Anais da Academia Brasileira de Ciências (2019) 91(4): e20180839
(Annals of the Brazilian Academy of Sciences)
Printed version ISSN 0001-3765 / Online version ISSN 1678-2690
http://dx.doi.org/10.1590/0001-3765201920180839
www.scielo.br/aabc | www.fb.com/aabcjournal

# Energy balance and $CO_2$ emission in mechanized biomass harvesting in pine stands under thinning

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*Manuscript received on August 8, 2018; accepted for publication on December 21, 2018*

**How to cite:** RODRIGUES CK, LOPES ES, SILVA DA, FIGUEIREDO FILHO A AND PELISSARI AL. 2019. Energy balance and $CO_2$ emission in mechanized biomass harvesting in pine stands under thinning. An Acad Bras Cienc 91: e20180839. DOI 10.1590/0001-3765201920180839.

**Abstract:** Biomass is an important component of the Brazilian energy matrix, with a potential contribution of co-products from thinned forests. The aim of this work was to evaluate the energy balance and $CO_2$ potential emission in mechanized biomass harvesting operations in *Pinus taeda* stands at 9 and 10 years-old and under thinning, searching to support the use of co-product biomass from thinning as a renewable energy source. Thinning was carried out through cut-to-length harvesting method, in which large logs for sawmill and small logs for energy were produced. In addition, tops, needles, barks, and branches were considered as co-products. The balance between consumed energy and emitted $CO_2$ by machines for thinning in relationship to the energy and $CO_2$ in thinned biomass was estimated. Thus, dry matter, energy potential, and $CO_2$ potential emission were evaluated and compared considering thinning stand ages as treatments. Mechanized thinning consumes a large energy and produces $CO_2$, however, the energy consumed by machines is lower than 1% of the estimated energy potential in thinned biomass, while the $CO_2$ emission is lower than 0.5% of the biomass. Therefore, the use of co-product biomass of thinning is an important way to mitigate greenhouse gas emission.

**Key words:** biomass energy, co-product forest biomass, forest harvesting, sustainability.

## INTRODUCTION

Biomass is an important component of the Brazilian energy matrix, which represents 25.4% of the total domestic supply, consisting of sugarcane biomass, firewood, and charcoal (EPE 2018). Moreover, the expectation for the coming years is an increasing contribution of the forest resources, mainly of co-product biomass from wood harvesting operations (Welfle 2017). This tendency is related to the introduction of proposals to mitigate greenhouse gas emissions, according to the Brazilian Decree No. 9,073 from June 5, 2017, which promulgates the Paris Agreement under the United Nations Framework Convention on Climate Change (Brasil 2017).

Wood harvesting can be an important source of co-products in stands under thinning, such as

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small logs, tops, barks, branches, leaves, stumps, and roots (Whittaker et al. 2011). In pine stands, thinning is applied along the forest rotation period, mainly in ages before the growth and yield biomass stagnation (Del Río et al. 2017, Rodrigues et al. 2018). The quantity of thinned co-products is higher than the quantity of products for industrial processes, and therefore co-products require appropriate use to mitigate the timber harvesting costs (Han et al. 2018); these costs are usually high due to the lower productivity and mobility of machines and the smaller volume of thinned trees (Acuna et al. 2017, Nuutinen et al. 2010, Rodrigues et al. 2018).

In Brazil, the use of co-product biomass for energy is limited to the forest final cutting through full-tree harvesting method and at short distances between field and consumer unit. On the other hand, mechanized thinning is predominantly carried out through cut-to-length harvesting, in which most co-products remain on the forest ground and due to the difficulty of removal and processing. Thus, Brazilian forestry companies usually choose to leave co-product biomass on the field, aiming to contribute for nutrient cycling and reduce soil compaction (Szymczak et al. 2014).

Thinning shows some advantages in relationship to clearcutting, such as the possibility to stock biomass on the field, which ensures the loss of biomass moisture without compromising future silvicultural activities; protection of soil to the weather, reducing nutrient losses and erosion; and sequestration of carbon dioxide ($CO_2$) by remaining trees in the stands (Alvarez et al. 2016, Borys et al. 2016, Mangoyana 2011). On the other hand, thinning is carried out by machines which consume high energy derived from fossil fuel that represents approximately 80% of the total energy consumption by the forest operations (Klvac et al. 2003), which may cause environmental impacts (Spinelli et al. 2014, Valente et al. 2011).

Co-product biomass sustainable use can be estimated through the balance of energy consumed and $CO_2$ produced by the forest machines and the energy potential and $CO_2$ in thinned co-product biomass. Studies carried out by Valente et al. (2011), Whittaker et al. (2011) and Zhang et al. (2006) determined the demand of forest biomass harvesting and transportation for fossil fuel, as well as its $CO_2$ emission. However, few researchers have associated these values with the quantities of energy and $CO_2$ in the thinned biomass, especially the co-products.

Some studies about the energy balance in wood harvesting systems were carried out (Klvac et al. 2003, Borys et al. 2016). However, there is a great variability about machines, harvesting operation methods, climatic conditions, as well as forest species. In this context, we highlight the absence of studies in Brazil about the energy balance of mechanized biomass harvesting in cut-to-length system with the biomass produced by thinning operations. Thus, the forestry companies do not know the residual thinning biomass potential for energy purposes.

In this context, the aim of this work was to evaluate the energy balance and $CO_2$ potential emission in mechanized biomass harvesting operations in *Pinus taeda* L. stands under the first thinning, searching to support the use of co-product biomass from thinning as a renewable energy source. Thus, we can demonstrate the use of co-product biomass is an important way to attenuate greenhouse gas emission, since the consumed energy and produced $CO_2$ by the harvesting machines can be mitigated by the thinned biomass.

## MATERIALS AND METHODS

### STUDY AREA

This study was carried out in *Pinus taeda* stands at 9 and 10 years-old (Table I) in a forestry company located in Quedas do Iguaçu, Paraná State, Brazil,

**TABLE I**
**Descriptions of *Pinus taeda* stands under thinning at 9 and 10 years-old.**

| Descriptions | Age of thinning (year) | |
|---|---|---|
| | 9 | 10 |
| Date of planting | 2006 | 2005 |
| Date of low pruning | 2010 | 2009 |
| Initial trees per hectare | 1.667 | 1.667 |
| Mortality rate (%) | 14.0 | 15.0 |
| Average diameter at 1.3 m above the ground (cm) | 19.6 | 19.1 |
| Average total height (m) | 15.2 | 15.6 |
| Average dominate height (m) | 17.9 | 17.9 |
| Average tree volume (m³) | 0.225 | 0.215 |
| Average distance from the consumer unit (km) | 50 | 50 |

between the coordinates 25º26’ S and 52º55’ W. The region’s climate is classified as humid subtropical (Cfa) through the Köppen criteria, with hot summer, annual mean temperature between 18 and 20°C, and annual rainfall of 1,900 to 2,200 mm (Alvares et al. 2013). The region’s soil is classified as Neolithic lithole, with average slope equal to 8% and altitude of 566 m.a.s.l.

In the first thinning, the fifth row of trees was systematically removed in the *Pinus taeda* stands at 9 and 10 years-old, corresponding to 20% of trees per hectare. Then, 30% of trees were selectively removed in the two rows on both sides of the machine traffic trail (fifth row) due to the reach of the harvester crane. Thinning operations decreased the initial stand basal area in 35%.

Two timber assortments were produced by the thinning, according to the forestry company goals: 1) large logs for sawmill (15 to 35 cm of diameter and length of 3.60 m), and 2) small logs for energy (3.5 to 15 cm of diameter and length of 3.05 m). In addition, top (final stem with diameter smaller than 3.5 cm), needles, barks, and branches were considered as co-products.

Thinning was carried out through cut-to-length harvesting system, in which trees were cut and extracted by harvester and forwarder machines, respectively (Figure 1). The harvester had 84 kW power, hour meter of 2,370 hours, crane reach of 7.2 m, continuous track, and harvester head with diameter of 63 cm. The forwarder had 158 kW power, load capacity of 16.5 Mg, hour meter of 5,540 hours, 8WD, crane with maximum reach of 7.8 m, and claw area of 0.28 m².

## ENERGY POTENTIAL AND CARBON DIOXIDE EMISSION OF HARVESTING MACHINES

Energy potential and carbon dioxide equivalent emission ($CO_2$) from thinning operations were evaluated by means of the effective time and fuel consumption of machines per hectare. Effective time was obtained through a time-motion study in an area of 10 ha in each stand (9 and 10 years-old), aiming to estimate the consumed effective time in cut and extraction operations per hectare. Machines’ fuel supply was measured through the ratio between supplied fuel quantity and machines’ hour meter. This value was multiplied by the machine’s effective time to obtain the mean fuel consumption per hectare.

Energy potential (EP) of harvesting machines was estimated by the fuel consumption per hectare (FC) multiplied by the fuel energy quantity (0.04 GJ $L^{-1}$) for diesel (Handler et al. 2014), according to Equation 1. Machines’ carbon dioxide equivalent emission ($CO_2$) was determined by the fuel consumption per hectare (FC) multiplied by a conversion factor (2.431 kg $CO_2$ $L^{-1}$) for diesel (FGV 2009) that represents the $CO_2$ quantity in each consumed fuel liter (Equation 2).

$$EP = FC \times 0.04 \qquad \text{Eq. (1)}$$

$$CO_2 = \frac{FC \times 2.431}{1{,}000} \qquad \text{Eq. (2)}$$

Where: EP is the energy potential (GJ $ha^{-1}$), FC is the fuel consumption (L $ha^{-1}$), 0.04 is the


**Figure 1-** Harvester **(a)** and forwarder **(b)** machines in the first thinning of *Pinus taeda* stands at 9 and 10 years-old.

conversion factor for energy potential for diesel (GJ $L^{-1}$), $CO_2$ is the potential carbon dioxide emission (Mg $ha^{-1}$), and 2.431 is the conversion factor for $CO_2$ emission for diesel (kg $CO_2$ $L^{-1}$).

### ENERGY POTENTIAL AND CARBON DIOXIDE POTENTIAL EMISSION OF THINNED BIOMASS

Thinned biomass energy potential was estimated by means a forest inventory, in which 10 plots of 630 m² were systematically allocated in each stand, considering a maximum error of 10% at the 95% confidence level. Then, a sample with 10 and 11 thinned trees, respectively in the stands of 9 and 10 years-old, were randomly selected according to stand diameter distribution and partitioned in large logs (when the tree size was possible), small logs, tops, needles, barks, and branches. A digital dynamometer of 500 kg capacity was used to measure the green matter.

Tree biomass component samples were collected to measure the dry matter, in which four stem disks with bark were collected at 0%, 25%, 55%, and 75% of the total height. Needle and branches were sampled at the base, middle, and top of the branches in the middle-third of tree crowns. These samples were dried at 105ºC in an oven with air circulation and renewal until constant weight, determining the dry matter with a precision balance of 0.01 g.

Hydrogen (H%) and carbon (C%) elemental contents were determined from samples composed of different trees biomass components and grouped in three diameter classes: low (3.5 to 13.5 cm), medium (13.6 to 21.0 cm), and high (21.1 to 33.5 cm). Perkin Elmer CHN 2400 equipment was used according to the Pregl-Dumas method, in which samples were exposed to combustion in a pure oxygen atmosphere, in which the combustion gases were quantified in a thermal conductivity detector.

Higher heating value (HHV) was determinate as described in ASTM D5865-03 (ASTM 2003), with an IKA-WERNE C5000 adiabatic calorimeter pump. Biomass samples were dried and crushed, in which subsamples were obtained to measure the lower heating values (LHV), according to the Equation 3 (Cortez et al. 2008).

$$LHV = HHV - \left(600 \times 9 \times \frac{H\%}{100}\right) \quad \text{Eq. (3)}$$

Where: LHV is the lower heating value (kcal $kg^{-1}$), HHV is the higher heating value (kcal $kg^{-1}$), 6009 is the conversion factor of latent heat of water, and H% is the hydrogen content (%).

Energy biomass of thinned trees and their components was determined by the mean dry matter (DM) for diameter class and number of thinned trees per hectare. These results were multiplied by the lower heating value (LHV) to obtain the energy potential (EP) (Equation 4). Also, using the carbon content (C%) in the elemental analysis, the equivalent carbon dioxide emission ($CO_2$) was estimated (Equation 5) as recommended by IPCC (2000).

$$EP=DM\times(LHV\times4.1868\times10^{-3}) \quad \text{Eq. (4)}$$

$$CO_2=DM\times\left(\frac{C\%}{100}\right)\times\left(\frac{44}{12}\right) \quad \text{Eq. (5)}$$

Where: EP is the energy potential (GJ $ha^{-1}$), DM is the dry matter of tree components per hectare (Mg $ha^{-1}$), LHV is the lower heating value (kcal $kg^{-1}$), $4.1868\times10^{-3}$ is the conversion factor from kcal $kg^{-1}$ to GJ $Mg^{-1}$, $CO_2$ is the potential equivalent carbon dioxide emission (Mg $ha^{-1}$), C% is the carbon content (%), and 44/12 is the conversion factor for equivalent carbon dioxide.

Energy and $CO_2$ percentage balances of consumed energy and produced $CO_2$ by machines for thinning operations in relationship to the energy and $CO_2$ in the thinned biomass were estimated. Thus, mean values of dry matter (DM), energy potential (EP), and $CO_2$ potential emission were compared by the Student's t-test at a 5% significance level, considering stand ages as treatments and inventory plots as replicates. In addition, energy consumed to dry the biomass in drying oven was not considered in the energy balance, since sun's natural light is used under operational conditions to dry the biomass in the field for 60 days.

## RESULTS

Harvester machine shows a mean effective time of 4.2 hours for cutting one hectare, consuming 66.5 L of fuel (Table II). When converting this fuel consumption for energy potential and $CO_2$ emission, we obtained 2.7 GJ $ha^{-1}$ and 0.17 Mg $ha^{-1}$, respectively (Table II). In wood extraction, forwarder machine shows an effective time of 2.5 hours per hectare, with a mean fuel consumption of 27.8 L, energy potential equal to 1.1 GJ $ha^{-1}$ and $CO_2$ emission of 0.07 Mg $ha^{-1}$ (Table II).

Energy biomass in the thinned tree components was higher than the large logs biomass for sawmill (Figure 2), representing 55% at 9 years-old (Figure 2a) and 56% at 10 years-old (Figure 2b) of the total biomass removed from the stands and composed predominantly of small logs, branches, barks, needles, and tops. Also, co-product biomass (branches, barks, needles, and tops) was 30% of the total biomass for both stands and higher than the small logs biomass (Figure 2), which is the only tree component currently used by the company for energy purposes.

Mean values of dry matter, energy potential, and $CO_2$ potential emission of the thinned tree biomass components did not show statistical difference between stands under thinning at 9 and 10 years-old at a 5% significance level (Table III). Total thinned dry matter was approximately 31 Mg $ha^{-1}$ (Table III), which is lower than 35 Mg $ha^{-1}$ expected by the Brazilian forestry companies to economic use. Moreover, the mean dry matter for small logs was 14.3 Mg $ha^{-1}$, whereas for branches, barks, needles, and tops, which normally remain on the field, the dry matter was greater and equal to 16.8 Mg $ha^{-1}$ (Table III).

Energy potential for thinned tree component biomass was 265.4 GJ $ha^{-1}$ for small logs and 323.0 GJ $ha^{-1}$ for co-products (Table III), with mean values equal to 172.6 GJ $ha^{-1}$ for branches, 81.1 GJ $ha^{-1}$ for barks, 61.7 GJ $ha^{-1}$ for needles, and 7.7 GJ $ha^{-1}$ for tops and similar behavior of dry matter mean values. These results indicate a potential use of thinned co-products for energy purpose. On the other hand, $CO_2$ potential emission was 24.6 Mg $ha^{-1}$ for small logs and 29.8 Mg $ha^{-1}$

**TABLE II**
**Mean values of effective time, fuel consumption, energy potential, and $CO_2$ emission of harvester and forwarder machines for thinning operations in *Pinus taeda* stands at 9 and 10 years-old.**

| Age of thinning (year) | Effective time (h ha$^{-1}$) | Fuel consumption (L ha$^{-1}$) | Energy potential (GJ ha$^{-1}$) | $CO_2$ emission (Mg ha$^{-1}$) |
|---|---|---|---|---|
| | | *Harvester* | | |
| 9 | 4.219 | 66.5 | 2.710 | 0.176 |
| 10 | 4.254 | | 2.732 | 0.177 |
| Mean | 4.236 | 66.5 | 2.721 | 0.176 |
| | | *Forwarder* | | |
| 9 | 2.400 | 27.8 | 1.082 | 0.065 |
| 10 | 2.363 | | 1.065 | 0.064 |
| Mean | 2.382 | 27.8 | 1.073 | 0.064 |

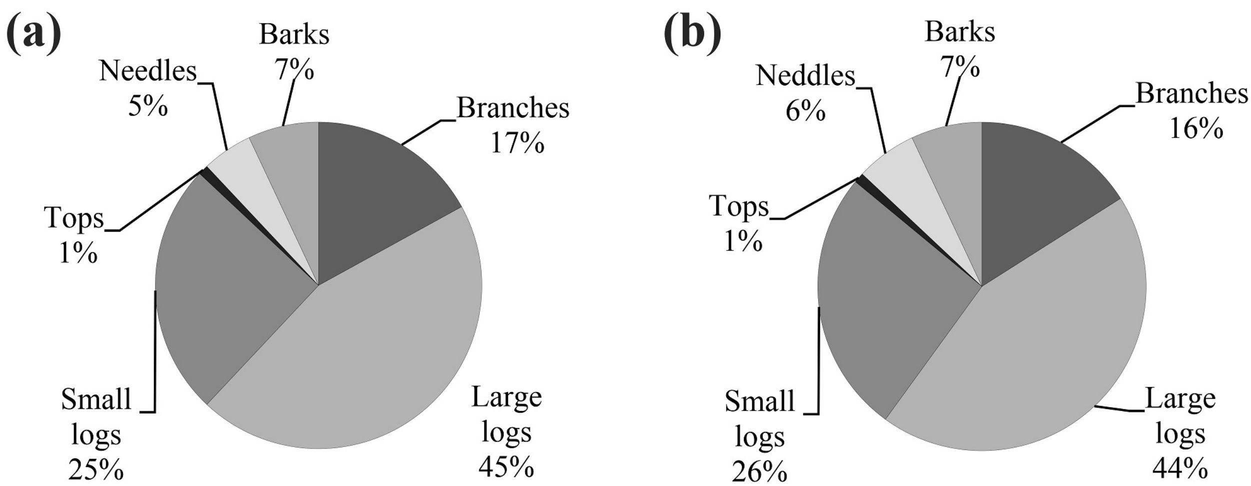


**Figure 2 -** Percentages of thinned tree components in *Pinus taeda* stands under thinning at 9 **(a)** and 10 years-old **(b)**.

for co-products with 16.0 Mg ha$^{-1}$ for branches, 7.5 Mg ha$^{-1}$ for barks, 5.5 Mg ha$^{-1}$ for needles, and 0.7 Mg ha$^{-1}$ for tops (Table III).

Harvester and forwarder machines consumed 3.8 GJ ha$^{-1}$ (Table II), while the total energy of thinned biomass was 588.4 GJ ha$^{-1}$ (Table III). The total $CO_2$ emission for the harvester and forwarder machines in thinning operations was 0.24 Mg ha$^{-1}$ (Table II), whereas the potential emission of the total energy biomass was 54.4 Mg ha$^{-1}$ (Table III). Thus, the energy consumed in wood harvesting represents 0.65% of the thinned biomass energy and 0.44% of the potential emission by its combustion. Therefore, the balance of energy and $CO_2$ emitted by thinning operations is lower than the potential energy and $CO_2$ in thinned biomass.

## DISCUSSION

By means of the effective time per hectare, harvester and forwarder machines spent a lot of time to cut and extract trees in the stands due to the selective thinning carried out at the two rows on both sides of the machine traffic trail (fifth row), in which the machines' mobility was difficult by the caution for avoiding damage in remain trees and the need to produce different wood assortments (Lopes et al. 2018). Thus, the machines showed high fuel consumption per hectare, mainly in the

**TABLE III**
**Mean values of dry biomass, energy potential, and $CO_2$ potential emission for thinned tree components in *Pinus taeda* stands under thinning at 9 and 10 years-old.**

| Age of thinning (years) | Tree component | | | | | |
|---|---|---|---|---|---|---|
| | Small logs | Tops | Needles | Barks | Branches | Total |
| | | | Dry matter (Mg ha$^{-1}$) | | | |
| 9 | 13.6 (±2.0) [a] | 0.4 (±0.02) [a] | 3.0 (±0.4) [a] | 4.0 (±0.5) [a] | 9.1 (±1.5) [a] | 30.1 (±4.0) [a] |
| 10 | 14.9 (±2.6) [a] | 0.4 (±0.03) [a] | 3.2 (±0.5) [a] | 4.2 (±0.5) [a] | 9.2 (±1.1) [a] | 31.9 (±4.5) [a] |
| Mean | 14.3 (±2.4) | 0.4 (±0.03) | 3.1 (±0.5) | 4.1 (±0.5) | 9.1 (±1.3) | 31.0 (±4.2) |
| | | | Energy potential (GJ ha$^{-1}$) | | | |
| 9 | 253.7 (±36.8) [a] | 7.8 (±0.4) [a] | 59.6 (±8.7) [a] | 79.2 (±10.3) [a] | 170.2 (±28.4) [a] | 570.5 (±75.9) [a] |
| 10 | 277.0 (±49.0) [a] | 7.5 (±0.6) [a] | 63.8 (±9.2) [a] | 83.0 (±10.0) [a] | 175.0 (±20.2) [a] | 606.3 (±84.6) [a] |
| Mean | 265.4 (±43.7) | 7.7 (±0.6) | 61.7 (±9.0) | 81.1 (±10.0) | 172.6 (±24.0) | 588.4 (±80.1) |
| | | | $CO_2$ potential emission (Mg ha$^{-1}$) | | | |
| 9 | 23.3 (±3.4) [a] | 0.7 (±0.1) [a] | 5.4 (±0.8) [a] | 7.4 (±1.0) [a] | 15.9 (±2.7) [a] | 52.7 (±7.0) [a] |
| 10 | 25.8 (±4.6) [a] | 0.7 (±0.1) [a] | 5.7 (±0.8) [a] | 7.7 (±0.9) [a] | 16.2 (±1.9) [a] | 56.1 (±7.8) [a] |
| Mean | 24.6 (±4.1) | 0.7 (±0.1) | 5.5 (±0.8) | 7.5 (±0.9) | 16.0 (±2.2) | 54.4 (±7.4) |

Same letter indicates non-significant difference ($p > 0.05$) between years.

cutting operation, which influenced on the $CO_2$ emissions (Prinz et al. 2018, Spinelli et al. 2014).

Machines' fuel consumption was also associated to the mechanized thinning characteristics (Spinelli et al. 2014), which provide greater energy consumption than the clearcutting and, consequently, highest $CO_2$ emissions (Handler et al. 2014). Thereby, the use of co-product biomass is emphasized, since the energy consumed by the harvesting machines can be mitigated using co-products biomass (Domke et al. 2012, Eker and Spinelli 2018). In addition, the quantity of co-product in first thinning is greater than the quantity of highest value-added products and its use can be intensified to increase the proportion of thinned biomass as an energy source (Hytönen and Moilanen 2014).

Energy biomass production can improve the financial sustainability of thinning operations and better forest management (Eker and Spinelli 2018). However, total thinned dry matter did not reach the desirable production required by the forestry companies, thus we can propose two alternatives to support the co-product management. The first is the use of alternative technologies, such as small machines to chip biomass on the field (Spinelli and Magagnotti 2013). The second is to increase the thinning intensity to 40% of removed basal area, which corresponds to an increase of 5 Mg ha$^{-1}$ without compromising the productive forest site (David et al. 2017).

According to David et al. (2017), basal area, total volume, and tree stem volume are under a greater forest site effect than the thinning intensity. Therefore, the increase of thinning intensity can be carried out in selective thinning areas, removing 5% of trees with lowest quality. In this situation, there would be more logs for energy and residual biomass, and the amount of biomass needed to meet the chippers' demand in forestry companies would be met.

Complete removal of tree components can result in soil degradation and nutrient loss, especially in the clearcut harvesting system, when the soil is exposed to the weather (Lattimore et al. 2009). Negative environmental impacts are increased by the removal of the leaves, since they present high levels of nutrients. Thus, Nurmi and Hillegrand (2002) recommended keeping the residual biomass in the field in sufficient time for the leaves to detach from the branches. On the other hand, this study evaluates thinning operations, in which the remaining tree components provide the cover for soil protection. In addition, woody debris was not considered, since it corresponds to the reserve necessary for the environmental balance and cycling of nutrients.

When the balance is evaluated, the energy consumed by machines is lower than 1% of the estimated energy potential in thinned co-product. Moreover, $CO_2$ emission from thinning was lower than 0.5% of the stocked $CO_2$ in co-product biomass and therefore the potential benefits need to be weighed considering its harvesting and transportation costs (Berhongaray et al. 2013, Eker and Spinelli 2018, Kinoshita et al. 2009), and logistics (Anderson and Mitchell 2016, Malladi and Sowlati 2018).

These results are limited to the residual biomass transport, since the transport of woodchips between forest and consumer unit is one of the weak points involved in the forest biomass chain. However, some studies have shown the energy consumed for transporting residual biomass is 2 to 10% of its energy value, which guarantees sustainability (Manzone and Balsari 2015). On the other hand, since the Brazilian forest sector is constituted by 1.58 million hectares of *Pinus* stands (IBÁ 2017), this study shows a first insight to future research about the potential use of co-product biomass from thinning as an important way to mitigate greenhouse gas emissions.

## ACKNOWLEDGMENTS

This study was carried out with Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Universidade Estadual do Centro-Oeste (UNICENTRO).

## AUTHORS CONTRIBUTIONS

RODRIGUES CK, LOPES ES, FIGUEIREDO FILHO A and SILVA DA conceived and designed the study; RODRIGUES CK performed the study; RODRIGUES CK and PELISSARI AL analysed the data; LOPES ES, FIGUEIREDO FILHO A and SILVA DA contributed to materials/analysis tools; RODRIGUES CK and PELISSARI AL wrote and revised the paper.

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