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Forest biomass and carbon estimation using vegetation indices and leaf area index

Daniele Arndt Erthal¹, Fábio Marcelo Breunig², Rafaelo Balbinot³, Paulo Afonso da Rosa⁴

¹ Engenheira Florestal Msc. em Agronomia – Agricultura e Ambiente, Doutoranda do Programa de Pós-Graduação em Geografia, Universidade Federal de Santa Maria (autor correspondente). ² Dr. em Sensoriamento Remoto, Professor do departamento de Engenharia Florestal da Universidade Federal de Santa Maria, Campus de Frederico Westphalen. ³ Dr. em Ciências Florestais Conservação da Natureza, Professor do departamento de Engenharia Florestal da Universidade Federal de Santa Maria, Campus de Frederico Westphalen. ⁴ Mestre em Geografia pelo Programa de Pós-Graduação em Geografia da Universidade Federal de Santa Maria.

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ABSTRACT

Among the consequences of the current dynamics of manmade land use and cover, forest fragmentation results in a large number of isolated fragments of different sizes. Forest provides many environmental services such as carbon sequestration and storage in the form of biomass, demonstrating the crucial role of native forests and the need to develop new methods that estimate forest biomass and carbon by non-destructive methods. This work aimed to develop a methodology to study and estimate the dynamics of forest biomass and carbon stock in successive stages of regeneration in the northwestern region of Rio Grande do Sul, which was the study area. Yearly images from 1985 to 2014 of the Normalized Difference Vegetation Index - NDVI were calculated, and a global regression was archived to obtain the leaf area index (LAI) and estimate the forest biomass. It was possible to observe the good relationship between the increase in LAI as a function of the NDVI, estimating the forest biomass of 61,156 Gg in 2014, where 602 Gg correspond to the initial regeneration stage, 8,287 Gg for the medium stage, and 52,267 Gg for the advanced stage of regeneration. The total estimated carbon for the study area in 2014 was 27,520 Gg CO₂ of which 271 Gg were present in the initial stage, 3,729 Gg in the medium stage, and 23,520 Gg in the advanced stage of regeneration.

Keywords: forest succession, remote sensing, normalized difference vegetation index (NDVI).

Estimativa da biomassa e carbono florestal com uso de índices de vegetação e índice de área foliar

RESUMO

Em meio às consequências da atual dinâmica do uso e ocupação do solo causadas pelo homem, está a fragmentação das florestas, resultando em um grande número de fragmentos isolados e de diferentes tamanhos. Entre os diversos serviços ambientais prestados, se destaca o sequestro e estocagem do carbono na forma de biomassa, demonstrando assim o fundamental papel das florestas nativas e a necessidade de desenvolver novos métodos que estimem a biomassa e carbono de florestas por meio de métodos não destrutivos. O objetivo do presente trabalho foi desenvolver uma metodologia para estimar e estudar a dinâmica do estoque da biomassa e do carbono florestal em estágios sucessionais de regeneração na Região Noroeste do Estado do Rio Grande do Sul, a qual foi a área de estudo. Foram usadas imagens de todos os anos desde 1985 a 2014, onde foi calculado o índice de vegetação Normalized Difference Vegetation Index - NDVI, e através de regressão gerada para o modelo global, se obter o Índice de Área Foliar - IAF e estimar a biomassa florestal. Foi possível observar a grande relação entre o aumento do IAF em função do NDVI estimando a biomassa florestal em 2014 foi de 61.156 Gg onde 602 Gg correspondem ao estágio de regeneração inicial, 8.287 Gg para o estágio médio e 52.267 Gg para o estágio avançado de regeneração. O total de carbono estimado para a área de estudo em 2014 foi de 27.520 Gg CO₂ sendo desses 271 Gg presentes no estágio inicial, 3.729 Gg no estágio médio e 23.520 Gg no estágio avançado de regeneração.

Palavras-chave: sucessão florestal; sensoriamento remoto; normalized difference vegetation index (NDVI).

Introduction

We now experience the “era of secondary vegetation” due to the removal of native vegetation until the end of the twentieth century since the original vegetation is reduced and in the process of adapting to new conditions (Oliveira, 2015). Agriculture, livestock and logging stand out among the main anthropic activities that reduce and modify forests (Santos et al., 2017; Santos e Pontes, 2022; Silva e Moura, 2021; Watrin et al, 2020). These activities have led to an increase in the concentration of greenhouse gases in the atmosphere, generally from emissions from the burning of fossil fuels and changes in land use (Brunes & Couto, 2017; UNFCCC, 2017; Oliveira et al, 2020).

Thus, the importance of carbon fixation is prominent among the various environmental services provided by forests (Lipinski, et al., 2017; Tejada et al, 2020) since they store a large amount of this gas by fixing it in the form of biomass (Roubuste et al, 2022).

In this scenario, the northwestern region of the state of Rio Grande do Sul, has significant remnants of mixed ombrophilous forest (FOM) and deciduous seasonal forest (FED), some protected in public areas and others present in private areas, with high capacity to store biomass and fix carbon dioxide, considering the trend of increasing forest cover in the region (ROSA et al., 2017a; 2017B).

According to Madugundu et al. (2008), the data from remote sensing are currently the most reliable for large-scale biomass estimation, still lacking new methodologies for processing these remote sensing data to estimate biomass, obtained through vegetation indices and leaf area index (Mabunda et al, 2021).

According to Galvão et al. (2016), some indices such as the normalized difference vegetation index (NDVI) (Rouse et al., 1973) and the enhanced vegetation index (EVI) (HUETE et al., 2002) are indices related to pigments (e.g., chlorophyll and carotenoids) and structural parameters of the plant/canopy such as the leaf area, measured by the leaf area index LAI (Silva Junior et al, 2021), respectively. Thus, we can predict that these indices are related to forest succession and regeneration stages before its saturation. The increase in LAI leads to a proportional increase in NDVI values (Knyazikhin et al., 1999; Madugundu et al., 2008), demonstrating that NDVI levels can be indicators of LAI values and, consequently, of vegetation biomass.

According to Albuquerque et al (2019), and as highlighted by Pereira et al (2020), a vegetation index is the integration of two or more spectral bands, in order to highlight vegetation characteristics, biomass, leaf area index between others. Thus, NDVI is widely used in environmental analysis, as it allows studies at different scales, for different areas.

Therefore, the hypothesis of this work is that it is possible to carry out the estimation of aboveground biomass and carbon, through remote sensing data and satellite images, using NDVI and IAF. Therefore, the objective of this study was to develop a methodology to estimate and study the dynamics of forest biomass and carbon stocks in secondary regeneration stages in the northwestern region of Rio Grande do Sul State, in South of Brazil.

Methods

The study area belongs to the Northwest mesoregion of the state of Rio Grande do Sul, covering the microregions of Frederico Westphalen and Três Passos (Pessetti e Gomes, 2020), totaling 9,127 km².

Multispectral data were collected at different dates from Landsat 5 and 7 satellites, forming a data time series, encompassing 30 images from 1985 to 2014. Most of the images were obtained in October and November to avoid seasonal effects. The data for the year 1990 was acquired in August, and the data for 1993, 1996, and 1999 were acquired in September. Some images were also obtained from February to April. We used the USGS - Global Visualization Viewer to obtain the images (available at <http://earthexplorer.usgs.gov/>). The images were acquired with the atmospheric corrections and orthorectification already applied. We sought to select scenes acquired at close dates to avoid forest and illumination seasonal variations. The images were processed using the ENVI software (5.0).

The NDVI was calculated for each year from 1985 to 2014 based on the surface reflectance images. According to Galvão et al. (2016), the NDVI is an index closely related to chlorophyll and carotenoids. Masks were created and applied after calculating the NDVI for each year, leaving only the forest polygons delimited by Rosa (2016). NDVI values were extracted per pixel from these forest areas and measurements per fragment were evaluated to determine the leaf area index (LAI) for each pixel in each year. The empirical model

proposed by Knyazikhin et al. was used to estimate the LAI (1999), which relates the NDVI values to LAI values, considering the nonlinear relationship between the variables. The NDVI values found in the study area for the stages studied were adjusted using a known global model.

It was possible to calculate a logistic function to estimate the LAI from the NDVI based on the global data generated by Knyazikhin et al. (1999). Thus, we reached the values of LAI for secondary forest in the three stages of regeneration, initial stage (IS), middle stage (MS), and advanced stage (AS) defined according to CONAMA Resolution nº 33 of 1994 (Brazil, 2021). Subsequently, it was possible to classify and generate the areas of each regeneration stage for the 30 images studied (1985-2014), and estimate the total biomass for all years in each of the forest successions.

The biomass values for the successional stages used were obtained from bibliography, according to the authors Watzlawick et al. (2012; 2007), Trautermüller (2015), Brun et al. (2005), Brun; Schumacher; Corrêa (2011), Vogel; Schumacher; Truby (2013), Socher; Roderjan; Galvão (2008), and Ribeiro et al. (2010). A linear carbon concentration factor of 0.45 was used to estimate the carbon stock of the study area, obtained according to Wang et al. (2001), and has served as the basis for numerous studies.

Results

To analyze the NDVI, the closer to one, the higher the forest cover (LAI) and the closer to zero the lower the green coverage of the area under study. Negative values refers to water coverage. Thus, although simplistic, the strategy for defining NDVI classes for the different secondary forest successional stages was based on the physical response of the forest, given the nonlinear proportionality that exists between the amount of leaves and the NDVI.

The values of the NDVI in this study ranged from 0.50 to 0.85 in the three successive stages, with IS in the range from 0.5 to 0.6, due to a low canopy vegetation, locally named 'capoeirão' (similar to savanna), vegetation with absence of young trees and shrubs, thus presenting a lower reflectance. The MS was in the range from 0.6 to 0.7, increasing the NDVI due to the presence of tree-sized plants and their greater reflectance. Finally, the NDVI of the AS was superior to 0.7 for all evaluated dates. The adjustment of the LAI intervals as a function of the NDVI to be estimated

and the stages was carried out based on known sites in the field.

Forest areas seasonal variations (winter-summer) are clearly represented at all stages of succession given some small variations of the date of image acquisition. Thus, as the forest loses leaves, NDVI presented lower values and as budding occurs, the value tends to increase. This may explain the discrepancy between the smallest and largest values since images such as those from 1999 were obtained in early September. In this period, most of the trees that make the top cover have new leaves and light shades of green, that is, a lower concentration of chlorophyll, which explains the low values of NDVI found. Also due to the period of image acquisition, the position of the sun can cause a great shading of the larger trees, which also explains the NDVI values (due to directional and angular effects).

The values of LAI vary from 1.0 for the IS regeneration to 2.2 when transitioning to the MS, obtaining values of 2.2 to 4.5 and values with LAI superior to 4.5 in the AS regeneration.

In this study, the maximum value obtained was 5.75 of LAI that corresponds to 0.85 of NDVI for the advanced stage of regeneration. The lowest value found was for the initial stage, with a LAI of 1.012. We classified the forests based on the LAI data estimated through the NDVI. This was fundamental to obtain the covered area of each successive stage for our time series (Table 1).

It is possible to observe that the area found in the advanced stage of regeneration in 1999 is not correct since most of it has IS NDVI. This occurs because the image was obtained at the beginning of September, when most of the arboreal plants belonging to this successional stage lost their leaves (seasonal effects). The deciduous and seasonal forests have a lighter green coloration due to shading caused by larger trees and the solar light incidence angle. The same can be observed on other dates, such as 1990 and 1993, when both images were obtained from August to September. Thus, the study demonstrates that images from this period should not be used to estimate biophysical data.

Still, many small isolated fragments in the early stage of regeneration ended up clustering, forming new larger fragments and accumulating a greater forest biomass. The same occurred for fragments in the middle and advanced stage of regeneration, where the junction of these fragments resulted in the formation of large fragments. At this point, it is important to remember that there was no

distinction between native and commercial forest and, thus, the measures presented include both types of forests.

Table 1. Area in hectares of regeneration stages after adjusting the LAI logistic model according to the NDVI.

Year	IS	MS	AS
1985	13,641	69,385	58,890
1986	23,336	105,852	10,221
1987	18,621	54,089	326,53
1988	12,316	44,260	108,364
1989	7,610	30,698	117,486
1990	37,810	81,675	4,997
1991	13,609	57,504	63,732
1992	11,642	39,459	96,494
1993	49,335	81,080	1,557
1994	7,979	36,472	130,633
1995	11,435	37,535	117,256
1996	20,458	95,665	447,09
1997	1,901	21,532	150,830
1998	12,316	44,260	108,364
1999	89,686	19,199	38,000
2000	13,452	69,865	80,536
2001	26,569	112,316	243,17
2002	5,527	29,484	135,673
2003	21,061	49,951	647,87
2004	10,586	44,941	110,975
2005	8,586	35,890	152,730
2006	9,142	36,519	145,429
2007	7,744	44,863	135,619
2008	7,289	27,491	122,766
2009	15,203	54,727	124,199
2010	10,670	41,239	142,161
2011	6,773	34,253	162,236
2012	6,596	25,125	128,465
2013	5,785	19,673	135,880
2014	8,935	46,756	137,295

The amount of biomass was 0.067 Gg/ha in the IS, 0.177 Gg/ha in the MS and 0.38 Gg/ha in the AS of regeneration. In 1985, the total area of initial stage was of 13,641 hectares, totaling 919 Gg of biomass, the area of medium stage was 69,385 ha, totaling 12,297 Gg, and in the advanced stage of 58,890 ha, totaling 22,419 Gg. The evolution of forest fragments in the 30 years and in

the three classes of regenerations can be observed in Table 2.

The total biomass found in 2014 was of 602 Gg for the initial stage, 8,287 Gg for the middle stage, and 52,267 Gg for the advanced stage of regeneration, totaling 61,156.50 Gg of forest biomass in secondary succession. In 1985, the total biomass was 35,636 Gg, almost half of the total

biomass in 2014, demonstrating an increase of about 41.7%. As it was possible to observe an increase in the area in hectares of the succession

stages, it is also possible to observe an increase in biomass and carbon, related to the increase in the LAI.

Table 2. Biomass in Gg for the study area at each regeneration stage.

Year	IS	MS	AS	TOTAL
1985	919	12,297	22,419	35,635
1986	1,573	18,761	3,890	24,224
1987	1,255	9,586	12,430	23,271
1988	830	7,844	41,253	49,927
1989	512	5,441	44,725	50,678
1990	2,548	14,476	1,902	18,926
1991	917	10,192	24,262	35,371
1992	784	6,993	36,734	44,511
1993	3,325	14,370	592	18,287
1994	537	6,652	49,730	56,919
1995	770	6,652	44,638	52,060
1996	1,379	16,955	17,020	35,354
1997	128	3,816	57,419	61,363
1998	830	7,844	41,253	49,927
1999	865	10,113	35,956	46,934
2000	901	12,382	30,659	43,942
2001	1,791	19,906	9,257	30,954
2002	372	5,225	51,649	57,246
2003	1,419	8,853	24,663	34,935
2004	713	7,965	42,247	50,925
2005	578	6,361	58,142	65,081
2006	616	6,472	55,363	62,451
2007	522	7,951	51,629	60,102
2008	491	4,872	46,735	52,098
2009	1,024	9,699	47,281	58,004
2010	719	7,309	54,119	62,147
2011	456	6,071	61,761	68,288
2012	444	4,453	48,905	53,802
2013	389	3,486	51,728	55,603
2014	602	8,287	52,267	61,156

The values obtained for 1999 were excluded because they were very different from the other years. Therefore, an average was generated between the values of 1998 and 2000 (due to the absence of an adequate image).

Analyzing the data obtained, it was possible to generate an average of the last five years studied, which served to dilute the error caused by

satellite images, resulting in an average value of 60,199.20 Gg of forest biomass, clearly demonstrating an increase in biomass in the study area.

The initial stage of regeneration did not have much presence in 1985 and 2014, when the total biomass was composed of the middle stage of regeneration, with few fragments in advanced

stage, which were generally concentrated in three protected areas found in the study area, two indigenous reserves and a state park (Figure 1). There was a confusion of reflectance and shading in 1999 because the leaves of the fragments of the advanced regeneration had fallen, since the period

of the image collection was in September, and the fragments were characterized as an initial stage. It is possible to observe a large evolution of the dynamics of forest fragments for 2014, especially for the advanced stage of regeneration (Figure 2).

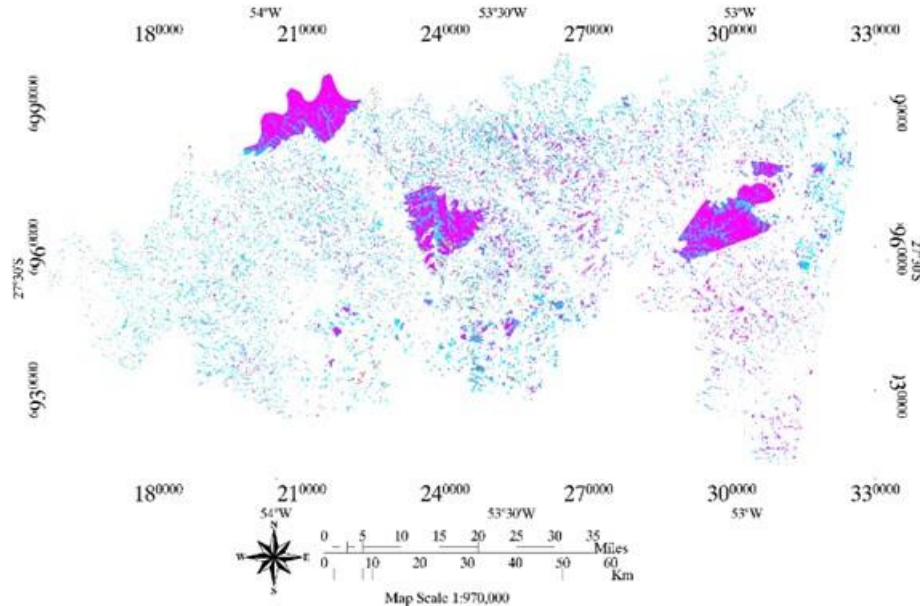


Figure 1. Map of the distribution of biomass stock in the succession stages for the year 1985. Caption: Wine: initial; Cyan: medium; Magenta: advanced.

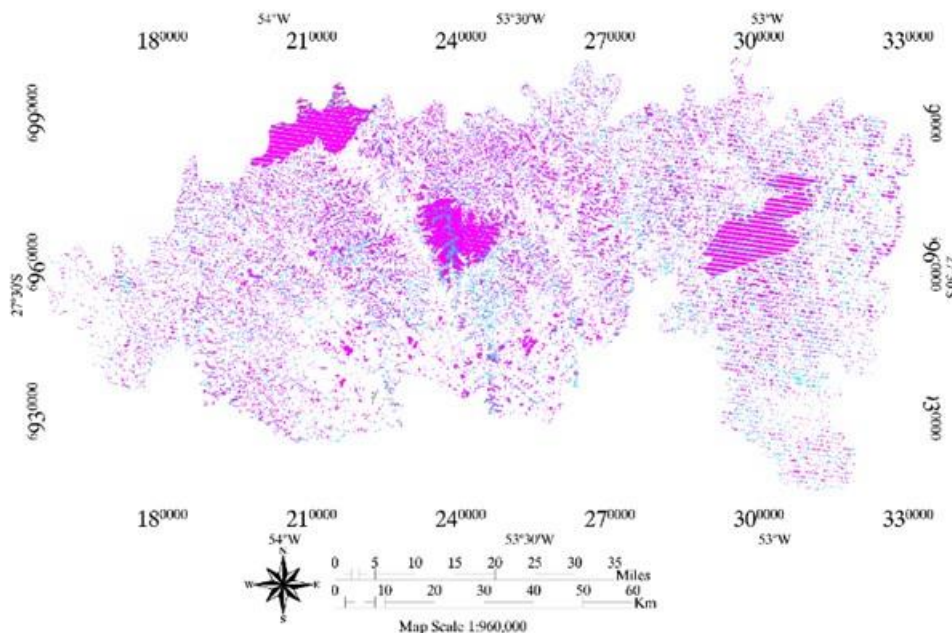


Figure 2. Map of the distribution of biomass stock in the succession stages for the year 2014. Caption: Wine: initial; Cyan: medium; Magenta: advanced.

The study area has three preserved remnants of native Atlantic Forest, very significant in terms of biomass, being the Parque Estadual do Turvo and the Guarita and Nonoai Indigenous Reserves, which have a high carbon stock and a

great potential for expansion of advanced biomass according to data found in the temporal study carried out.

It is possible to emphasize that there was a great evolution of biomass in the study area,

proving the consolidation of areas. Very small forest fragments ended up joining with larger fragments or were simply increasing due to the abandonment of the areas surrounding them. With the evolution of technology, these areas were no longer mechanizable, and therefore became an early stage shrubbery forest, thus evolving to medium and advanced stage of regeneration. Examining the fragments spatial distribution it is

noticed that most of them are located in areas close to the areas of permanent preservation of rivers, lakes, and springs, as well as on land unsuitable for mechanized farming.

Another relevant question for this study is the quantification of carbon present in forest biomass, where carbon constitutes 45% of the estimated biomass (Table 3).

Table 3. Carbon in Gg for the study area at each Successional Stage

Year	IS	MS	AS	TOTAL
1985	413	5,533	10,088	16,034
1986	707	8,442	1,750	10,899
1987	565	4,314	5,593	10,472
1988	373	3,530	18,776	22,679
1989	203	2,448	20,126	22,777
1990	1,146	6,514	856	8,516
1991	412	4,586	10,918	15,916
1992	353	3,147	16,530	20,030
1993	1,496	6,467	266	8,229
1994	242	2,993	22,379	25,614
1995	347	2,993	20,087	23,427
1996	621	7,630	7,659	15,909
1997	58	1,717	25,839	27,613
1998	374	3,530	18,564	22,467
1999	60	1,531	6	1,598
2000	405	5,572	13,797	19,774
2001	806	8,958	4,166	13,929
2002	167	2,351	23,242	25,761
2003	639	3,984	11,098	15,721
2004	321	3,584	19,011	22,916
2005	260	2,862	26,164	29,286
2006	277	2,912	24,913	28,103
2007	235	3,578	23,233	27,046
2008	221	2,192	21,031	23,444
2009	461	4,365	21,276	26,102
2010	324	3,289	24,354	27,966
2011	205	2,732	27,792	30,730
2012	200	2,004	22,007	24,211
2013	175	1,569	23,278	25,021
2014	271	3,729	23,520	27,520

The amount of carbon was 0.030 Gg/ha in the IS, 0.079 Gg/ha in the MS, and 0.171 Gg/ha in the AS of regeneration. The total estimated carbon

for the study area in 2014 was 27,520 Gg CO₂, of which 271 Gg were present in the initial stage, 3,729 Gg in the middle stage, and 23,520 Gg in the

advanced stage. It is possible to observe that the carbon present in this study had a significant increase from 1985 to 2014, especially in the advanced stage, which doubled in less than 30 years.

Before the beginning of colonization, the study area was fully covered by native forests, belonging to the Atlantic Forest biome, with FOM and FED forest typologies. Colonization opened up spaces for agriculture, livestock, and housing, modifying the land use, where only a few forest fragments remained, resulting in large emissions of CO₂ to the atmosphere. As technological evolution occurred, areas impossible to be mechanized were abandoned, regenerated their initial formations. Thus, it is possible to observe that the abandoned or otherwise evolving areas of the fragments still have a great capacity to store the CO₂ present in the atmosphere, which helps to reduce this gas and positively add to the context of climate change.

In turn, the three large areas present in the study (Guarita and Nonoai Indigenous Reserves and Parque Estadual do Turvo) have a high stock of biomass and carbon, which are very important and should be treated with greater attention. Incentive programs such as REDD can be installed to further increase the potential of these areas in mitigating and storing carbon.

It is possible to observe a trend from 2012, where biomass and carbon began to increase, coinciding with the enactment of Law 12,651, which provides for native vegetation, where the suppression of new areas of native vegetation for other purposes is prohibited. With the growing concern about climate change and large CO₂ emissions to the atmosphere, the stock of CO₂ in plants tends to only increase, until the vegetation reaches the stage of primary forests and stagnates the growth and mitigation, becoming a forest with great importance of carbon stock.

Therefore, we can conclude that in 30 years of study (1985 to 2014), there was an increase of 11,486 Gg of carbon that corresponds to 42,119 Gg of CO₂ removed from the atmosphere.

Discussion

Estimates based on remote sensing data and the size of the fragments can be evaluated

through vegetation indices since these depict vegetative vigor and leaf cover in the area under study and did not reach the saturation. Therefore, in this study, the forest biomass and carbon for each successive stage was estimated throughout the northwestern region of Rio Grande do Sul, through the NDVI and LAI, adjusting a global model with local bases, using remote sensing data.

In studies carried out by Luz et al (2022), vegetation indices related to caatinga vegetation showed a positive and significant correlation with aboveground biomass values estimated by allometric equations. Furthermore, Pedreira Junior et al (2020) analyzed the biophysical parameters of the surface in different uses and occupations in Cuiabá. The sites with the highest amount of plant biomass (DV) had the highest values of NDVI and radiation balance, in addition to the lowest values of surface albedo and surface temperature. Such studies agree to our results, considering the use of NDVI stratus.

According to Madugundu et al. (2008), the NDVI presents a strong relationship with the LAI and the global model generated by Knyazikhin et al. (1999) allowed the adjustment of a logistic regression, and from it, the estimation of the LAI. From this equation adjustment and the NDVIs calculated for each image, it was possible to calibrate the LAI model according to NDVI levels. The generated model behaved very well for the adjustment of the NDVI values found, where we obtained 30 samples of LAI with model significance (p-value) inferior to 0.0001 and R² 0.99. As the NDVI values increased, it was possible to observe an increase in the LAI estimate.

According to studies carried out by Caruzzo and Rocha (2000), the estimate of the accumulated LAI in a pasture region was 2.63, while for a forest region, it was 4.97, thus demonstrating that the LAI increases from the initial stage known as shrubbery forests, to the advanced stage, a mature forest.

According to Breunig et al. (2015), in studies conducted in the Parque Estadual do Turvo, the LAI from January to December ranged from 6.5 in the summer to 3.4 in the winter. The values were the lowest in September, reaching 3.4, demonstrating large oscillations when plants lose leaves and chlorophyll decreases, which leads to a

decrease in the absorption of electromagnetic radiation by pigments and incurs an increase in reflectance in the visible spectral range. This fact reaffirms the care that must occur when selecting the date when the images are obtained. Furthermore, one should be careful with the geometry of illumination during the winter, which leads to changes in reflectance and, consequently, in the value of NDVI and biophysical parameters calculated in sequence (Breunig et al., 2015).

The studies conducted by Rosa (2016) demonstrate a trend of a greater density of rural population in the 1980s and earlier, due to which there was an advance of anthropic occupation over native forest areas, causing forest suppression and fragmentation (in part associated with the government's agricultural expansion policy). As the rural exodus increased (for various reasons), the labor force in the countryside decreased and areas of difficult cultivation or access were abandoned and/or occupied by cultivated forests. Thus, there was a high emergence of new forest fragments, which are at an early stage of development.

Another important highlight is the development of rich snippets over the next 30 years. Such areas ranged widely and remained constant only from in 2007, later coinciding with the creation of a new Forest Code, Law 12,651 of May 25th, 2012 (BRASIL, 2012), in which the extraction activity began to be more precisely controlled, leading the people to a greater awareness of preserving and adding value to the forest. As result a tendency to stabilize the decline of the forest fragments, thus, resulting in an increase in forest biomass and carbon.

According to the studies carried out by Costa and Lameira (2022), who studied the characterization of the NDVI through Pléiades images in two forest areas, one managed and the other secondary forest. Regarding the minimum and maximum reflectance data found by the authors in the two study areas, the NDVI was higher in the secondary forest, indicating a value of approximately 0.736 and 0.849 respectively with an average of 0.790.

According to Madugundu et al. (2008), when an increase in LAI occurs, there is also a proportional (nonlinear) increase in NDVI values,

demonstrating that NDVI levels are good indicators of LAI values, and that as the leaf area (LAI) increases, there is an increase in accumulated biomass. The same occurred with this study. As the NDVI increased, an increase in leaf area occurred, demonstrating the difference in the succession stages and causing an increase in forest biomass according to the succession stage.

In studies conducted by Goswami et al. (2015), all NDVI relationships with the LAI and biomass demonstrated strong exponential relationships, with $R^2 \geq 0.7$ indicating that NDVI saturates to estimate higher values of biomass and LAI. On the other hand, the strong linear relationship between LAI and biomass suggests that there is no saturation in the measurement of biomass and LAI. R^2 was superior to 0.7 for this study, indicating that there will be NDVI saturation at some point, but there will be no LAI and biomass saturation. The strong relationship observed between NDVI and LAI with the biomass found in this study is similar to studies conducted in other ecosystems such eucalyptus plantations (Berger, et al. 2019) and the high arctic tundra (Walker et al., 2003).

According to studies conducted by Boelman et al. (2003), the greener the leaf area, the higher the LAI and photosynthetically active radiation (PAR), and the higher the NDVI values, which was also observed in this study.

Piazza et al. (2016) proved that all the sample units studied when mapping the early forest remnants are represented by inhomogeneous vegetation. The initial regeneration classes presented the highest digital number values along the spectrum due to the more regular structuring of the canopies. The opposite was found for the advanced vegetation classes, where there is a greater irregularity of the canopies, and thus a greater influence caused by shade. This study conducted by Piazza et al. (2016) demonstrated the similarity of the succession stages in spectral terms, once again emphasizing the importance of care, such as the date of acquisition of images, due to the difficulty of classifying heterogeneity through images.

The methodology proposed by this study demonstrated the possibility of using remote

sensing data spectral response to estimate biomass and carbon. However, it should be noted that biomass estimation based on remote sensing encompasses several factors, such as image quality and pixel size, data saturation, biophysical environments, extracted remote sensing variables, and the algorithm variables that may affect the estimation (Luther et al., 2006). Thus, the results archived required care and more validation procedures.

The use of remote sensing as a tool for environmental analysis, such as the survey of vegetation cover, can facilitate environmental control for researchers for the monitoring of vegetation cover, associating the use of technologies aimed at planning and environmental control (PEREIRA et al, 2020).

Conclusion

An indirect empirical estimation model was applied, where the classification was performed according to the leaf area index adjusted by the NDVI to calibrate the biomass stock estimates. Due to this fact, the model estimated more exact values, closer to the real ones.

It is possible to estimate the forest biomass and carbon stock for the entire northwest region of the state of RS, in primary and secondary forests, in the three stages of regeneration, using the proposed methodology.

According to the methodology, the forest biomass in 2014 in the northwestern region of the state of Rio Grande do Sul was 61,156 Gg, divided into three stages of initial (602 GG), medium (8,287 Gg), and advanced regeneration (52,267 Gg).

The estimated carbon stock for the study area in 2014 was 27,520 Gg, which were also estimated according to the succession stage, initial (271 Gg), medium (3,729 Gg), and advanced (23,520 Gg).

Therefore, according to the methodology developed in this study, considered the most realistic and conserved, we can conclude that there was an increase of 11,486 GG of carbon that corresponds to 42,119 Gg of CO₂ removed from the atmosphere in the study area in 30 years of study (1985 to 2014).

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