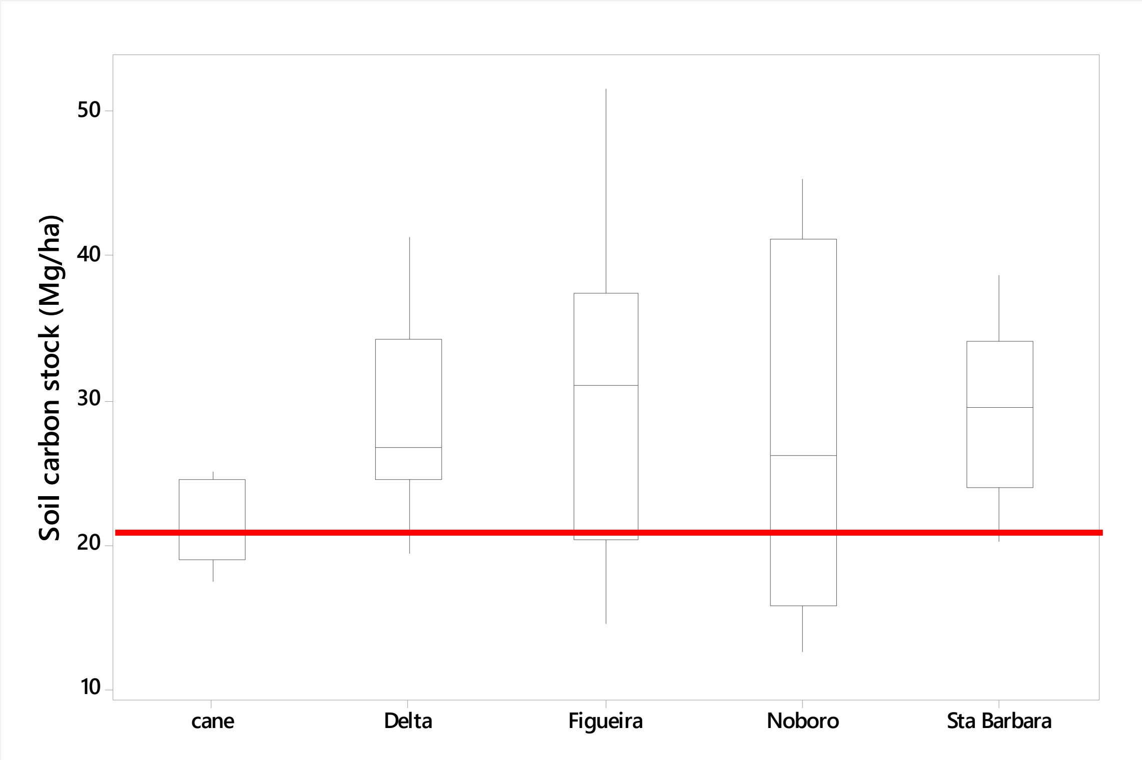
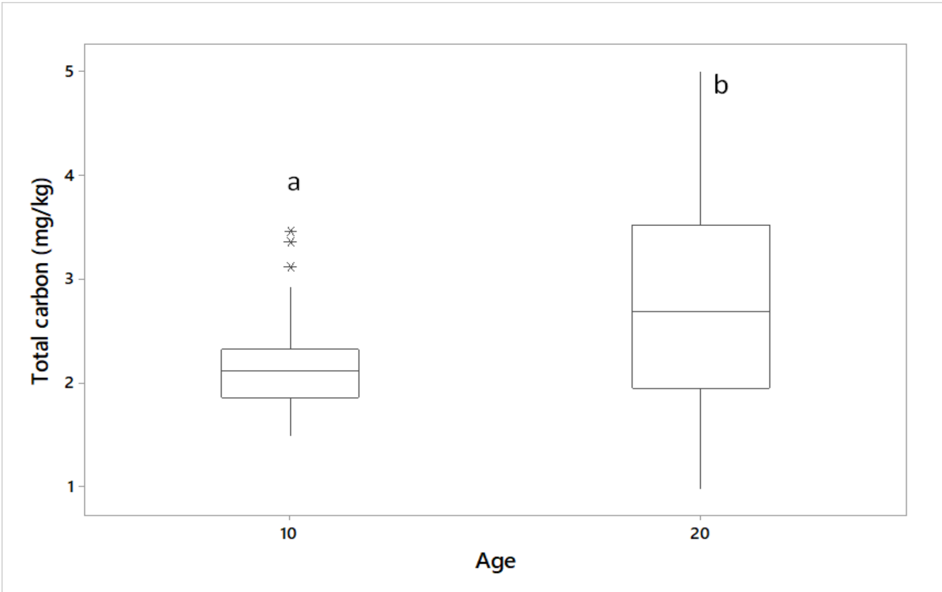


Figure 7: Mean soil carbon stock (0-30cm depth) in four different reforested fragments (Delta – DE, Figueira – FI, Noboro – NO and Santa Bárbara – SB) and in sugar cane areas around the Volta Grande State Hydroelectric Power Plant, Minas Gerais, Brazil. The red line helps to visualize that the average value of C stock in sugarcane areas is lower than the stocks in the planted forest areas.



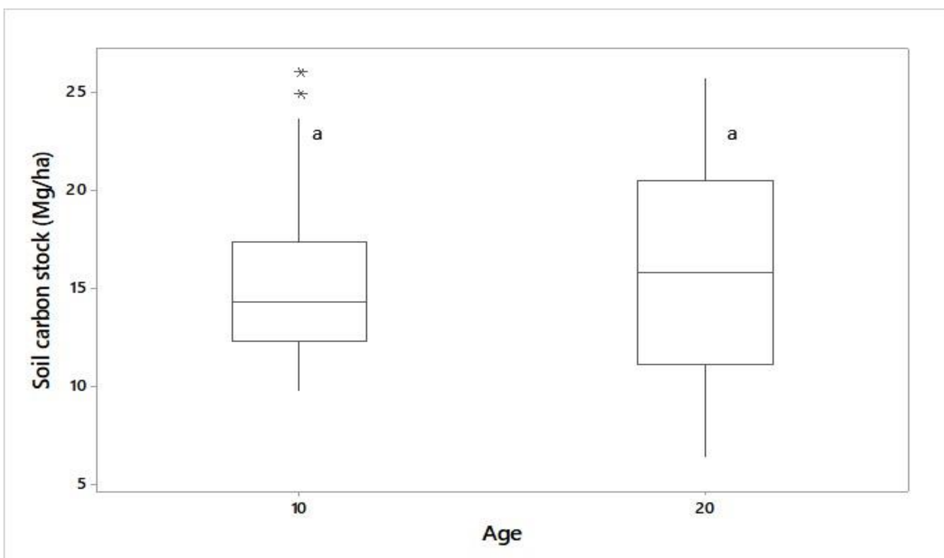


Figure 8: Total soil carbon concentration (mg.kg^{-1}, top chart) and soil C stock (0-30 cm depth, bottom chart) in relation to age (years) of the four reforested riparian fragments (10-years old: Santa Barbara and Delta; 20-years old: Noboro and Figueira) around the Volta Grande State Hydroelectric Power Plant, Minas Gerais, Brazil. Different letters indicate significant differences among ages.

The top 10 cm of soil store greater amounts of C than the lower layers (Figure 9).

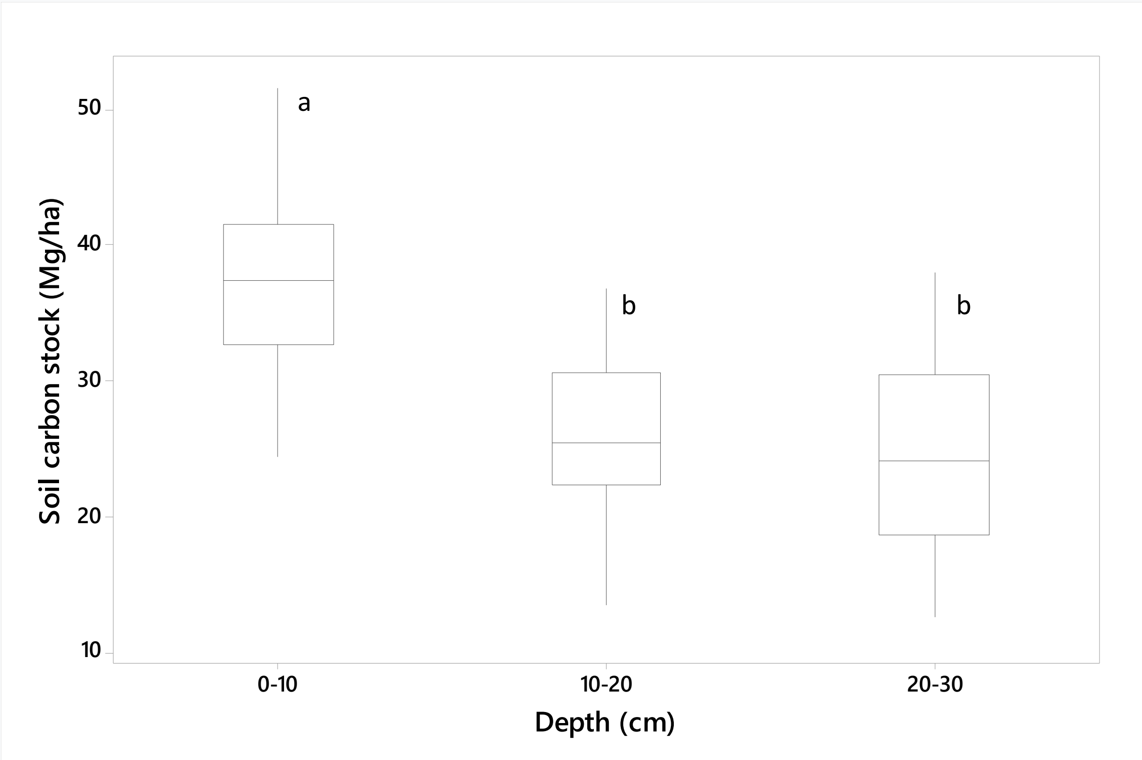


Figure 9: Average soil carbon stock at different depths in four reforested fragments (Noboro, Santa Barbara, Figueira and Delta) around the Volta Grande State Hydroelectric Power Plant, Minas Gerais, Brazil. Different letters indicate significant differences among depths.

4.0 Discussions

We hypothesize that (1) older and narrower fragments (with greater edge effect) will present higher C stocks than the younger and larger ones and that (2) even the very young reforested areas (10 years-old) will already be able to increase carbon stocks in the soil in relation to the levels of the surrounding sugarcane areas, despite of its size.

To answer these questions, we begin with the hypothesis 1 discussed below.

Despite the higher values of carbon concentration in the soil found in the older (fig 8) reforested areas (20 years) and the higher stocks of C in the litter in the narrower planting strips (fig 6), which are in agreement with our first hypothesis, the synergy of these two factors, as expected to be expressed by significantly higher overall C stocks in Noboro forest, was not observed. The large variation among intra-site plots reflects the functional heterogeneity of these fragments of new riparian forests undergoing the first two decades of restoration. In fact, the studied sites varied in a combination of factors (see tables 1 and 2) capable of affecting carbon sequestration and storage in different ways in riparian forests, creating a mosaic of conditions and possibilities of compensatory or confounding effects with those of aging and width of the planted areas (Dhiedt et al. 2021, Nunes et al. 2018, Culot et al. 2017, Magnago et al. 2017, Chaplin-Kramer et al. 2015, Berenguer et al. 2014). Another consideration to be made is that if the different carbon stocks evaluated in this study have the same sensitivity to the time scale (10 and 20 years of planting) and to the small-scaled edge effect (30 and 100m planting width). It was also reported by (William et al, 2019) that older forests continue to accumulate carbon in the soils. As trees get older, they absorb more carbon every year, and because they are bigger, they store more carbon. He adds that preserving existing mature forests will have an even more profound effect on slowing global warming in the coming decades, since immature trees sequester far less CO_2 than older ones. Functional groups of tree species distribution, as the proportion of pioneer trees, can also influence the C sequestration as shown in table 2 (Forrester et al. 2017). Another explanation for the patterns found in the accumulation of C in the aerial biomass in the studied areas may be related to the edge effect, since in smaller fragments there is greater entry of light, facilitating the establishment of pioneer species that normally have higher densities but a reduced stock of carbon per hectare (Magnago et al. 2017). In fact, the highest percentages of pioneers were found in the reforestations Noboro and Santa Barbara, which were 30m.

According to McKinley et al (2011), forests of different ages play different roles in removing carbon from the atmosphere and storing it in the wood. Old forests accumulated more carbon than younger or pioneer forests; however, young forests grow more rapidly, sequestering carbon at a faster rate than older forests, but also showing faster turnover. Also, pioneers compete greatly, they are very hyper active and carryout photosynthesis much often than older forest thereby accumulating or increasing carbon stocks. By this; loss of leaves, reduction in root strength, thin leaves and roots, tissues become less resistant to sun and rain. Thus, trees-sites of different ages can stock almost equal amount of carbon overtime. Trees shed leaves when CO2 uptake is low to support photosynthesis. When photosynthesis is equal to respiration, plants maintain its position. At light intensities below this point, more respiration occurs and at higher light intensities, more photosynthesis occur and the trees becomes more active and productivity increases. The photosynthetic compensation point is where light intensity is at the point where the rate of photosynthesis is equal to the rate of respiration. For shade-adapted plants, the compensation point is lower - their rate of photosynthesis will exceed the rate of respiration at lower light intensities than the plants adapted to sun. Moreover, as reported by Ash & Helman (1990), similarities in carbon biomass stock between age and width of restored forest can be attributed, in part, to differences in past logging activity and time since last disturbance. Considering that all areas had the same past, they donated soil for the construction of the dam, their different levels of protection after planting and management may have increased the variation in carbon sequestration between areas, potentially explaining our results. The 20-year-old Noboro fragment was the one that received management after the first planting and was more protected against the entry of people, showing an average stock of aerial C that was twice as large compared to younger fragments. In contrast, Delta had the highest levels of disturbance, due to the continuous presence of people, in addition to being younger, a combination that led to the lowest C stock value.

Other factors must still be considered. According to Dybala et al. (2018) and Melo &Durigan (2006), narrow strips planted around reservoirs in soil conditions with high nutrient availability may suffer less from competition for light and water. As a result, young planted forests can exceed C stocks in relation to natural riparian forests or upland forests.

The differences we found in the litter stock were that areas of narrow width produce more litter than those of higher width. This may be attributed to the higher amount of stand density found in narrow width. Higher stand densities (e.g. trees per hectare) are associated with smaller size due to increased competition for physical space or available resources such as light, nutrients and water (Long et al, 2004). Also, tree height may be another factor according to a similar report by Ruiz-Jaen & Potvin (2011) for natural tropical forests in Panama, and it is not surprising considering that height is a good predictor of total biomass of the plants, which directly influences the amount of C contained in both the above and below-ground portions of the standing vegetation and incorporated into the soil as litter at aging. We found that soil carbon concentration was higher in older ages of 20years than younger ages of 10years and no difference in the stock. This was as a result of higher litter and organic matter decomposition in the soil overtime. Soil organic matter (SOM) is formed from decomposing biomass and increases the water holding capacity of the surface. Also, root and leaf litter production and the accumulation of coarse woody debris might be highest in old-growth forests (Pregitzer and Euskirchen, 2004).

The difference observed in litter stock at different widths can be explained, since the highest productions were verified in the areas of greater widths (Martins, 2016), but we did find significant differences, this shows a greater decomposition rates in the larger-width fragments. Areas with higher width produce more litter decomposition comparing to those with lower width because of the residency and transition period. It allows the area to rejuvenate itself and also nutrients thereby allowing or helping in more new establishment and thus increase in productivity in wider areas.

The 0-10 cm depths differed from the 10-20 and 20-30 layers, with the highest stocks being verified at the lowest depths. This pattern was already expected, since the nutrient cycling process predominates in the surface layers (Schumacher et al., 2003). Moreover, plots located near the lake were also at a lower altitude (Sämuel et al., 2011). Greater biomass productivity and carbon inputs are expected to increase soil carbon stocks in older forest fragments. As the litter is decomposed, some of the C is emitted as CO_2 into the atmosphere, and some is incorporated into the soil, increasing stocks. This increase in stocks has been observed in experiments in other countries, under various climate and soil conditions and this was similar to reports found in Atlantic forest and Cerrado areas. Coelho *et al.* (2017) found that natural edges of gallery forests have invariable number of individuals and basal area between natural and anthropogenic edges, revealing that natural edges are also prone to resource limitation and stressful conditions (e.g. soil fertility, moisture and fire).

We expected soil carbon stock growth to be influenced by climate and previous work has identified differences in the effects of land use and land cover change on soil carbon stock by climate, soil depth and short-term decreases in soil carbon stocks have been attributed to soil disturbances caused by planting (Laganière et al., 2010). Further, biomass and soil carbon stocks are expected to be larger in riparian forests in wide, complex floodplains with frequent inundation (Sutfin et al., 2016).

The estimated values of C stock in the soil of the new riparian forests studied demonstrate that even in their first decade of growth, such reforestations are capable of significantly increasing the baseline of the surrounding agricultural areas, dominated by the cultivation of sugarcane. The corroboration of our second hypothesis indicates that active restoration can be an essential tool to accelerate carbon sequestration in tropical riparian environments. Although implantation and maintenance costs are in general higher when compared to those of passive restoration the relationship with the benefits may be more advantageous.

Similarly, Silva et al (2007) reports low carbon stocks in sugarcane areas. The cultivation of sugarcane for nearly 50years following deforestation at the São Martinho farm resulted in a decrease in carbon stocks, compared to the soil under native or restored vegetation. Similarly, the measured soil carbon stocks in areas with more than 50years of continuous sugarcane cropping in Hawaii were 12–26% smaller than in adjacent native forest areas. Silva et al. (2007), describing a sugarcane chronosequence study, observed a sharp decrease in soil carbon soon after the deforestation and planting, followed by a slow recovery in the soil C concentration.

5.0 Conclusions

The variations observed in the arboreal carbon in the reforested plots may be a warning about the importance of applying appropriate techniques in forest recovery, since we found plots with enormous variation in carbon stocks. Trees compatible with other surveys in reforested tropical areas, and good management can increase the carbon stock capacity of all areas.

In the present article we add more value to such fragments, demonstrating that they were able to accumulate in their initial decade around 40% more C in the soil than the baseline of surrounding agricultural areas. In addition to the soil, we present estimates of C stocks in litter and tree aboveground biomass in fragments that differ in age, size and level of protection inserted in matrices dominated by agricultural activities. We hope these will contribute to the databases and discussions on the subject in Brazil and in the world, helping to define more efficient protocols, support of money from rich countries and public policies that promote the restoration of riparian forests.

REFERENCES

1. Alexander Koch and Jed O. Kaplan (2022): Tropical forest restoration under future climate change. Department of Earth Sciences and Institute for Climate and Carbon Neutrality, The University of Hong Kong, Hong Kong, Hong Kong SAR, China. https://doi.org/10.1038/s41558-022-01289-6
2. Antonini Y, Beirão MV, Costa FV, Azevedo CS, Wojakowski MM, Kozovits AR, Pires MRS, Sousa HC de, Messias MCTB, Fujaco MA, Leite MGP, Vidigal JP, Monteiro GF, Dirzo R (2022): Riparian forest restoration as sources of biodiversity and ecosystem functions in anthropogenic landscapes. Bio Rxiv, 2021.09.08.459375, ver. 3 peer reviewed and recommended by Peer Community in Ecology. https://doi.org/10.1101/2021.09 .08.459375
3. Araújo GJ, Monteiro GF, Messias MCTB & Antonini Y (2018): Restore it, and they will come: trap-nesting bee and wasp communities (Hymenoptera: Aculeata) are recovered by restoration of riparian forests. Journal of Insect Conservation, 22(2), 245–256. https://doi.org/10.1007/s10841-018- 0058-8
4. AshJ, & Helman C (1990): Floristics and vegetation biomass of a forest catchment, Kioloa, south coastal New South Wales. *Cunning hamia*, *2*(2), 167-182.
5. Brancalion PHS, Meli P, Tymus JRC, Lenti FEB, Benini M, Silva APM, Holl KD (2020): What makes ecosystem restoration expensive? A systematic cost assessment of projects in Brazil. Biological Conservation, 240, 108274. https://doi.org/10.1016/j.biocon.2019. 108274
6. Berenguer E, Joice F, Toby AG, Luiz EOCA, Plinio BDC, Carlos EC, Mariana D, Raimundo CDOJ, Ima CGV, J Barlow (2014): A large-scale field assessment of carbon

stocks inhuman-modified tropical forests. *Global Change Biology (2014) 20*, *3713–3726*, doi: 10.1111/gcb.12627

7. Camilla VJS, Luiz EOCA, Paul JY, Espirito-Santo F & Erika B (2021): Estimating the multi-decadal carbon deficit of burned Amazonian forests. https://doi.org/10.1088/1748-9326/abb62c

8. Cerri CC, Bernoux M, Maia SMF, Cerri CEP, Costa CJr & Feigl BJ (2010): Greenhouse gas mitigation options in Brazil for land-use change, livestock and agriculture. *Scientia Agricola*, **67**, 102– 116.

9. Chaplin-Kramer R, Ivan R, Richard S, Nick MH, James SG, Paul CW, Lisa M, Peder E, Alessandro B, Sarah S, Carina M, Henry K (2015): Degradation in carbon stocks near tropical forest edges. 6:10158, DOI: 10.1038/ncomms10158 www.nature.com/naturecommunications

10. Coelho GAO, Terra M CNS & Almeida HS (2017): What can natural edges of gallery forests teach us about woody community performance in sharp ecotones? *J Plant Ecol*, **10**:937–48.

11. Correa A, Windhorst D, Tetzlaff D, Crespo P, Célleri R, Feyen J & Breuer L (2017): Temporal dynamics in dominant run-off sources and flow paths in the Andean P áramo. *Water Resources Research*, *53*(7), 5998-6017.

12. Culot L, Carolina B, João LFB, Hilton TZC, Mauro G (2017): Synergistic effects of seed disperser and predator loss on recruitment success and long-term consequences for carbon stocks in tropical rainforests. www.nature.com/scientificreports, 7: 7662 DOI: 10.1038/s41598-017-08222-4

13. Davidson AD, C L Hewitt (2014): How often are invasion-induced ecological impacts missed? Biological Invasions (2014) 16:1165–1173, DOI 10.1007/s10530-013-0570-4

14. Dhiedt E, Kris V, Pallieter DS, Quentin P, Lander Baeten (2021): Early Tree Diversity and Composition Effects on Topsoil Chemistry in Young Forest Plantations Depend on Site Context. https://doi.org/10.1007/s10021-021-0060 5-z.

15. Dybala KE, Matzek V, Gardali T & Seavy NE (2018): Carbon sequestration in riparian forests: A global meta-analysis data set (Version 1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.1252510

16. Embrapa, Soils. 1997: Handbook of Soil Analysis Methods. Rio de Janeiro: Embrapa Soils.

17. Ferreira WC (2009): Estoque de biomassa e carbono e parâmetros indicadores de recuperação de mata ciliar. Tese de Doutorado. Universidade Federal de Lavras, MG.

18. Filardi FLR, Garcia FCP & Carvalho-Okano R (2007): Espécies lenhosas de Papilionoideae (Leguminosae) na Estação Ambiental de Volta Grande, Minas Gerais, Brasil. *Rodriguésia* 58(2): 363-378.

19. Forrester DI, Tachauer IHH, Annighoefer P, Barbeito I, Pretzsch H, Ruiz-Peinado & Sileshi GW (2017): Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. *Forest Ecology and Management*, *396*, 160-175.

20. Freixo AA, Machado PLOA, Guimarães CM, Silva CA & Fadigas FS (2002): Estoque de carbono e nitrogênio e distribuição de frações orgânicas de Latossolo do cerrado sob diferentes sistemas de cultivo. *Revista Brasileira de Ciência do Solo*. 26(2):425–434.

21. Gandolfi Jr A, Gjovik LR, Carlos VJ, SA M Q, Viana RF, Han-Rosenblum M & America L (1991): Wood preservation. *Forest Products From*, 99.

22. Guerra CA, Patoine G, Eisenhauer N, Cesarz S, Phillips HR, Xu X, Zhang L (2022): Drivers and trends of global soil microbial carbon over two decades. *Nature Communications*, *13*(1), pp.1-10.

23. Gundersen P (2021): Old-growth forest carbon sinks overestimated. Nature https://doi. org/10.1038/s41586-021-03266-z (2021).

24. Holl KD & Aide TM (2011): When and where to actively restore ecosystems? Forest Ecology and Management, 261(10), 1558–1563. https://doi.org/10.1016/j.foreco.2010.07.004

25. IPCC (2022). The critical role of funders in shrinking the carbon footprint of research. *The Lancet Planetary Health*, *6*(1), e4-e6.

26. Laganière J, Angers DA, & Paré D (2010): Carbon accumulation in agricultural soils after afforestation: A meta-analysis. Global Change 66 | Dybala et al. Biology, 16(1), 439–453. https://doi.org/10.1111/j.1365-2486.2009. 01930.x

27. Leitao-Filho HF & Begossi A (1993): Ethno-botany of Atlantic Forest coastal communities: diversity of plant uses in Gamboa (Itacuruçá Island, Brazil). *Human Ecology*, *21*(4), 419-430.

28. Lewis SL, Wheeler CE, Mitchard ETA & Koch A (2019): Restoring natural forests is the best way to remove atmospheric carbon. Nature, 568, 5–28. https://doi.org/10.1038/d41586-019-01026-8

29. Londe V, Messias MCTB & de Sousa HC (2020): Vegetation restoration is associated with increasing forest width. New Forests, 52(1), 129–144. https://doi.org/10.1007/s11056-020-09786-2

30. Londe V, Messias MCTB & Hildeberto Caldas de Sousa (2021): Vegetation restoration is associated with increasing forest width. Department of Biodiversity, Evolution and Environment, Federal University of Ouro Preto, Ouro Preto, Minas Gerais, Brazil. New Forests (2021) 52:129–144 https://doi.org/10.1007/s11056-020-09786-2

31. Long JN, Dean TJ, Roberts SD (2004): Linkages between silviculture and ecology: Examination of several important conceptual models. For. Ecol. and Manage. 200: 249-261.

32. Luyssaert S et al (2008): Old-growth forests as global carbon sinks. Nature 455, 213–215 (2008).

33. Magnago LFS, Ainhoa M, J Barlow, Carlos EGRS, William FL, SVMartins, David PE (2017): Do fragment size and edge effects predict carbon stocks in trees and lianas in tropical forests? *Functional Ecology 2017, 31, 542–552,* doi: 10.1111/1365-2435.12752

34. Martins R & Antonini Y (2016): Can pollination syndromes indicate ecological restoration success in tropical forests?. Restoration Ecology, 24(3), 373-380.

35. Matzek V, David L, Anthony O, Michael L, Sean D H, Shane TF, Valerie E & Kenneth WT (2020): Carbon Balance Management (2020) 15:16 https://doi.org/10.1186/s13021-020-00150-7

36. McKinley DC, Ryan MG, Birdsey RA, Giardina CP, Harmon ME, Heath LS & Skog KE (2011): A synthesis of current knowledge on forests and carbon storage in the United

States. *Ecological applications*, *21*(6), 1902-1924.

37. Melo ACG & Durigan G(2006): Carbon fixation in forest reforestation riparian areas in Vale do Parana panama, SP, Brazil Carbon sequestration by planted riparian forests in Parana panama Valley, SP, Brazil
38. Morais MC, Siqueira-Neto M, Guerra HP, Satiro LS, Soltangheisi A, Cerri CE & Cherubin MR (2020): Trade-offs between sugarcane straw removal and soil organic matter in Brazil. *Sustainability*, *12*(22), 9363.
39. Nunes MH, Marcela de Castro NST, Izabela RCO, Eduardo VDB (2018): The influence of disturbance on driving carbon stocks and tree dynamics of riparian forests in Cerrado: *Journal of plant ecology Vol 11, Num 3, Pages 401–410.* Doi: 10.1093/jpe/rtx007
40. Peterman RM (1990): The Importance of Reporting Statistical Power: The Forest Decline and Acidic Deposition. Ecology, Vol. 71, No. 5 (Oct., 1990), pp. 2024-2027; http://www.jstor.org/stable/1937612
41. Philipson CD, Cutler ME, Brodrick PG, Asner GP, Boyd DS, Moura CP & Burslem DF (2020): Active restoration accelerates the carbon recovery of human-modified tropical forests. *Science*, *369*(6505), 838-841.
42. Powers JS, Corre MD, Twine TE & Veldkamp E (2011): Geographic bias of field observations of soil carbon stocks with tropical land-use changes precludes spatial extrapolation. Proceedings of the National Academy of Sciences of the United States of America, 108(15), 6318–6322. https://doi.org/10.1073/pnas.1016774108
43. Pregitzer KS, Euskirchen ES (2004): Carbon cycling and storage in world forests: biome patterns related to forest age. Glob Change Biol 10:2052–2077

44. R Development Core Team, 2013. R: A language and environment for statistical computing. Version 2.13. User's guide and aplication published: http://www.R-project.org.

45. Robinson SJ, van den Berg E, Meirelles GS & Ostle N (2015): Factors influencing early secondary succession and ecosystem carbon stocks in Brazilian Atlantic Forest. *Biodiversity and Conservation*, *24*(9), 2273-2291.

46. Rui et al (2022): Persistent soil carbon enhanced in Mollisols by well-managed grasslands but not annual grain or dairy forage cropping systems. Proc. Natl. Acad. Sci. U.S.A.119, e2118931119 (2022).

47. Ruiz-Jaen MC & Mitchell AT (2005): Restoration success: how is it being measured? *Restoration ecology*, *13*(3), 569-577.

48. Ruiz-Jaen MC & Potvin C (2011): Can we predict carbon stocks in tropical ecosystems from tree diversity? Comparing species and functional diversity in a plantation and a natural forest. *New Phytologist*, **189**, 978– 987.

49. Sämuel D, Ziche RY, I Kowarik, D Overdieck (2011): "Grazing as driver for *Populus euphratica* woodland degradation in the semi-arid" AibiHu Region, northwestern ChinaJ. Arid Environ, 75 (2011), pp. 265-269.

50. Schumacher MV, Brun EJ, Rodrigues LM & Santos ED (2003): Retorno de nutrientes via deposição de serapilheira em um povoamento de acácia-negra (Acacia mearnsii De Wild.) no Estado do Rio Grande do Sul.*Revista Árvore,* 27(6), 791-798.

51. Scolforo JRS, Oliveira AD & Acerbi FWJ (2008): Inventário Florestal de Minas Gerais: equações de volume, peso de matéria seca e carbono para diferentes fisionomias da flora nativa. Lavras: UFLA, 216.

52. Silva AJN, Ribeiro MR, Carvalho FG, Silva VN, Silva LESF (2007): Impact of sugarcane cultivation on soil carbon fractions, consistence limits and aggregate stability of Yellow Latosols in Northeast Brazil**.** Soil & Tillage Research, 94, pp. 420-424

53. Sutfin NA, Wohl EE & Dwire KA (2016): Banking carbon: A review of organic carbon storage and physical factors influencing retention in floodplains and riparian ecosystems. Earth Surface Processes and Landforms, 41(1), 38–60. https://doi.org/10.1002/esp.3857

54. William MR, Masino SA & Faison EK (2019): Intact forests in the United States: Proforestation mitigates climate change and serves the greatest good. *Frontiers in Forests and Global Change*, 27.

55. Wilson D, Santika T, McAlpine CA, Lunney KA & Rhodes JR (2011): Assessing spatio-temporal priorities for species' recovery in broad-scale dynamic landscapes. *Journal of Applied Ecology*, *52*(4), 832-840.

CHAPTER 2

DOES THE SIZE OF RESTORATIONRIPARIAN FOREST INFLUENCE THE RECOVERY OF DIVERSITY AND STRUCTURE? A CASE STUDY IN BRAZILIAN CERRADO

Authors: Kafinga M.H[1, 2], Kozovits A.R[1], Messias MCTB[1], Antonini Y[1*].

1- Post-Graduate program in Ecology of Tropical Biomes, Federal University of Ouro Preto, Department of Biodiversity, Evolution and Environment, Federal University of Ouro Preto, Ouro Preto, Brazil; 2- Department of Forestry and Wildlife, Kano University of Science and Technology, Wudil, Nigeria.

***Corresponding author: antonini@ufop.edu.br**

ABSTRACT

Riparian buffers safeguard the only remaining forest fragments in many agricultural landscapes of the Brazilian Cerrado region. These linear landscape elements contribute to the conservation of terrestrial and aquatic biodiversity in agricultural landscapes by providing shelter, reproduction sites, food, and connectivity. Riparian buffer restorations are used as management tools to produce favorable water quality impacts, moreover among the many benefits riparian buffers may provide, their application as instruments for water quality restoration rests on a relatively firm foundation of research. Thus, the objective of the study was to determine if the forest structure of restored strips of riparian forest, of the Volta Grande Reservoir, will change in terms of age and width since restoration. For this we asked the hypothesis that the structure of the vegetation will be different regarding age and size of the riparian stripes and is expected that tree richness and abundance is higher in older riparian strips. Areas with high landscape heterogeneity index composition are said to be more productive than areas with low heterogeneity index composition. The work was carried out in four actively restored sites and one passively restored riparian stripes, around the Volta Grande Hydroelectric Reservoir (UHE-Volta Grande). We found that the five studied areas are different regarding the structure of the restored riparian stripes while the PCA axes explained 63% of the variation with 26.48% in axes one and 37.11 in axes two are influenced by the age and width of the riparian strips. Based on the result obtained, the forest structure of the riparian stripes influenced the response variables (Tree high, Density, DBH, Canopy cover, Shannon index and Landscape Heterogeneity Index) at different rates and also the forest structures are influenced by the age and width of the riparian strips. Lastly, it is very important to recovery reforested riparian strips and also by providing proper monitoring and management of the area.

1.0 Introduction

Riparian forest serves as physical barriers against transport of solid particles and substances into water bodies thereby preventing silting and contamination. It helps to provide thermal, physical and chemical balance of water bodies, quality water, source of food for animals, shelter and reproductive place. It helps in nutrient cycling, flooding possibility, pollution and loss of biodiversity (Echeverría et al. 2015). In agricultural landscapes, on the other hand, these zones are often narrow strips, heavily modified due to physical modifications of the streams, including widening and deepening of the stream channel and, furthermore, highly influenced by agricultural practice, including drainage and application of fertilizers and pesticides. Thus, the biodiversity value of the vegetation in buffer strips in agricultural areas is likely to vary with land use intensity.

Restoring and maintaining intact and diverse riparian areas on the agricultural landscape are critical to mitigate the effects of disturbance and ensure ecosystem functioning (Hale et al. 2018; Hood and Naiman 2000; McDonald et al. 2008; Wilkerson et al. 2006). Assisted revegetation can be an effective strategy to restore degraded riparian forest because it prevent the establishment and spread of invasive plants and can strongly accelerate the secondary succession creating conditions to new species to establish (Hale el at, 2018). Also, active habitat restoration of native plant communities may be an essential tool in maintaining ecological integrity, biodiversity, and ecosystem functioning. It is very important to restore degraded areas in order to mitigate the extent of the ecological crisis that we are currently facing and protect the biodiversity for future generations. Also, our food systems and the revival of forest and agrarian crops depend on healthy soils.

Ecological restoration is an alternative to return this historical trend and, also to promote a new paradigm of socioeconomic development better integrated with nature (Echeveria et al. 2015). The need for ecosystem restoration is clear. An estimated 25% of the world's land area is degraded, threatening global sustainability. Deforestation, forest degradation, desertification, soil erosion, loss of productivity potential, biodiversity loss, water shortage and soil pollution are ongoing degradation processes.

Ecosystem restoration is defined as “a process of reversing the degradation of ecosystems, such as landscapes, lakes and oceans to regain their ecological functionality; in other words, to improve the productivity and capacity of ecosystems to meet the needs of the organism and also human society. Worldwide, an estimated two billion ha of forests are degraded with roughly half in tropical countries. Degradation of ecosystems is an ongoing process in Latin America (LA), where land use and land cover changes due to the expansion of urban areas and agro-industrial crops represent major threats (DeClerk et al. 2010).

During the restoration of forest, it is important to monitoring forest structure and functionality (Barbosa 2000, FAO 2012). Forest structure usually refers to the way in which the attributes of trees are distributed within a forest ecosystem. Trees are immobile, but they are living things that propagate, grow and die. The production, dispersal of seeds and the associated processes of germination, seedling establishment and survival are very important factors of plant population dynamics and structuring (Barbosa 2000, FAO 2012).

Trees compete for essential resources, and tree growth and mortality are also important structuring processes. Tree growth and the interactions between trees depend, to a large degree, on the structure of the forest. Forest structure is comprised of numerous components representing the vertical and horizontal spatial arrangement of biomass which influence and maintain favorable microclimatic conditions for biota (Ehbrecht et al 2017, Kovács et al, 2017) as well as provide niche space for dependent organisms (Sukma et al, 2019).

Forest structure can be divided into two main components: Structural attributes and Structural complexity (McElhinny et al, 2005). Structural attributes capture the spatial heterogeneity within a forest and describe the presence or abundance of individual attributes such as species diversity, forest biomass, canopy cover, tree DBH, tree height, density, tree species and presence of deadwood. In contrast, structural complexity can either be quantified as the overall number and relative abundance of the different forest structural attributes or defined more holistically using techniques that consider the stand as an entity (McElhinny et al, 2005).

Active forest restoration promotes greater recovery of canopy cover, tree density, tree height-diameter ratio, tree diversity and native tree regeneration than spontaneous natural regeneration in degraded tropical rainforest fragments. Increasing density is an effective strategy to increase the basal area of a forest undergoing restoration in an area (Meli et al, 2017).

The availability of older trees and the nearness of healthy forest patches help in influencing species regeneration in the restored sites. Also, fast regeneration of tree species in restored sites depends on the density of older trees in the site. It is very important to have a narrow width between areas to have a good seed dispersal means for effective restoration (Cole et al, 2013). Seed dispersal is very important factor in forest recovery and restoration. It can be obtained through abundance and richness of the restoration plants (White el al, 2004). Other important restoration ecological indicators are seed rain; tree DBH and the canopy cover as well (Brancalion et al, 2012).

Canopy cover can facilitate rainforest recovery by creating favorable microhabitats for tree regeneration as well as contributing to explaining patterns of seedling density, diversity, and composition across plots. Restoration of canopy cover through tree planting can assist in overcoming barriers to natural regeneration and catalyze recovery of degraded areas (Ashton et al, 2014). The faster recovery in managed forests can most likely be attributed to canopy openings in the absence of any human intervention (Nováková M.H et al, 2015). The number of forest patches in abundance and variability within a forest cover may affect ecological restoration process (Crouzeilles et al, 2019).

The age of the restoration area is also a variable that leads to significant changes in the composition of plant species in the process of restoration and in vegetation structure (Crouzeilles et al, 2016). Another variable that influences the success of restoration project is the width of the restored strips which influence the nutrient cycling. Each stage of a forest, or “age class” as foresters say, plays different major roles in restoration process of a forest. Restoration sites or areas will green-up amazingly fast and the number of trees will actually increase due to the presence of younger generations of trees (Osborne and Kovacic, 1993).

The forest is still there, but with fewer trees, or less species of trees, plants or animals, or some of them affected by plagues. This degradation makes the forest less valuable and may lead to deforestation.

To know if active restoration was succeeded in recovering of forest structure, in this study we evaluate if the forest structure of four planted riparian stripes will change in terms of age and width since restoration, compared to a passive restored site (reference area i.e. Nativa).

For this we asked the hypothesis that the structure of the vegetation will be different regarding age and size (width) of the riparian stripes and we expected that;

1. Diameter at Breast Height, Height, and Canopy cover will be higher in older riparian stripes.
2. We expect that density will be higher in younger riparian stripes.
3. Tree richness and abundance is higher in older riparian strips and finally we expected that areas with high landscape heterogeneity index composition are said to be more productive than areas with low heterogeneity index composition.

2 Methods

2.1 Study Area

The study was carried out in four actively restored sites and one passively restored, around the Volta Grande Reservoir (UHE) located on the Grande, between the municipalities of Conceição das Alagoas (MG) and Miguelópolis (SP) (Figure 1).

The climate of the region is classified by Köppen as Kwa, with an average annual temperature between 22°C and 24°C. The average annual precipitation over the last 18 years is close to 1500 mm, with a well-defined dry season, comprising the months from April to September and a rainy season from October to March (Figure 2). The predominant soil type in the region is eutrophic purple latosols (Filardi et al, 2007; Ferreira, 2009).

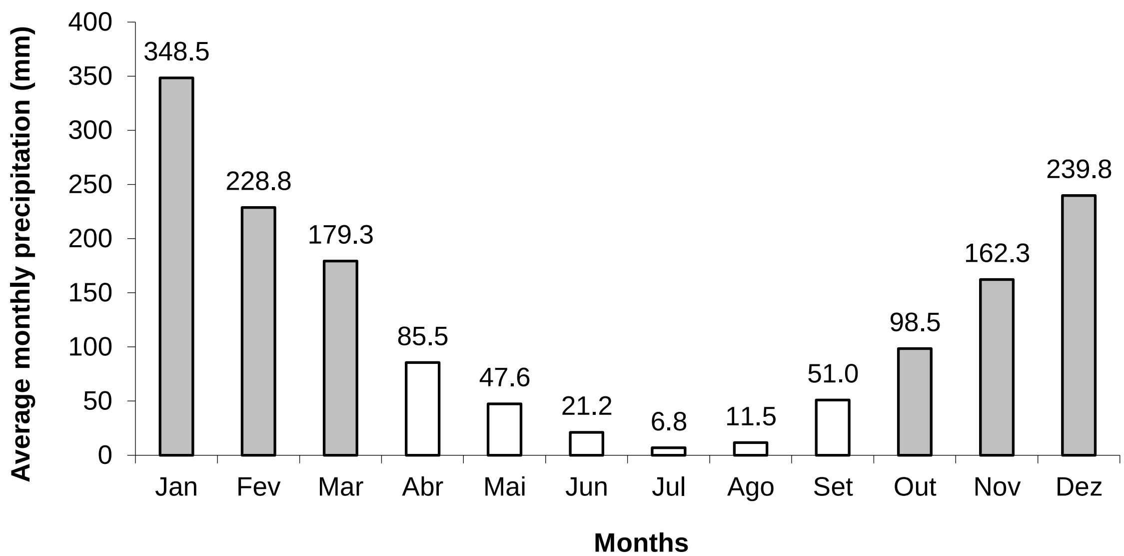


Figure 1: Average monthly rainfall is between 1994 -2012 in the study area. Source: UHE Porto Colombia (Furnas Centrais Elétricas S/A). Gray bars represent the rainy season and white bars the dry season.

Figure 2: Location of UHE Volta Grande. Image: use and occupation represented by a 6 km buffer around the reservoir. Highlight for the location of the study areas (Nativa, Noboro, Santa Barbara, Figueira and Delta).

2.2 Sample design

In each studied site (Table 1) four blocks were allocated, within which 3 plots of 10 x 10 meters were delimited to study phytosociology. The Santa Bárbara, Noboro, Figueira and Delta areas were respectively 30, 30, 100 and 100 meters wide while the reference area (Nativa) was 400m wide. The plots are parallel and the distance between them varies according to the width of the forest evaluated: 5 m distance in areas of 30 m wide and 15 m in areas with 100 m wide. Regarding the age of planting; Santa Bárbara, Delta, Noboro and Figueira present 10, 10, 20 and

20 years respectively. In each area, three plots of 1 x 10meters were marked and demarcated for soil sample collection. The plots are parallel and the distance between them is 100 meters.

Table 1: Characteristics of the secondary and riparian forest areas located around the Volta Grande Hydroelectric Power Plant (location, age and width and landscape matrix of the fragments)

Site	Municipality	Age (years)	width (m)	Landscape Matrix	Coordinates (UTM)
Nativa	Conc. das Alagoas-MG	-	400	Cerrado and sugarcane	22K - 791531 / 7783262
Noboro	Água Comprida-MG	20	30	Rubber tree and sugarcane	22K - 800294 / 7768027
Santa Bárbara	Miguelópolis-SP	10	30	Sugarcane	22K - 798082 / 7775015
Figueira	Igarapava-SP	20	100	Sugarcane	23K - 205429 / 7786874
Delta	Igarapava-SP	10	100	Sugarcane	23K - 208838 / 7787209

2.3 Canopy opening

The evaluation of the canopy opening (%) was performed with a digital camera, model Panasonic Lumix DMC-LX5, coupled to a Cal FC-E8 lens. To obtain the images, a tripod with a platform at a height of 1.3 m and a compass for North orientation was used. For the analysis of the hemispherical photographs, the program WinSCANOPY 2013a from Regent Instruments Inc was used. The photos were taken in early September/2014 (end of the dry season) and early March/2015 (end of the rainy season) in plots of 10 x 10 meters, with three photos per plot in each area and season, totaling 72 photos per plot in the studied fragment.

2.4 Phytosociological Parameters

Richness and abundance data were obtained through a floristic survey carried out in all 10 x 10 meters plots. Tree heights were measured by the use of hypsometer. The height is calculated through the measurement of the other sides and an angle in the triangle composed by tree top, bottom, and the viewer. The angles are measured using gravity sensor by distance between tree and viewer was taken using measuring tape. A diameter tape is used to measure the tree DBH; it is measured at 4.5 feet up the trunk of the tree from the ground, a thumbtack to mark the height on the tree and put round the truck. The length of the string is measured to get the circumference of the tree and finally converted to get the DBH. The identification of plants was carried out by the project's phytosociology team, coordinated by Prof. Dr. Maria Cristina Teixeira Braga.

2.5 Statistical Analysis

A Generalized linear models (GLMs) were built to test whether explanatory variables (independent) (Delta, Figueira, Nativa, Noboro and Santa Bárbara) influence the response variables (dependent) (Tree high, density, DBH, canopy cover, Shannon index and Landscape Heterogeneity index) in each area of study. This model was also used to test whether the response variables are influenced by the age and width of the fragments.

Another Generalized Linear Model (GLM) was carried out to test the principal component analysis (PCA analysis) in order to reduce the dimension of such datasets, increase interpretability and at the same time minimize information loss.

Contrast analysis was performed after building the models. All statistical analysis was performed using R software (R Development Core Team, 2013).

3.0 Results

We found the five studied areas are different regarding the structure of the restored riparian stripes. The site with highest tree richness and abundance and density was in Nativa. The site with highest tree high and DBH was in Delta. The site with highest Canopy cover was in Santa Bárbara. Lastly, the site that produces the highest LHI was in Noboro.

Table 2: Parameters of the structure of the forest fragments (mean ± standard deviation) around the Volta Grande Hydroelectric Power Plant near the MG427 km 40 Highway, between the municipalities of Conceição das Alagoas (MG) and Miguelópolis (SP), Brazil

Parameters	Nativa	Santa Bárbara	Noboro	Delta	Figueira
Tree High (m^2)	9.68 ±1.31	6.48 ± 0.30	8.42 ± 0.65	12.51±0.89	9.45 ± 2.66
Tree Density (m^2)	0.05 ±0.01	0.02 ±0.004	0.03 ±0.004	0.01 ±0.002	0.01 ±0.003
Tree DBH (cm)	30.05 ± 0.71	49.71 ± 6.03	39.27±13.28	60.04±12.51	57.49±18.10
Tree Canopy cover (%)	11.11 ± 0.33	15.13 ± 0.66	11.36 ± 1.45	9.77 ± 1.40	12.63 ± 1.93
Tree Shannon index (%)	3.01 ± 0.04	2.76 ± 0.11	2.40 ± 0.28	2.85 ± 0.13	2.45 ± 0.09
Tree LHI (%)	0.92 ±1.18	0.44 ± 0	1.18 ± 0	0.82 ± 0	0.94 ± 1.18

Legend: DBH= Diameter at breast height, LHI= Landscape heterogeneity index.

3.1 PCA ANALYSIS

We found that the five studied areas different regarding the structure of the restored riparian stripes. The PCA axes explained 63% of the variation with 24.68% in axes one and 37.11 in axes two (Figure 3a). Tree high and DBH was important to the separation of Delta and Figueira. Canopy cover was important to Santa Bárbara separation and the LHI and Shannon Diversity Index was important to Nativa separation. Finally, tree density was important to separate Noboro from the others stripes (Figure 3b).

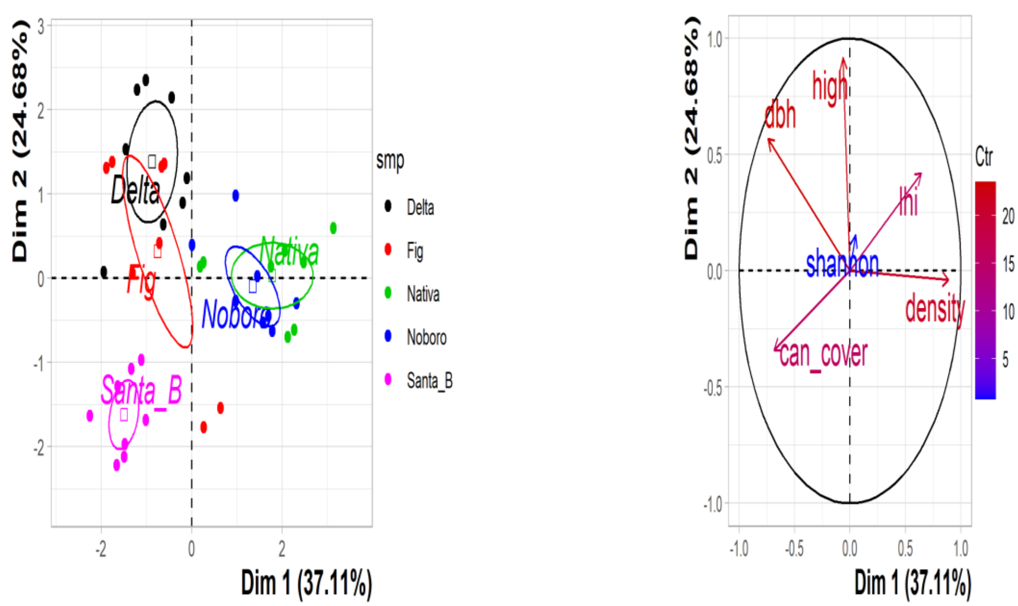


Figure 3: PCA analysis showing the summary of the relationship between the explanatory variables and the response variables.

3.2.1 FOREST STRUCTURE OF THE RIPARIAN STRIPES

Tree high was greater in wider reforest patches and the reference site. We found highest tree high in Delta, compared to other areas. There’s no significant difference between Figueira and Nativa while the lowest height was recorded in Santa Bárbara (Fig 4a). There was not a relationship of tree density with age and width of the reforest strips. The reference site presented the highest tree density, followed by Noboro compared to the other areas. There’s was not significant difference of tree density among the other areas (Fig 4b). Tree diameter (DBH) was higher in the wider reforest patches (Delta and Figueira) than the reference site. Delta, Figueira and Santa Bárbara presented trees with higher DBH, with no significant difference among them while the lowest DBH was recorded in Nativa (Fig 4c).

There was not relationship between canopy cover and age or width. Santa Bárbara (the youngest and narrower strip) presented the highest canopy cover, followed by Figueira (the older and wider strip). No significant canopy cover difference was observed among other areas (Fig 4d). The reference area (Nativa) presented the highest Shannon index, all the other patches were different with no relationship with size or age, the lowest value was found in Noboro (Fig 4e). We found highest LHI in Noboro and differ significantly when compared to other areas while the lowest was recorded in Santa Bárbara (Fig 4f).

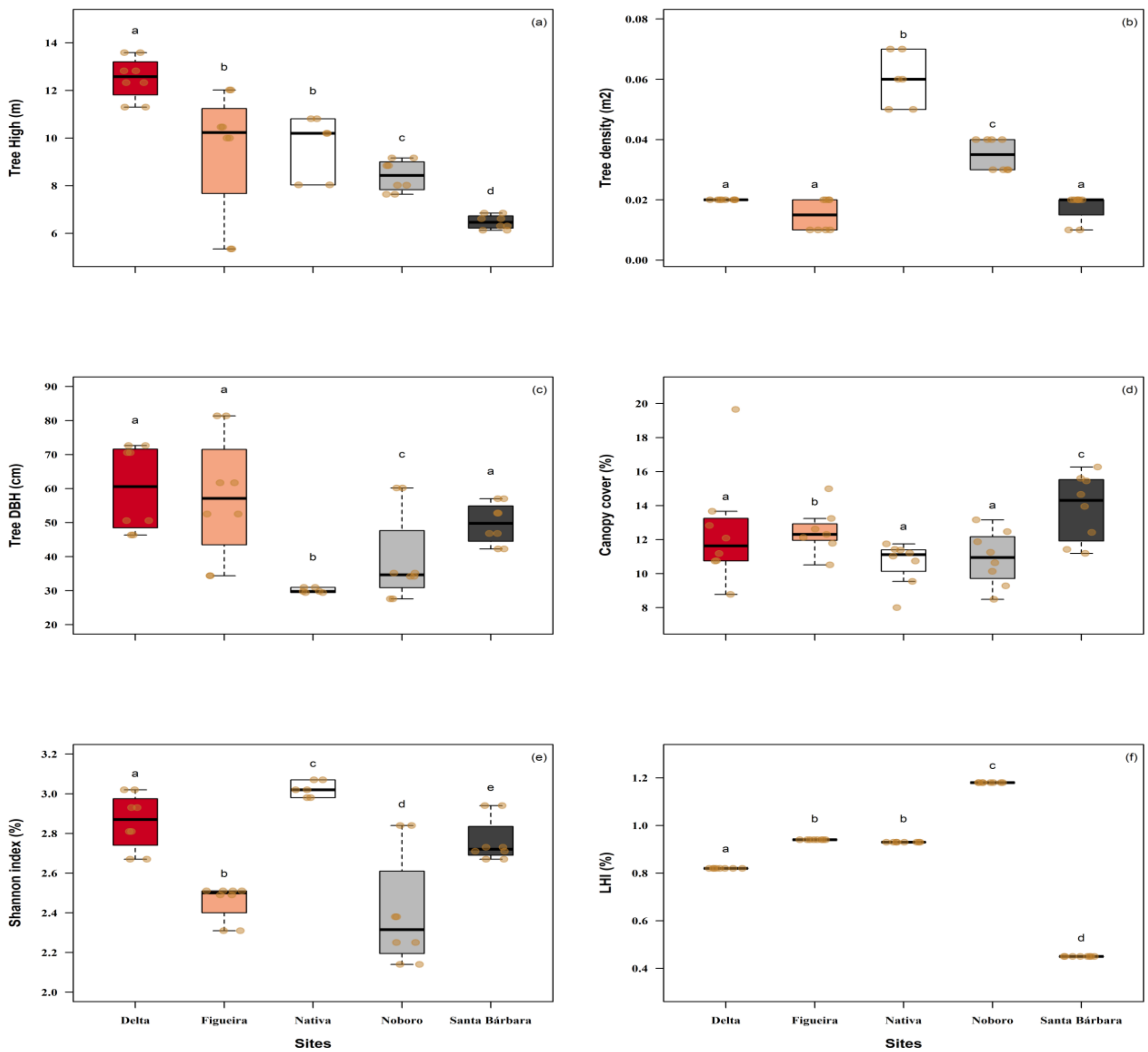


Figure 4: Response variables (Tree high, Density, DBH, Canopy cover, Shannon index and Landscape Heterogeneity Index) against restoration sites (Delta, Figueira, Nativa, Noboro and Santa Bárbara). Alphabets indicate differences and similarities between areas.

3.2.2 FOREST STRUCTURE AND AGE OF THE RIPARIAN STRIPES

We found highest Tree Density in Areas of 30 years when compared to other areas and no significant between other ages (Fig 5a). We found highest Tree DBH in Areas of 10 and 20 years while area of 30 years recorded the lowest DBH (Fig 5b). We found highest canopy cover in Areas of 10 and 20 years while area of 30 years recorded the lowest canopy cover (Fig 5c). There's difference between areas of 10 and 30 years but no difference between areas of 20 and 30 years (Fig 5c).

We found highest Shannon index in Areas of 30 years when compared to other while the lowest was recorded in 20 years (Fig 5d). We found highest LHI in Areas of 20 and 30 years when compared to other areas while the lowest was recorded in 10 years (Fig 5e).

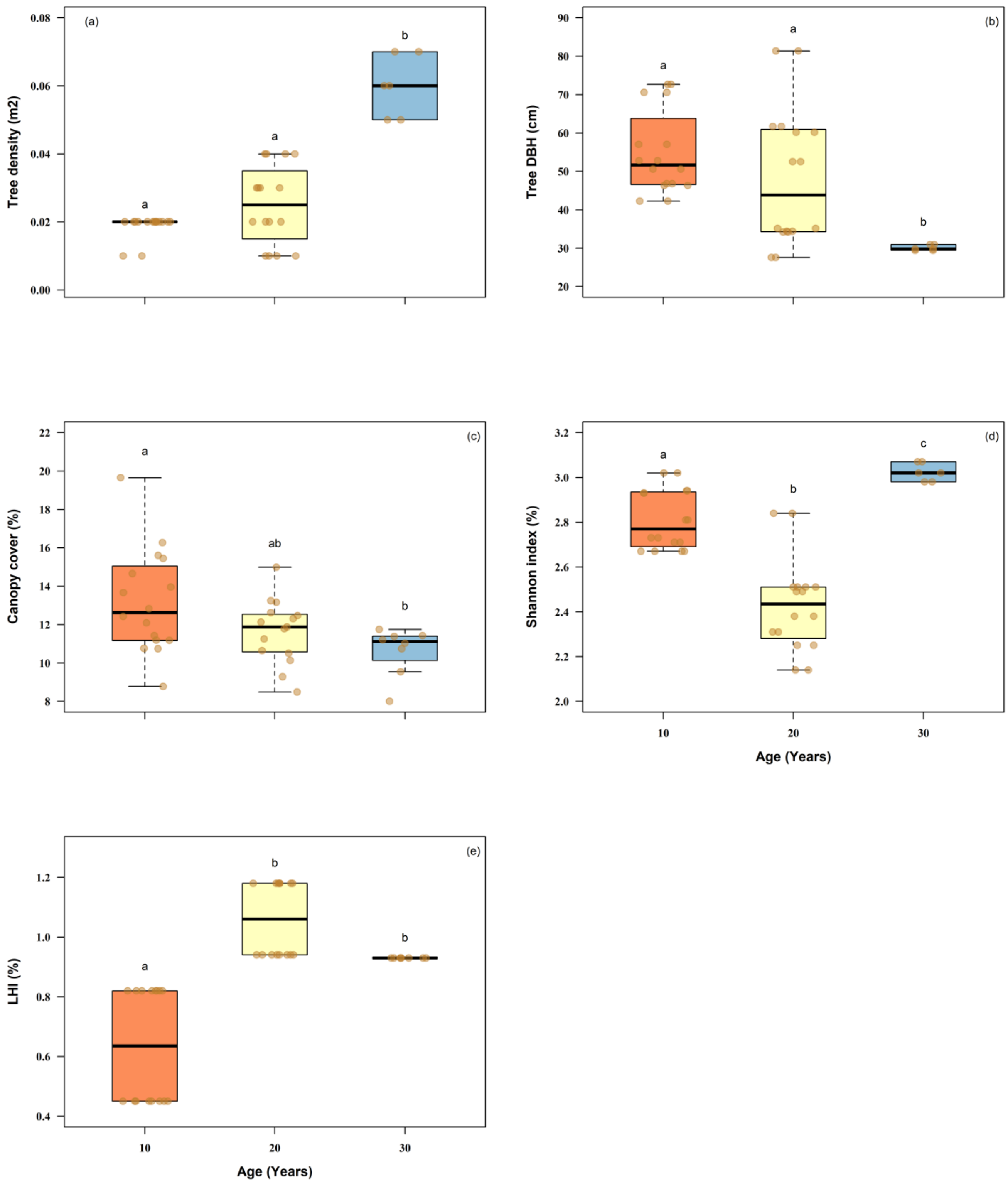


Figure 5: Response variables (Density, DBH, Canopy cover, Shannon index and Landscape Heterogeneity Index) against Age of sites (10, 20 and 30). Alphabets indicate differences and similarities between areas.

3.2.3 FOREST STRUCTURE AND WIDTH OF THE RIPARIAN STRIPES

We found highest tree high in wider areas (100m and 400m width) when compared to the 30m width ones (Fig 6a). We found significantly highest Tree Density in Area of 400m width when compared to other areas while area of 100m width recorded the lowest (Fig 6b).

We found significantly highest Tree DBH in Area of 100m width when compared to other areas while area of 400m width recorded the lowest (Fig 6c). We found significantly highest Shannon index in Area of 400m width when compared to other areas (Fig 6d).

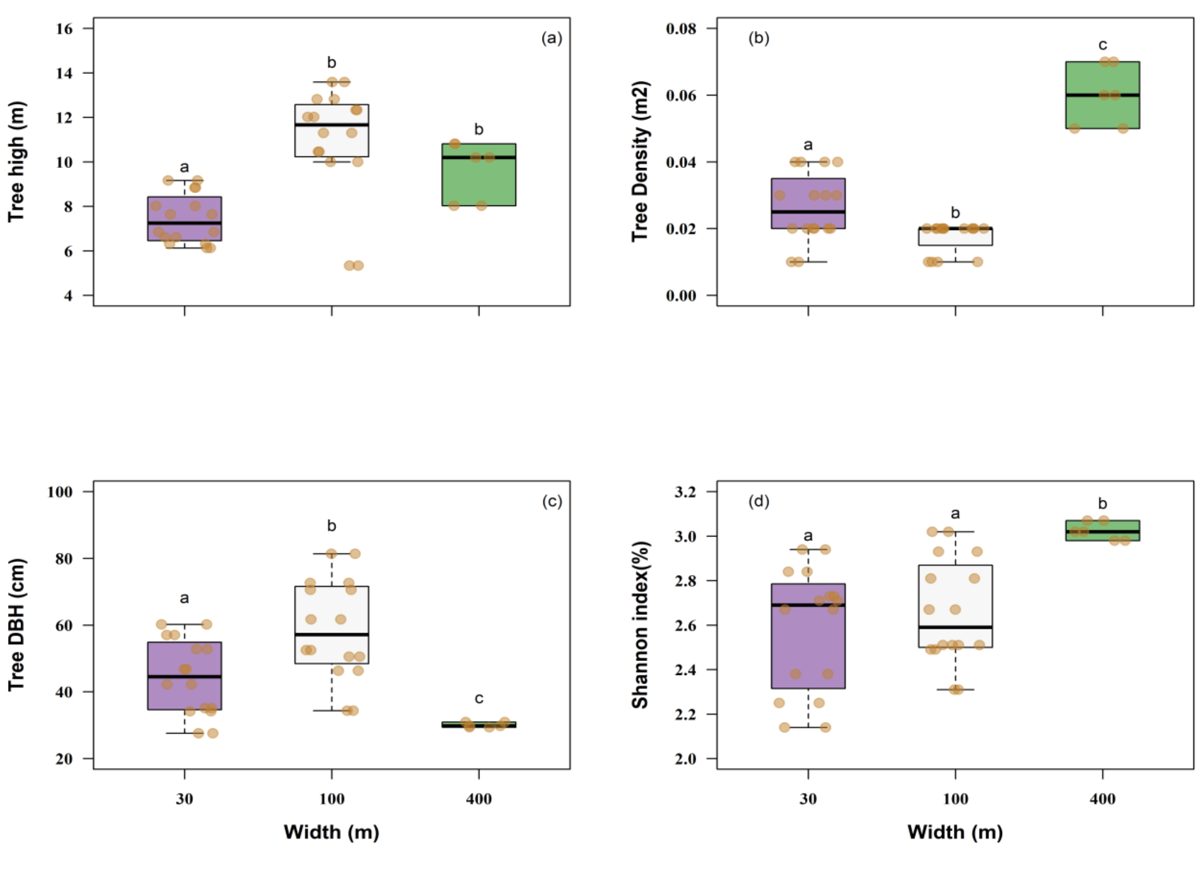


Figure 6: Response variables (Tree high, Density, DBH and Shannon index) against Width of the sites (30, 100 and 400). Alphabets indicate differences and similarities between areas.

4.0 Discussions

Our findings indicate that structure features are good ecological indicators of forest recover in a relatively short period of time (20 years). Several forest structure features can recover in the first decade of restoration (Londe et al. 2020), even though some of them presented lower values than the reference ecosystem.

Age and width influenced forest structure in several predictors. Similarly, the study areas were isolated and surrounded by agricultural matrices, and the age and size of the nearest remnant of native vegetation are relevant ecological filters influencing restoration success (Suganuma et al, 2018). Occurrence of exotic grasses in the understory of some restoration forests is due to the older and larger forest. Thus, the presence of exotic grasses may be a strong impediment to ecological restoration, as evidenced in previous studies (Londe et al. 2017). Increase in seed rain abundance was associated with increasing forest age, probably because of the natural development of the forests (Del Castillo and Ríos 2008). Stand density and stand age had larger effects on forest productivity. At low stand densities, the interactions among trees do not occur or will be weak so that niche interrelation effects are not significant (Forrester & Bauhus, 2016). As stand density increases, the interactions will be more intensive, trees occupy more space and utilize more resources (such as light, water, and nutrients), possibly leading to an increase in productivity and structure (Forrester & Bauhus, 2016).

Species richness and number of regenerating individuals and height of tree were better explained by the increase of forest width. It is likely that by increasing the width of the restoration forests, more individuals and species regeneration will be found in the areas. Therefore, it is advisable to restore wider areas with good forest cover in the surroundings to recover various vegetation attributes (Lomolino and Weiser 2001).

We found that the stripes of restored riparian forest are different regarding forest structure. Significant changes were detected in structural vegetation after an active restoration with increased densities of trees; tree high and canopy cover with the time since restoration of the restored riparian stripes.

We predict that tree high (as shown in fig 4) would be higher in the older forest with higher width, in comparison with the other restored sites and that older sites will present higher tree high. In fact, we found younger sites with different widths with taller trees. This may be explained by the edge effects in which the higher recruitment rates in forest margins, which suggest that the growth of young trees is directly linked to increased tree mortality and canopy disturbance near forest edges. Young trees respond positively to lateral light penetration along fragment margins (Lawrence et al, 1991). Also, the potential of pioneer species to allocate more resources and energy to height instead of diameter growth and longer stripes showing low DBH is another factor, thereby promoting fast soil coverage and canopy formation (Lawrence et al, 1991).

Forest ecosystems that have exhibited edge-related declines in biomass typically have either large, tall stature trees (up to 50–60 m) or shallow roots, and these factors are commonly associated with increased wind-induced tree mortality (Martin-Benito D et al, 2015).

We predict that canopy cover will be higher in the older forest with higher width in comparison with the other sites. But, we found younger sites with different widths producing higher canopy cover. These results imply that enrichment planting of late-successional, shade-tolerant species can start as early as five years after the initial planting because they will not have to compete with herbaceous weeds. Also, it has indicated that seedling and tree mortality rate was higher in older tree canopies (Dodd et al. 2005).

We predict that tree DBH will be higher in the older forest with higher width, in comparison with the other restored sites and that older sites will present higher tree DBH. In fact, we found younger sites with different widths producing higher tree DBH. This can be interpreted as an indication of post-restoration disturbance. Smaller trees recover relatively faster while studies measuring large trees only may not detect early successes as attributes of larger trees take longer to recover. He concluded that the biodiversity and structural attributes in younger restoration planting sites and regrowth forests increased over time towards those in the old-growth forest (Greipsson, 2011).

We predict that tree density will be higher in younger forest sites when compared to older sites. However, we found the highest density in older sites. This is related to the species type and also a strong positive correlation existing between the density and age of forest. The greater density was found to be higher in older areas and could be initially explained by better micro-site conditions for seedling establishment combined with a higher seed deposition over time. In older sites, the present seedling bank may be a result of the accumulated seed deposition of the last years or even decades, because shade-tolerant species may survive as seedlings in the forest understory for long periods, until small gaps are opened to favor their growth (Kitajima & Fenner 2000). In addition, older sites may have more trees producing seeds, which may have an important contribution to seed rain abundance in landscapes with dispersal limitation (Rodrigues et al. 2011). According to a report by (Chazdon; 2008), high woody species density was recorded in older areas. This is because of the open space, which provides favorable conditions for the regeneration of light-demanding species and means there is no competition for light due to upper strata vegetation; thus, scrub vegetation starts to grow and as a result, the number of stems increases in numbers.

Also, we expected richness and abundance to be higher in older restored site; in comparison with the other restored areas. The result we found agrees with our hypothesis and we found higher richness and abundance in older sites. As expected, the number of tree species increases with increasing ages of the species. According to Hubbell (2001), there is a relationship between area size and species number. His theoretical three-phase-curve of species diversity shows that at the local level the number of species increases rapidly with increasing area, age and width. At the regional level, the cumulative increase in the number of species is not influenced so much by the relative species frequency, but more by the balance between species formation, spatial distribution and extinction. The continental and intercontinental bio-geographic scale produces spatially segregated evolutionary developments. Younger restored areas or sites are often relatively small and isolated, which makes them especially sensitive to problems associated with habitat fragmentation. Habitat fragmentation occurs when continuous areas of habitat become disconnected by natural or human causes (for example, building roads through a forest). Fragmentation generally leads to small, isolated patches of hospitable habitat. Pioneer habitats support fewer species and smaller populations, which are at greater risk of inbreeding and local extinction. Fragmentation may also intensify negative edge effects on younger generations. For instance, invasive weeds are more abundant along forest edges, so younger forests with narrow width are more likely to be invaded (Palmer et al 2005). Higher numbers of individuals are expected in the older forest (Munro et al, 2009). This size class can represent an intermediate layer between canopy and shrubs. Hence, this layer may reflect increased structural complexity of the natural forest. Although structural complexity may increase with age of planting (Munro et al. 2009), it is likely that this change may take much longer in restoration sites.

The species richness and number of regenerating individuals were better explained by the increase of forest width. For tree species richness, it was verified that the total number of trees and the richness of climax species are higher in wider forests (Metzger et al. 1997), corroborating with our results.

Disturbances are environmental changes that alter ecosystem structure and function. Common disturbances include logging, damming rivers, intense grazing, hurricanes, floods, and fires. Ecosystem restoration is defined as “a process of reversing the degradation of ecosystems, such as landscapes, lakes and oceans to regain their ecological functionality; in other words, to improve the productivity and capacity of ecosystems to meet the needs of society. Worldwide, an estimated 2 billion ha of forests are degraded with roughly half in tropical countries (FAO, 2010). Plants of the riparian forest have numerous morphological, physiological and reproductive adaptations for life in variable environments.

Specific adaptations include those related to flooding, sediment deposition and physical abrasion. Riparian forest serves as physical barriers against transport of solid particles and substances into water bodies thereby preventing silting and contamination. It helps to provide thermal, physical and chemical balance of water bodies, quality water, source of food for animals, shelter and reproductive place. It helps in nutrient cycling, flooding possibility, pollution and loss of biodiversity.

Riparian zones are very important in ecology, environmental resource management and civil engineering because of their role in soil conservation, their habitat biodiversity, and the influence they have on fauna and aquatic ecosystems, including grasslands, woodlands, wetlands, or even non-vegetative areas. In some regions, the terms riparian woodland, riparian forest, riparian buffer zone, riparian corridor**,** and riparian strip are used to characterize a riparian zone.

Invasive species may impose additional constrains to the establishment of native species in areas undergoing restoration with more opened canopy, and future studies on this issue are needed.

In the State of Minas Gerais, the situation is not different from that found in the rest of the country, with human activities being the main factor in the loss of riparian forest. This type of forest formation, in general, constitutes the main barrier for pollutants that would be carried into the watercourse, influencing the quantity and quality of water, and, consequently, the aquatic fauna and the availability of fishing resources (Martins et al, 2007). The forest also plays other relevant roles for human societies, such as offering a place for recreation, meditation, fruits, fibers, construction material and medicinal products, in addition to cycling water and nutrients, including carbon, an important greenhouse gas (Millennium Ecosystem Assessment, 2005).

5.0 Conclusions

Monitoring the efficiency of forest restoration processes is important to ensure environmental integrity and the important ecological services provided by riparian forests. We found that some structure attributes can be recovered in the first decade of forest restoration. Other ecological indicators, however, may require more time (over than two decades) to recover. These early ecological attributes can be used to monitor and evaluate the efficiency of reforestation process in the early stages.

Moreover, we found that the increase of reforest strip width promotes the recovery of more ecological indicators.

REFERENCES

1. Ashton MS, Gunatilleke CVS, Gunatilleke IAUN, Singhakumara BMP, Gamage S, Shibayama T, Tomimura C (2014): Restoration of rain forest beneath pine plantations: a relay floristic model with special application to tropical South Asia. *Forest Ecology and Management* **329**: 351– 359
2. Barbosa LM (2000): Considerações gerais e modelos de recuperação de formações ciliares. *Matasciliares: conservação e recuperação. São Paulo: EDUSP*, 289-312.
3. Brancalion PHS, Viani RAG, Rodrigues RR, Gandolf S (2012): Avaliação e monitoramento de áreas em processo de restauração. In: Martins SV (ed) Restauração Ecológica de Ecossistemas Degradados. Editora UFV, Viçosa, pp 262–291
4. Chaplin-Kramer R et al (2015): Degradation in carbon stocks near tropical forest edges. Nat Community 6:10158.
5. Chazdon RL (2008): Restoring Forests and Ecosystem Services on Degraded Lands. Science, 320, 1458–1460. [CrossRef]
6. Cole ARJ, Holl KD and Zahawi RA (2013): Seed rain under tree islands planted to restore degraded lands in a tropical agricultural landscape. Ecological applications 20 (5): 1255-1269.
7. Crouzeilles R, Curran M, Ferreira MS et al (2016): A global meta-analysis on the ecological drivers of forest restoration success. National Community 7:11666. https://doi.org/10.1038/ncomms11666
8. Crouzeilles R et al (2019): A new approach to map landscape variation in forest restoration success in tropical and temperate forest biomes. *J. Appl. Ecol.* **56**, 2675–2686.

9. DeClerck F, Chazdon R, Holl K, Milder J, Finegan B, Martinez-Salinas A, Imbach P, Canet L, Ramos Z (2010): Biodiversity conservation in human-modified landscapes of Mesoamerica: past, present and future. Biological Conservation 143:2301–2313.
10. Del Castillo RF, Ríos MAP (2008): Changes in seed rain during secondary succession in a tropical montane cloud forest region in Oaxaca, Mexico. J Trop Ecol 24:433–444. https://doi.org/10.1017/S0266 4674080051 42
11. Dodd MB, AW McGowan, IL Power and BS Thorrold (2005): Effects of variation in shade level, shade duration and light quality on perennial pastures. New Zealand Journal of Agricultural Research 48:531–543.
12. Echeverría C, Smith-Ramírez C, Aronson J, Barrera-Cataño JI (2015): Establishing the ecological restoration network in Argentina: from Rio1992 to SIACRE2015. Restoration Ecology 23:95–103.
13. Ehbrecht M, Schall P, Ammer C, Seidel D (2017): Quantifying stand structural complexity and its relationship with forest management, tree species diversity and microclimate. Agriculture for Meteorology 242:1–9. https://doi.org/10.1016/j.agrformet.2017.04.012.
14. FAO (2010): Global Forest Resources Assessment, Forest paper 163. Food and Agriculture Organization, Rome.
15. FAO (2012): State of the World's Forests. Rome, Italy. URL:<http://www.fao.org/docrep/016/i3010e/i3010.e.pdf. State of the World's Forests.
16. Ferreira WC (2009): Biomass and carbon stock and indicator parameters of riparian forest recovery. Doctoral thesis: Federal University of Lavras, MG

17. Filardi FLR, Garcia FCP & Carvalho-Okano R (2007): Woody species of Papilionoideae (Leguminoseae) at the Volta Grande Environmental Station, Minas Gerais, Brazil. Rodrigues 58(2): 363-378.

18. Forrester DI & Bauhus J (2016): A review of processes behind diversity–productivity relationships in forests. *Current Forestry Reports*, *2*,45–61. https://doi.org/10.1007/s40725-016-0031-2

19. Greipsson S, (2011): *Restoration ecology*. Jones & Bartlett Learning, LLC.

20. Hale R, Reich P, Daniel T, Lake PS, Cavagnaro TR (2018): Assessing changes in structural vegetation and soil properties following riparian restoration. Agric Ecosystem Environment 252:22–29

21. Hood and Naiman, Hood GW, Naiman RJ (2000): Vulnerability of riparian zones to invasion by exotic vascular plants. Plant Ecol 148:105–114

22. Hubbell SP (2001): The unified neutral theory of biodiversity and biogeography. Princeton University Press, Princeton/Oxford, 375 p

23. Hubau W et al (2020): Asynchronous carbon sinks saturation in African and Amazonian tropical forests. Nature 579, 80–87.

24. Kitajima K, Fenner M (2000): Ecology of seedlings regeneration. Pages 331–360. In: Fenner M (ed) Seeds: the ecology of regeneration in plant communities. Commonwealth Agricultural Bureau International, Wallingford, United Kingdom

25. Kovács B, Tinya F, Ódor P (2017): Stand structural drivers of microclimate in mature temperate mixed forests. Agric For Meteorology 234–235:11–21. https://doi.org/10.1016/j.agrformet.2016

26. Lomolino MV, Weiser MD (2001): Towards a more general species-area relationship: diversity on all islands, great and small. J Biogeography 28:431–445. https://doi.org/10.1046/j.1365-2699.2001.00550 .x

27. Londe V, de Sousa HC, Kozovits AR (2017): Exotic and invasive species compromise the seed bank and seed rain dynamics in forests undergoing restoration at urban regions. J For Res. https://doi.org/10.1007/s1167 6-017-0370-2

28. Martins E, WL Silver, and R Ostertag (2007): Long-term patterns in tropical reforestation plant community composition and aboveground biomass accumulation. Ecological Applications 17:828–839.

29. Martin-Benito D, Pederson N (2015): Convergence in drought stress, but a divergence of climatic drivers across a latitudinal gradient in a temperate broadleaf forest. J Biogeography 42(5):925–937.

30. Metzger JP, Bernacci LC, Goldenberg R (1997): Pattern of tree species diversity in riparian forest fragments of different widths (SE Brazil). Plant Ecol 133:135–152. https://doi.org/10.1023/A:1009791831294

31. McDonald RI, Motzkin G, Foster DR (2008): Assessing the influence of historical factors, contemporary processes, and environmental conditions on the distribution of invasive species. J Torrey Bot. Soc 135:260–271

32. McElhinny C, Gibbons P, Brack C, Bauhus J (2005): Forest and woodland stand structural complexity: its definition and measurement. For Ecological Management 218:1–24. https://doi.org/10.1016/j.foreco.2005.08.034

33. Meli PKD, Holl JM, R Benayas, HP Jones, PC Jones, D Montoya and DM Mateo (2017): A global review of past land use, climate, and active vs. passive restoration effects on forest recovery. PLOS ONE 12:e0171368.

34. Millennium Ecosystem Assessment. 2005: Ecosystems and human wellbeing: a framework for assessment. Island Press: New York.

35. Munro NT, Fischer J, Wood J and Lindenmayer DB (2009): Revegetation in agricultural areas: the development of structural complexity and floristic diversity. Ecological Applications 19: 1197–1210.

36. Nováková MH, Edwards-Jonášová M (2015): Restoration of Central-European mountain Norway spruce forest 15 years after natural and anthropogenic disturbance. For Ecol Manage 344:120–130.

37. Nunez-Mir GC, Liebhold AM, Guo Q, Brockerhoff EG, Jo I, Ordonez K, Fei S (2017): Biotic resistance to exotic invasions: its role in forest ecosystems, confounding artifacts, and future directions. Biological Invasions 19:3287–3299.

38. Osborne LL, Kovacic DA (1993): Riparian vegetated buffer strips in water-quality restoration and stream management. Freshwater Biology 29:243–258. https://doi.org/10.1111/j.1365-2427.1993.tb00761.x

39. Palmer MA, Bernhardt ES (2005): Standards for ecologically successful river restoration. Journal of Applied Ecology 42, 208–217.

40. Rodrigues RR, Gandolfi S, Nave AG, Aronson J, Barreto TE, Vidal CY, Brancalion PHS (2011): Large-scale ecological restoration of high-diversity tropical forests in SE Brazil. Forest Ecology and Management 261:1605–1613

41. Suganuma MS, Torezan JMD, Durigan G (2018): Environment and landscape rather than planting design are the drivers of success in long-term restoration of riparian Atlantic forest. Applied Vegetation Science 21:76–84. https://doi.org/10.1111/avsc.12341
42. Sukma HT, Di Stefano J, Swan M, Sitters H (2019): Mammal functional diversity increases with vegetation structural complexity in two forest types. For Ecological Management 433:85–92. https://doi. org/10.1016/j.foreco.2018.10.035.
43. White E, Tucker N, Meyers N, Wilson J (2004): Seed dispersal to re-vegetated isolated rainforest patches in North Queensland. For Ecological Management 192:409–426. https://doi.org/10.1016/J.FORECO.2004.02.002.
44. Wilkerson E, Hagan JM, Siegel D, Whitman AA (2006): The effectiveness of different buffer widths for protecting headwater stream temperature in Maine. For Sci. 52:221–231.