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Loss in CO_2 assimilation by forest stands relative to its emissions generated by the economic sector as an indicator of ecological consequences of a windstorm in the municipality of Brusy, NW Poland

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Abstract. The extent of damage to state and private forests as well as roadside and field buffer strips of trees in the urban-rural municipality of Brusy in the Pomerania Province, Poland, following the powerful windstorm on 11–12 August 2017, was calculated based on different data. The size of losses was expressed in m^3 of large (merchantable) timber harvested from windsnap or windthrow. The biomass of the destroyed assimilation apparatus was estimated using expansion factors and ratios of individual compartments of damaged trees representing 20 species. By applying conversion factors expressing the amount of carbon dioxide fixed during the year per unit of dry leaf biomass of each tree species, the total loss in net and gross photosynthesis, corresponding to the biomass of the destroyed assimilation apparatus, was estimated. The obtained values were compared with CO_2 emissions generated by the commune in 2006, 2013 and 2020. It has been found that the sum of losses in photosynthesis and CO_2 emissions generated by economic activity is a good indicator of environmental threats, and the percentage of losses accounted for by photosynthesis is a good indicator of ecological losses caused by the windstorm in the forest stands.

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Contents:

1. Introduction

Exacerbating climate change brings both global and local threats, including, for example, hurricane-force winds destroying nature, especially forest ecosystems. Strong winds are among the main factors threatening forest ecosystems. At the beginning of this century, Schelhass et al. (2003) reported that hurricane-force winds were responsible for about 53% of all losses that occurred in European forests in 1950–2000. The contribution of other adverse factors was much lower: fire accounted for 16% of losses, snow – 3%, and other abiotic factors – about 5%. Biotic factors accounted for 16% of all losses, of which damage caused by insects accounted for half, and the causes of the remaining 7% were unknown or constituted a combination of the above factors.

Such a devastating event in Poland in recent years was the windstorm on the night of 11–12 August 2017, which brought extensive damage to state and private forests and wooded buffers (Hościło & Lewandowska, 2018; Sulik & Kejna, 2020). The damage to Polish state-owned forests was roughly estimated at 12 million m^3 of windsnap and windthrow volume (Dmyterko & Bruchwald, 2020). The most severe damage was recorded in forests under the jurisdiction of the State Forests Regional Directorate (SFRD) in Toruń, where 4,659,000 m^3 of timber was harvested in 2017 and 2018 (i.e. after the 2017 windstorm), which accounted for 52.5% of the total harvest of 8,875,000 m^3 in five SF divisions (Dmyterko & Bruchwald, 2020). The forest divisions under the SFRD Toruń most affected by the 2017 windstorm were Rytel, Czersk and Przymuszewo (Fig. 1A). The volume of wood harvested from windsnap and windthrow after the windstorm in these forest divisions in 2017–2018 amounted to 1,350,000, 741,000 and 491,000 m^3 (Dmyterko & Bruchwald, 2020).

A significant part of the area occupied by the three above-mentioned forest divisions belongs to the municipality of Brusy, which is one of the most attractive in terms of nature and the most dynamically developing municipalities in the Pomerania Province and the entire Pomerania region. The municipality effectively and consistently implements an economy of sustainable development, conducts environmental monitoring and economic development planning, and implements an ambitious programme of economy aimed at reducing CO_2 emissions and carbon footprint. The said windstorm in August 2017 considerably disrupted and complicated the implementation of these plans by disturbing the structure of forest ecosystems and causing economic losses. A significant change in the structure of forest phytocoenoses was the reduction in the assimilation apparatus of trees and

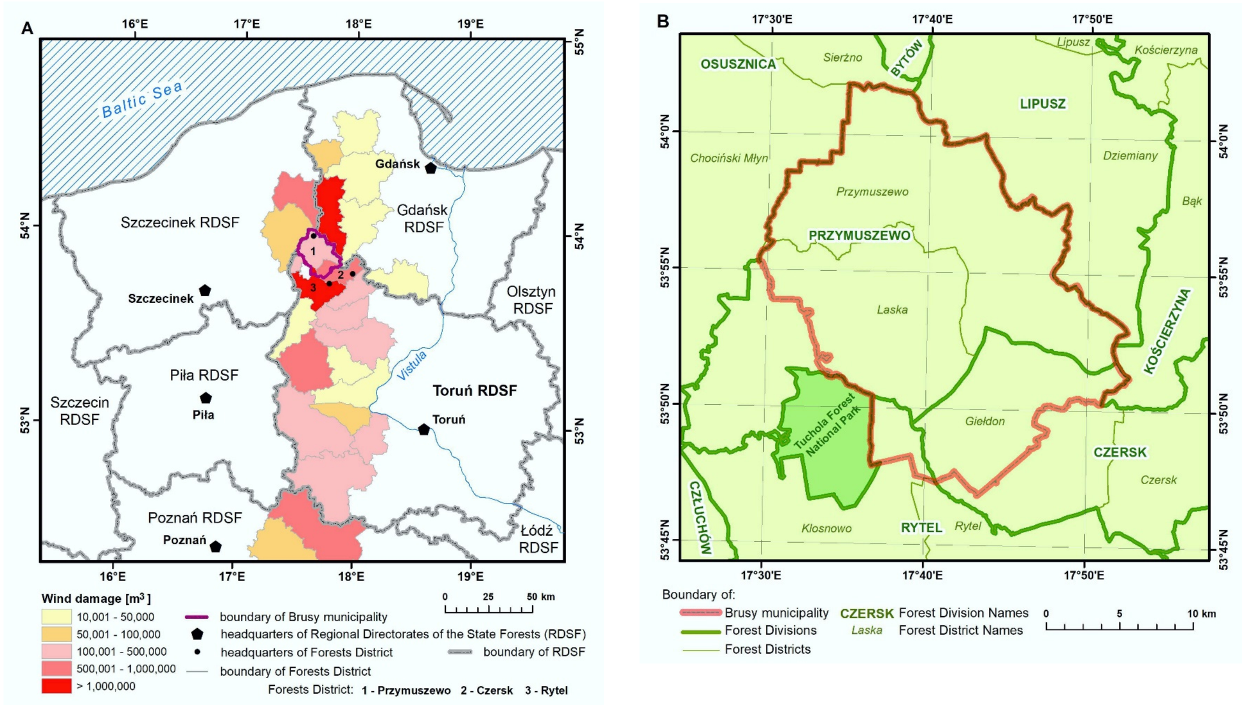

Fig. 1. Location of Brusy municipality relative to windstorm route on 13 August 2017 (A); and relative to State Forest administrative division units (B)

Source: author's own work

wood harvested from windsnap and windthrow exported outside the ecosystem. The biomass loss by the assimilation apparatus of forest stands leads to a reduction in the amount of CO_2 captured in the process of photosynthesis by this crucial compartment of a forest ecosystem.

Wind damage caused in forests is most often estimated in volume units of fallen and broken trees or in m^3 of wood harvested from disaster areas. In the era of climate change, counteracting the greenhouse effect and recommendations to analyse the carbon footprint in various economic activities, when analysing losses, the carbon content in the damaged stand or harvested wood is also estimated. So far, such damages have not usually been quantified on the basis of carbon sequestration losses resulting from the destruction of the assimilation apparatus of wind-fallen trees on large forest areas.

In the 1990s, the Przymuszewo Forest Division, affected by the windthrow of August 2017, was a testing ground where losses in gross primary production of forests resulting from the use of clear felling were studied. The methodology for calculating these losses developed at that time was described in detail in a series of publications (Barcikowski, 1991, 1992, 1994, 1996; Barcikowski & Loro, 1993, 1995; Nienartowicz & Barcikowski, 1996; Deptuła, 2006; Deptuła et al., 2017; Jarzębski et al., 2010; Wilkoń-Michalska et al., 2006). We therefore decided to use the same methods and conversion factors obtained at that time to estimate CO_2 sequestration losses in the same area, but caused 25 years later by a hurricane, and not by planned logging.

Since almost all the damage recorded in the Przymuszewo Forest Division occurred simultaneously in the area belonging to the municipality of Brusy, we decided to compare the amount of losses resulting from the destruction of the tree assimilation apparatus to the level of CO_2 emissions from the entire economy of this commune, both current and projected after the introduction of the emission reduction programme.

Therefore, the objective of this study was to assess the magnitude of windstorm losses in carbon assimilation (fixation) in the entire municipality during the year in relation to the annual emissions of carbon dioxide from the economic activity in this area, as established and forecasted. The analysis included the losses incurred by the State Forests as well as those occurring in private forests and in various wooded buffers in the municipality.

We undertook the assessment and comparison in the belief that the obtained results would allow both ecologists and people managing the commune to more comprehensively consider and more accurately assess the amount of losses incurred in terms of natural, technical and financial possibilities to counteract the greenhouse effect.

2. Study area

The municipality and the town of Brusy are located in the Chojnice district in the Pomerania Province in northern Poland. The area of the municipality is 400.74 km^2, of which the town occupies 5.1 km^2 and the rural areas cover 395.64 km^2. In 2017, the entire area was inhabited by 14,494 people and the population density was 36 people per km^2 (*Gmina miejsko-wiejska Brusy Powiat Chojnicki. Statystyczne Vademecum Samorządowca*, 2021). There are 100 human settlements, including mainly small and large villages, and the town of Brusy.

Of the three State Forests units, the Przymuszewo Forest Division covers the largest area of the municipality (Fig. 1B) – 14,966.43 ha, i.e. 80.53% of its total area of 18,584 ha is located in the municipality. A total of 3,315.37 ha from the Czersk Forest Division and 1,014.90 ha from the Rytel Forest Division fall within the borders of the municipality, i.e. 22.84 and 5.78% of the total area of these forest divisions, respectively. Forests occupy the largest part in the land-cover/land-use structure of the entire municipality (Fig. 2A). *According to the Environmental protection programme for the Brusy municipality for 2016–2019* (2016), their

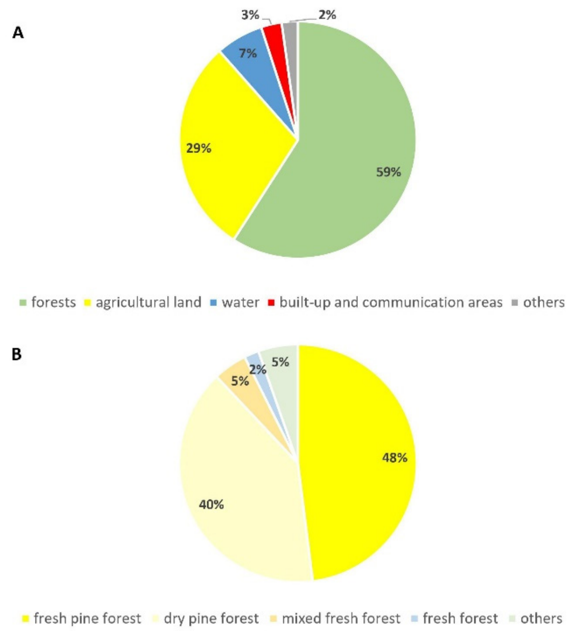

Fig. 2. Characteristics of Brusy municipality: land-use/land-cover structure (A); forest habitat structure (B)
Source: author's own work

area is 23,684 ha, which accounts for 59.1% of the municipality's area. Agricultural land constitutes 30.4%, including arable land 20.5%. Land under water represents 6.2%. There are six lakes with a surface area of more than 100 ha and 23 lakes with a surface area of more than 10 ha. Built-up land and transportation areas account for 2.1% of the municipality's area, and wooded land (covered with trees or shrubs) – about 0.2%.

The forest areas are dominated by coniferous forest sites, mainly dry and fresh pine forests (Fig. 2B). In the Przymuszewo, Czersk and Rytel Forest Divisions, they account for 93.2, 93 and 78%, respectively. Forests dominated by deciduous trees cover about 12% of the total forest area. The average age of forest stands is 61 years, and the average annual growth of wood biomass is about 4.4 m^3 per hectare.

Forest areas, mainly state-owned forests, are located mostly on the outskirts of the municipality. The central part, the so called "Brusy island", is occupied by agricultural land, the town of Brusy, and larger villages such as Kosobudy, Zalesie, Czyczkowy. Private forests grow on the periphery of the "island", adjacent to the state forests located further from the central part of the municipality.

A significant part of the forest area is protected by different forms of nature conservation. The south-western part of the municipality is occupied by the Tuchola Forest National Park, while most of the western part belongs to the Zaborski Landscape Park. In addition, there are eight nature, forest, bog and aquatic reserves, as well as 42 ecological sites. There are also two Protected Landscape Areas, two Special Protection Areas (to protect habitats of birds) and two Special Areas of Conservation Natura 2000. *According to the Environmental protection programme for the municipality of Brusy for 2016–2019* (2016), there are 74 natural monuments in the area, including 44 single old trees, 22 groups of old trees and one wooded area (wooded buffer). The remaining ones include seepage areas (4), localities of rare and protected species of lichens (1) and vascular plants (2). The entire municipality is part of the Tuchola Forest Biosphere Reserve established under UNESCO's MAB Programme in 2010.

In addition to forestry, agriculture and fishing are the main economic sectors of the municipality. According to data of the local tax office, in 2020 the largest number of inhabitants of the entire commune (both the town of Brusy and rural areas) were engaged in cultivation of plants and breeding of animals on small farms with an area of less than 1 ha, which amounted to as many as 2,127 farms. There were 1,411 farms of more than 1.0 ha, including as many as 754 farms with an area ranging from 1 to 5 ha, 521 farms with an area of 5–20 ha, 131 farms of 20–50 ha and only 5 farms of 50–100 ha.

Fish production is carried out in a system of breeding ponds located on the Kłonecznica River in the village of Laska. The ponds are managed by Zakład Hodowli Pstrąga Mylof Sp. z o.o. (a trout breeding farm) in the village of Zapora. Small private trout production facilities operate in the villages of Lamk and Leśno. Fisheries on most of the lakes in the municipality are managed by Gospodarstwo Rybackie S.A. (a fish farm) in the village of Charzykowy.

Apart from the agricultural and fishing sector, a large number of professionally active residents of the municipality are employed in industry and construction (a total of 36.4%) and services (19%; *Gmina Brusy w liczbach*, 2021). There are no large industrial plants in this area. The most important economic entities in this sector are forest by-product (mushrooms and blueberries) processing plants, such as Bydgoskie Przedsiębiorstwo Produkcji Leśnej "Las" in Brusy, Gminna Spółdzielnia "Samopomoc Chłopska" in Brusy, Zakład Produkcji Spożywczej Skwierawski Stefan, "BRUSPOL", "FUNGOPOL", and "Skup i Przetwórstwo Runa Leśnego" located in the town Brusy. They continue the tradition of businesses started here in the second half of the 19th century. Sawmills and small wood processing plants operate in larger villages. Tourism and recreation, based not only on private accommodation but also on recreation centres and hotels in the villages of Swornegacie, Czernica, Męcikał, Leśno, are an important branch of the economy in this area.

The municipality of Brusy is supplied with water through a water distribution system comprising 2,595 house connections (951 connections in urban areas and 1,644 connections in rural areas). The water supply network is used by 13,090 people, which is about 92% of the entire local population. The remaining residents are supplied with water from private wells. The total length of the water supply network installed in the municipality is 173.86 km, 26.562 km of which runs in the town and 146.94 km in rural areas (*Program ochrony środowiska dla gminy Brusy na lata 2016–2019,* 2016).

A collective mechanical and biological wastewater treatment plant operating in the municipality of Brusy serves mainly the town of Brusy. The treated sewage is received by the Niechwaszcz River. The total length of the sewerage network (sanitary and combined) in urban and rural areas is 140.4 km, including 82.1 km of gravity sewers (*Program* *ochrony środowiska dla gminy Brusy na lata 2016–2019,* 2016). In addition, there are 6.7 km of stormwater sewers in the town.

Sewage treatment plants operate in the forest villages of Asmus and Przymuszewo governed by the Przymuszewo Forest Division. In some localities there are onsite wastewater treatment systems (OWTS) at private buildings (a total of 123 OWTSs). The remaining area of the Brusy municipality lacks a sanitary sewerage system. Most of the sewage from this area is collected in 95 septic tanks, from which it is transported to the sewage treatment plant in Brusy. The rural area of the municipality also lacks a stormwater drainage system. Rainwater is drained in a traditional way with roadside and drainage ditch systems.

A significant portion of the solid waste from the Brusy municipality is transported to Regional Municipal Waste Processing Installations in the neighbouring municipalities of Chojnice and Przechlewo, where mainly green waste is treated. A municipal waste selective collection station is located in the town of Brusy, where segregated waste is collected.

Energy consumption in the area consists mainly of carriers converted to heat supplied and generated in single-family buildings, multi-family private and municipal buildings, public buildings (schools, kindergartens, sport and recreation facilities, shops, fire brigade and police stations, healthcare facilities, etc.) as well as in commercial and industrial buildings. The heat supplied to consumers primarily meets the needs of heating and ventilation of facilities, technological use at industrial recipients and water heating.

Two boiler houses are the basic source of heat in the town of Brusy, fired mainly with coal, solid biofuels (sawdust, woodchips) and light fuel oil. Out of the total number of buildings used by residents (including the industry and services sector), about 62% are heated with biomass (mainly wood and less frequently straw briquettes) and about 35% with hard coal (*Plan gospodarki niskoemisyjnej dla gminy…,* 2015).

Electricity is supplied to the commune through two high-voltage 110-kV lines running between Chojnice and Brusy and between Czersk and Brusy. The main transformer station is located in the town of Brusy, from which a 15-kV medium-voltage network is led, and then, through the overhead network and transformer stations, individual recipients are supplied. The residential sector accounts on average for 4.12 MWh of electricity consumption per building, the tertiary sector – 52.9 MWh, and the industrial area – 76.27 MWh. The annual energy consumption by road lighting amounts to 600.24 MWh.

Two main provincial roads, 20 km and 12 km, run through the municipality and the town of Brusy. Other transportation routes include 114.32 km of district roads and 207 km of municipal roads. The municipality is also provided with rail transport between the towns of Chojnice and Kościerzyna.

Petrol and diesel vehicles account for the largest number of vehicles on the roads in the area – 40 and 47%, respectively, while electrical vehicles account for only 13%. Every third household has more than one vehicle. The average age of vehicles is 15 years, which means that most of them are characterised by increased emissions of pollutants into the air.

Renewable energy accounts for 47.3% of the total energy consumption in the municipality of Brusy in 2014, including mainly plant biomass used for heating purposes. Despite good conditions for wind energy development, there are no wind turbines in the area, mainly due to the location of many protected areas. There are two systems of hydropower facilities operating in the area: a watermill in the village of Rolbik and a hydroelectric power station in the village of Kaszuba, with a power of 25 kW each, both located on the Zbrzyca River. In addition, there are several solar collectors installed in the area in 2014 for water heating. Solar panels with a power of 2.25 KW were installed on sports facilities in 2014 in the town of Brusy. Heat pumps have been installed on the following public buildings: the Municipal Office building in Brusy (power 90 KW), a social and cultural building in the village of Leśno (35 kW) and a cultural sports building in the village of Lubnia (35 kW).

There are no heat transformers in operation in the municipality and no facilities for the use of geothermal energy. There are also no agricultural biogas plants, mainly due to the high cost of installation and the lack of regular access to large quantities of feedstock, with a small area of agricultural land and not particularly high stocking rates of farm animals.

3. Method

Data on the size of losses in the three state forests were obtained from databases of three forest division offices that collected data according to procedures and frameworks developed by the SFRD in Toruń. Records on species composition and growing stock (volume of all living trees) before the windstorm as well as volume of windsnap and windthrow in the forest subdivisions located in the municipality of Brusy were extracted from the databases. Data for the subdivisions expressed in m³ were totalled by division. Biomass loss in % was calculated for each division. A map of spatial variation in growing stock losses was compiled (Fig. 3) along with a table of windsnap and windthrow merchantable timber volume by species and stand age classes.

Using conversion factors for wood density, the weight of longwood (trunks, tops) was calculated, and using data on the percentage contribution of individual fractions to the total biomass of trees, the weight of branches and leaves was calculated. Conversion factors were obtained from the extensive literature on physical and chemical properties of wood, biomass equations for determining fractions and biomass expansion factors for all species of trees occurring in the study area. The conversion factors used in particular were those developed for the purpose of EKG/FAO and UNFCCC reporting in Poland (Jabłoński & Budniak, 2014) and those obtained from our direct dendrometric surveys carried out in the Przymuszewo Forest Division.

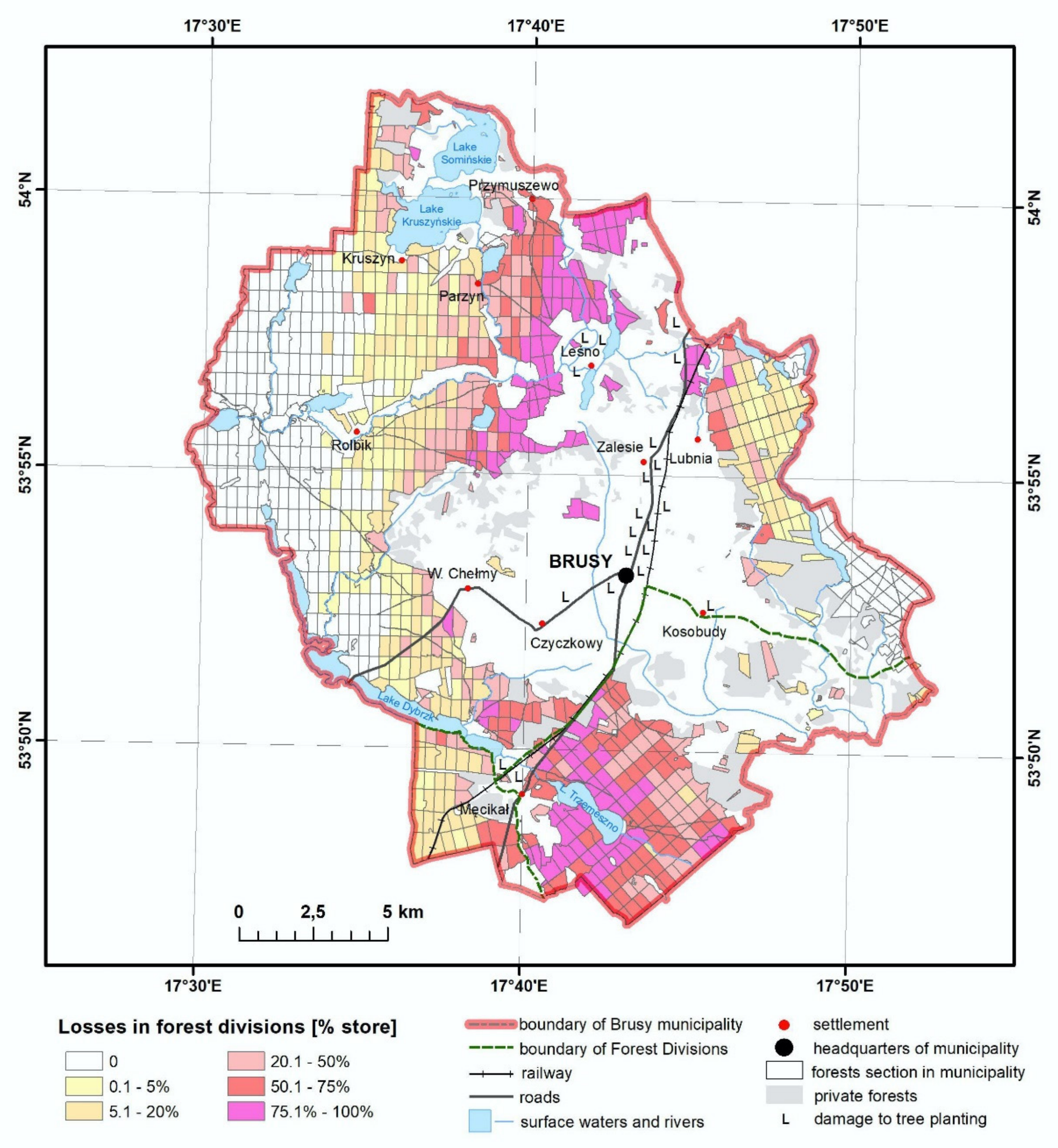

Fig. 3. Structure of spatial division of forests in Brusy municipality together with estimation of losses in forest divisions
Source: author's own work

Detailed descriptions of the methods used in the development of conversion factors obtained in the research carried out in the 1990s and continued in the next century in the forests of the Przymuszewo Forestry Division are contained in a series of articles and book chapters listed in part 1 – Introduction.

Dry leaf biomass was multiplied by coefficients defining the number of tons of CO_2 captured annually per 1 t of dry leaf biomass. In the case of pine needles, this value was 14.13 t CO_2 t^{-1} d.w.leaves per year. It was determined based on the results of research on gross primary production (GPP) of uneven age pine stands of in the Przymuszewo Forest Division carried out by Barcikowski (1991, 1994, 1996). When converting the values of annual solar energy absorption provided in those works into a unit of green biomass, the conversion factor of 1 g C = 10 kcal = 41.86 KJ adopted in IBP was used (Winberg, 1971), while the conversion factor of 3.67 was applied when converting the amount of C into CO_2 (*Method for Calculating Carbon Sequestration by Trees*…., 1998). For some tree species, i.e. *Larix decidua, Alnus glutinosa, Fagus sylvatica* and Fraxinus excelsior, conversion factors were calculated based on GPP values and leaf biomass, provided in the ecological literature for these four species by Havranek & Matyssek (2005), Dilly et al. (2008), Lebaube et al. (2000) and Le Goff et al. (2004), respectively. For other species of trees injured by the windstorm, the starting point for calculating the conversion factors were the annual sequestration rates by tree type and growth rate found in the *Method for Calculating Carbon Sequestration by Trees*… (1998). From the table provided in that study, values for the oldest tree age, i.e. 59 years, were selected for the analysed species, and from the three options of the growth rate, i.e. slow, moderate, and fast, the second option (moderate) was selected. The starting point for the calculation of leaf biomass of a single tree was the biomass of large (merchantable) timber in m^3 per ha divided by the number of trees in such an area. Both parameters for the analysed tree species at the age corresponding to the average age of damaged stands of this species in the study area were derived from the "Stand growth and yield tables" prepared by Szymkiewicz (1986).

The GPP value, corresponding to the amount of CO_2 not captured by the damaged assimilation apparatus of stands in the entire area of the Brusy municipality during a year, was calculated by multiplying these values by the biomass of the lost assimilation apparatus of the corresponding tree species and summing up the quotients. To calculate the NPP value, the conversion factor of 0.47 was used, as reported in the literature on the relationship of this parameter to the GPP of forests in the temperate zone (Waring et al., 1998). Values of all conversion factors used in the calculations are listed in the Appendix, Table A.1.

The same procedure and the same conversion factors were applied in calculations of losses in gross and net photosynthesis in private forests and wooded buffers in the municipality of Brusy. The initial data for the calculations, i.e. the volume of windsnap and windthrow in private forests, were obtained from a district office in Chojnice. This value was calculated based on estimates made during the process of preparing applications for financial compensation submitted to the district authorities. Data on the location and size of losses in wooded buffers were obtained from the Department of Environment of the Municipal Council in Brusy.

The amount of losses in carbon fixation due to losses in state and private forests and wooded buffers was compared with the annual CO_2 emission from the economic activity in the entire area of the Brusy municipality in 2013 and with the anticipated emission in 2020. The size of this emission was obtained from the assessment report prepared by Pomorska Grupa Konsultingowa S.A. (Pomeranian consulting group) in Bydgoszcz (*Plan gospodarki niskoemisyjnej dla gminy Brusy*…, 2015).

This document, containing a detailed description of the standard methodology for obtaining and processing data for estimating the level of CO_2 emissions, developed in accordance with EU recommendations, is available from the website of the Brusy Commune Office (https://bip.brusy.pl/dokumenty/5420).

4. Results

4.1 Losses in State Forests

As a result of the inventory, 20 tree taxa, including eight coniferous and 12 deciduous trees, were identified in the recorded losses incurred by the State Forests. The total losses were estimated at 988,278.32 m^3 of merchantable timber (Table 1), of which softwood (wood of coniferous trees) accounted for 968,176.89 m^3, i.e. 97.97%, and hardwood (wood of deciduous trees) accounted only for 20,101.43 m^3, i.e. 2.03%. *Pinus sylvestris* accounted for the largest part of the softwood – 961,048.10 m^3, i.e. 99.26%, while *Betula pendula* constituted the main part of the hardwood – 15,846.36 m^3, i.e. 78.83%. Age class IV trees accounted for the largest part of pine

Table 1. Losses in merchantable timber volume and biomass of leaves and in corresponding gross and net annual assimilation of state forest (SF) stands in Brusy municipality

Taxon	Merchantable timber volume	Biomass of leaves	Assimilation per year		
			gross	net	percentage
	m³	t	t CO_2/year	t CO_2/year	%
Pinus sylvestris	961,048.10	17,208.26	243,152.77	114,281.80	96.46
Picea abies	5,549.27	124.98	2,059.70	968.06	0.82
Larix decidua	961.56	38.53	473.89	222.73	0.19
Pinus strobus	610.99	4.82	109.55	51.49	0.04
Pseudotsuga menziesii	2.77	0.05	0.97	0.45	0.00
Abies alba	2.70	0.06	0.89	0.42	0.00
Pinus nigra	1.40	0.02	0.24	0.11	0.00
Pinus banksiana	0.10	0.002	0.032	0.02	0.00
Total conifers	**968,176.89**	**17,376.72**	**245,798.04**	**115,525.08**	**97.51**
Betula pendula	15,846.36	185.17	5,168.12	2,429.02	2.05
Alnus glutinosa	3,487.48	34.22	885.56	416.21	0.36
Fagus sylvatica	432.01	6.93	132.02	62.05	0.05
Quercus robur	217.34	2.48	37.56	17.65	0.02
Populus tremula	68.91	1.38	33.003	15.51	0.01
Tilia cordata	21.38	0.21	5.45	2.56	0.00
Quercus rubra	14.43	0.29	5.58	2.62	0.00
Carpinus betulus	4.37	0.08	1.54	0.72	0.00
Acer platanoides	3.45	0.06	1.46	0.69	0.00
Robinia pseudacacia	3.20	0.05	1.10	0.52	0.00
Fraxinus excelsior	1.60	0.04	0.69	0.33	0.00
Salix spp.	0.90	0.02	0.28	0.13	0.00
Total deciduous	**20,101.43**	**230.93**	**6,272.38**	**2,948.02**	**2.49**
Total losses in SF	**988,278.32**	**17,607.65**	**252,070.42**	**118,473.10**	**100.00**

Source: author's own work

losses (30.32%), while age class III trees dominated in birch losses (30.60%; Fig. 4).

After applying conversion factors to wood-specific gravity and percentage contribution of each tree fraction, it was determined that dry biomass losses in pine amounted to 413,250.68 t of large timber and 17,208.26 t of leaves. For other coniferous species these values were 2,752.05 t and 68.46 t, respectively. The biomass of silver birch was estimated at 8,240.11 t of large timber and 185.17 t of leaves, whereas for other deciduous species at 1,870.26 t of large timber and 45.76 t of leaves. The total biomass of large timber of all tree species was estimated at 426,113.10 t and of leaves at 17,607.66 t.

Using conversion factors to the amount of carbon dioxide captured annually by 1 tonne of leaves, it was calculated that the loss in gross CO_2 assimilation due to the destruction of the pine assimilation apparatus was 243,152.77 t CO_2/year and in net carbon assimilation – 114,281.80 t CO_2/year (Table 2). For other coniferous species, these losses amounted to 2,645.27 and 1,243.28 t CO_2/year, respectively.

In the case of silver birch, which ranked first on the list of injured deciduous tree species, the loss in gross assimilation was 5,168.12 t CO_2/year, and in net assimilation – 2,429.02 t CO_2/year. For other deciduous tree species, the total loss was 1,104.26 t in gross assimilation and 519.00 t CO_2/year in net assimilation.

4.2 Losses in private forests and wooded buffers

Losses in private forests, assessed based on data from district authorities in Chojnice, amounted to 250,193 m³ of merchantable timber – mainly pine. The weight of this timber was estimated at 107,582.99 t and the biomass of leaves at 4,479.89 t. The loss of the assimilation apparatus corresponded to a gross assimilation loss of 63,300.84 t CO_2/year and net assimilation loss of 29,751.40 t CO_2/year (Table 3).

Losses in wooded buffers were insignificant compared to those in forests, especially state forests.

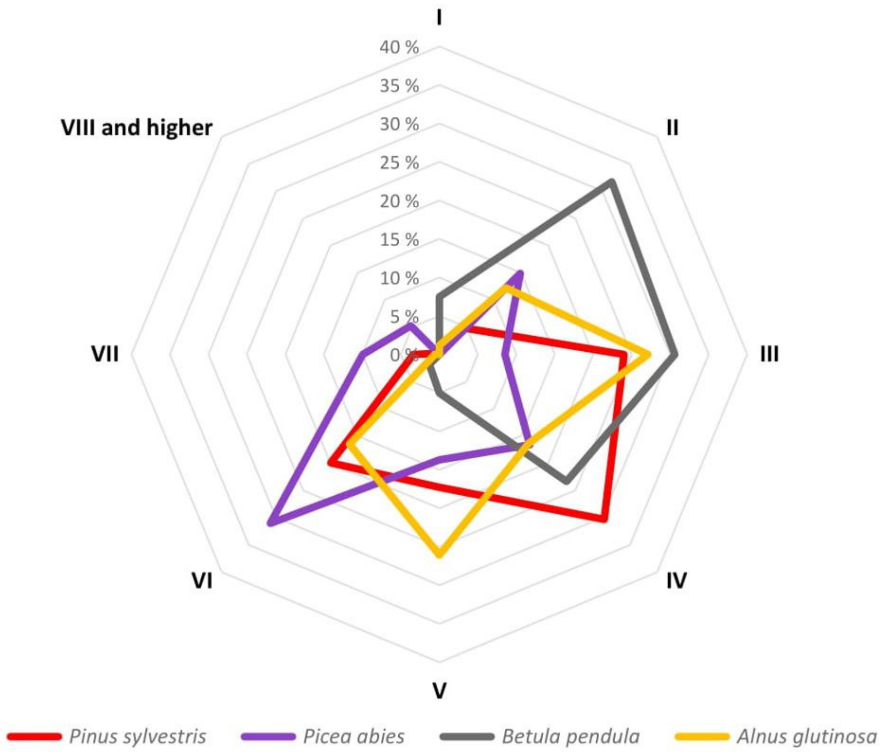

Fig. 4. Structure of damaged biomass of dominant tree species by forest stand age classes
Source: author's own work

Table 2. Losses in private forests and buffer strips relative to total losses in state forests

Type of forest stand	Biomass		Assimilation per year		
	harvested timber m³	foliage lost t	gross t CO_2/year	net t CO_2/year	percentage %
state forests	**988,278**	**17,607.66**	**252,070.44**	**118,473.10**	**79.86**
private forests (*Pinus sylvestris*)	**250,193**	**4,479.89**	**63,300.84**	**29,751.40**	**20.06**
Wooded buffers:					
located in field; conifer trees (*Pinus sylvestris*)	312	5.59	113.03	53.12	0.04
located in field; deciduous trees (*Betula pendula*, *Alnus glutinosa*, *Populus* spp., *Quercus robur*)	328	4.50	104.55	49.14	0.03
roadside; deciduous trees (*Populus nigra*)	205	1.40	33.53	15.76	0.01
Total wooded areas	**845**	**11.49**	**251.11**	**118.02**	**0.08**
Total losses	**1,239,316**	**22,099.04**	**315,622.39**	**148,342.52**	**100.00**

Source: author's own work

These were surface destructions (in 35 locations) ranging from 0.1 ha to 2.79 ha. They occurred in the southern part, near the village of Męcikał, and in the northern part, near the villages of Leśno, Lamk and Główczewice. A total of 640 m³ of timber was harvested in the wooded buffers, including 312 m³ of pine; the remaining 328 m³ comprised wood

Table 3. Energy consumption and CO_2 emissions into the atmosphere by the economic sector in Brusy municipality, 2013

Carrier	Total energy consumption MWh/year	%	CO_2 emissions from energy carrier consumption t/year	%
Electricity	8,907.63	6.37	8,747.29	28.24
Heat/cooling	2,947.84	2.11	1,155.55	3.73
Fossil gas	154.39	0.11	31.19	0.10
LPG	936.41	0.67	212.56	0.69
Fuel oil and diesel	37,704.27	26.94	10,512.62	33.93
Petrol	363.47	0.26	90.50	0.29
Hard coal	24,798.53	17.73	8,778.68	28.34
Biofuel	62,740.02	44.84	0.00	–
Renewable energy	1,353.00	0.97	0.00	–
Waste	0.00	–	1,450.00	4.68
Total	**139,905.56**	**100.00**	**30,978.39**	**100.00**

Source: author's own work

of deciduous tree species – *Betula pendula*, *Alnus glutinosa*, *Populus* spp. and *Quercus robur*.

Damage to roadside trees occurred mainly along provincial road No. 235, between the village of Lubnia and the town of Brusy. Less damage occurred along local roads between the village of Kosobudy and the town of Brusy, and between the village of Wielkie Chełmy and Brusy. Forty-one *Populus nigra* specimens, with a breast height diameter ranging from 110 to 370 cm, were damaged. The volume of the harvested wood was 205 m^3.

The total biomass of the harvested timber of all tree species was estimated at 359.50 t and that of leaves at 11.49 t of dry matter. The loss of the assimilation apparatus of trees corresponded to an annual gross assimilation loss of 251.11 t CO_2/year and net assimilation loss of 18.02 t CO_2/year (Table 3).

Total losses in gross carbon dioxide assimilation by forest stands amounted to 315,622.39 t CO_2/year and in net assimilation to 148,342.52 t CO_2/year. The proportion of state forests, private forests and wooded buffers was 79.86, 20.06 and 0.08%, respectively.

4.3 Losses in forest assimilation relative to CO_2 emissions from the economic activity in the municipality of Brusy

Energy consumption in the municipality of Brusy in 2013 as well as the level and structure of CO_2 emissions from the economic activity, in relation to which forest assimilation losses were compared, are

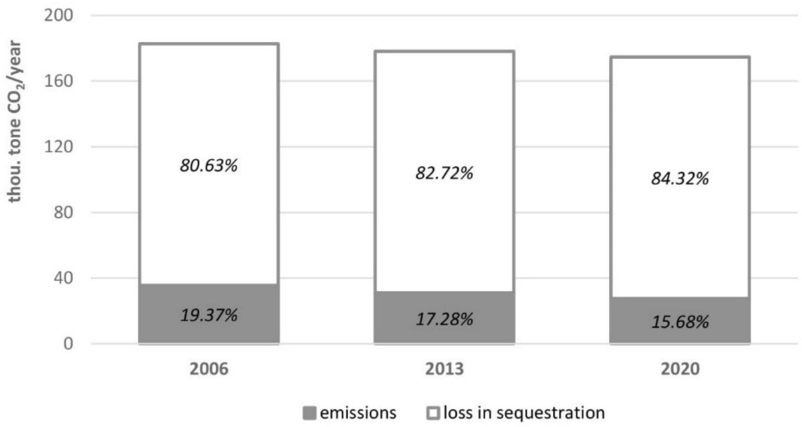

Fig. 5. Net carbon assimilation loss caused by forest stand damage in relation to annual CO_2 emissions from the economic sector in Brusy municipality
Source: author's own work

presented in Table 3. In 2013, with a total energy consumption amounting to 139,905.56 MWh/year, CO_2 emission was 30,978.39 t CO_2/year, with the largest share of emissions related to fuel oil and diesel consumption (33.93%) as well as hard coal (28.34%) and electric energy (28.24%).

Losses in CO_2 assimilation were also compared to CO_2 emissions from the economic sector calculated based on energy carrier consumption determined in 2006 and projected for 2020. CO_2 emissions in 2006 amounted to 35,630 t and were projected to decrease in 2020 to 27,593 t. The ratio of the estimated net assimilation loss to CO_2 emissions from the economic sector in 2006, 2013 and 2020 is 4.16, 4.79 and 5.38, respectively.

The total loss in net carbon assimilation of CO_2 and the size of its emissions resulting from living and economic activities can be considered as a value reflecting the ecological risk in the municipality. It amounted to 183,972.52, 179,321.52 and 175,935.52 t CO_2/year in 2006, 2013 and 2020, respectively. Figure 5 presents the percentage of both components in these totals. With decreasing emissions in the subsequent years, the share of net assimilation losses increases from 80.63% for 2006 to 84.32% for 2020.

5. Discussion

The losses in net carbon assimilation can be described as significant. They exceed almost five times the annual carbon dioxide emissions from the entire economic sector of the municipality with a population of approximately 14,500. The starting point for the assessment of assimilation losses was the size of merchantable timber of damaged trees. Extension indices and percentage ratios of each compartment in the above-ground biomass of trees were applied to these values. To increase the accuracy of calculations, indices developed for trees from the study area were mostly used, mainly for Scots pine and silver birch, published by Deptuła (2006), Jarzębski et al. (2009) and Deptuła et al. (2017).

A similar principle of using mainly indices developed for forests growing in the municipality of Brusy was adopted for further calculations of photosynthesis rate indices, i.e. g of CO_2 per gram of leaf dry mass per year. However, such an index developed in the study area was available only for Scots pine. It was an index used by Barcikowski (1991, 1994, 1996) for the assessment of the assimilation rate in successive development phases after forest regeneration in the habitat of fresh pine forest and dry coniferous forest, and by Barcikowski & Loro (1993) for the assessment of gross photosynthesis loss as a result of logging in the Przymuszewo Forest Division. For other species of coniferous trees and all species of deciduous trees, conversion factors described in the literature for other, often remote areas were employed. For some species these were mean values of indices determined for other species from relevant groups. It should be noted, however, that the proportion of Scots pine, for which conversion factors developed in the study area were used in this study, accounted for as much as 97.24% of the merchantable timber volume and 97.73% of the assimilation apparatus biomass of all damaged trees.

Only the biomass of leaves was taken into account in these analyses, whereas the biomass of green twigs as well as the biomass of bryophytes and epiphytic lichens was neglected, because their contribution to the total green biomass (ca. 0.4%), and thus to the photosynthesis, is small (Barcikowski, 1996; Wilkoń-Michalska et al., 2006). Losses of other forest layers, e.g. understorey, undergrowth and forest floor, whose green biomass in a 90-year old pine stand on the habitat of dry coniferous forest reaches 44.9%, and in a 120-year old stand on the habitat of fresh coniferous forest – 38.7% of green standing crop of total plant communities (Barcikowski, 1994, 1996), were not taken into consideration either. The rate of the assimilation apparatus recovery and the whole "chlorosphere" in the first several years after the windstorm was not included either.

The assimilation conversion factors used were developed based on studies of pine primary production carried out in the 1980s and 1990s. It is not known what value they reach after thirty years. They probably changed quite significantly under the impact of climate change, especially the increase in temperature and threats of drought. A number of recent studies have indicated that, of various ecological factors, net primary production is most affected by the duration of the growing season (e.g. Danielewska et al., 2015; Ziemblińska et al., 2016; Usoltsev et al., 2019) – NPP increases with increasing duration of the growing season. On the other hand, rising temperatures and consequent droughts reduce plant biomass production.

Using the conversion factor of 14.13 t CO_2/t DM leaves/year and multiplying by the average biomass of leaves per forest area unit, as presented by Barcikowski (1994), GPP values comparable with data reported in the literature were obtained. For three pine stands, aged 12, 24 and 120 years in the fresh coniferous forest habitat in the Przymuszewo

Forest Division and the municipality of Brusy, the mean GPP value was 56.94 t CO_2/year. For 30-, 45- and 90-year-old pine stands in the habitat of dry coniferous forest in the same study area, the mean value was 49.74 t CO_2/year. A similar GPP value ranging from 48.63 to 64.40, with a twelve-year average of 56.08 t CO_2/year, was reported by Urbaniak et al. (2020) for a research station in the Tuczno Forest Division in north-western Poland. These results were obtained using the eddy covariance technique. Measuring apparatus for continuous measurements of gas exchange between forest and atmosphere was installed in 65-year-old forest stand of Scots pine mixed with birch and oak, and the study was carried out from 2008 to 2019 (Chojnicki et al., 2009; Urbaniak et al., 2020).

We assumed that net production accounts for 47% of GPP, both for the main species, i.e. Scots pine Pinus sylvestris, and for other species of trees. Such a constant value in the ecophysiological literature on plant biomass production was provided by Waring et al. (1998). Only a slightly lower value of 45% was given by Odum (1969), which was used in calculations by, for example, Gosz et al. (1978) and Finn (1980). If NPP is assumed to be 47% of GPP, the respiration of autotrophs is Ra = 53% of GPP. In the case of pine forest analysed by the aforementioned Tuczno research station, the mean annual respiration of the entire ecosystem R_{eco} accounted for 75% of GPP (Urbaniak et al., 2020).

The starting point in our calculations of CO_2 assimilation losses was the first assessment of biomass losses in state forests. Losses estimated in this way are usually overestimated compared to those assessed based on biomass harvested in the affected area in the following period. In April 2021, the Regional Directorate of State Forests reported that the harvest of merchantable timber from forest stands affected by the windstorm on 11–12 August 2017 amounted to 5.1 million m^3, whereas the loss, according to the preliminary assessment, was 5.3 million m^3. The difference between the initial and subsequent assessment was therefore less than 4%.

The analysis of the data collected by the State Forests shows that the windstorm on 11–12 August 2017 caused greater losses in older forest stands (age class IV) compared to younger forest stands (age classes II and III), whose area was larger than those of the former. Such a correlation, found also after earlier windstorm events in Tuchola Forest (Koziński & Nienartowicz, 2006), resulted from the fact that the risk of wind damage in older forest stands is much higher than in young forest stands (Gardiner & Quine, 2000; Henewinkel, 2005; Bruchwald & Dmyterko, 2010; Ikonen et al., 2020). In terms of carbon balance, older forest stands are less efficient carbon sinks. Their net ecosystem production (NEP) is lower than that of younger forest stands, with a maximum in stands aged around 30–40 years (Olejnik et al., 2020). However, the important role of older forest stands in maintaining biodiversity must not be overlooked.

The carbon emission from the economic sector used in the comparisons may be slightly understated (underestimated) as it has been calculated by a consulting agency using a “bottom-up” methodology, which involves data collection at source. Each inventory unit provides data, which are then aggregated in such a way that they are representative of a larger population or area. This methodology increases the likelihood of error in data analysis and data processing, and the uncertainty of whether the entire target population is included (*Plan gospodarki niskoemisyjnej dla Gminy Brusy na lata 2015–2020*, 2015). The calculations were performed for two main sectors – the community and the local government, according to their equipment and energy consumption and equipment efficiency. Only people permanently residing and employed in the municipality of Brusy were taken into account. The analysis did not take into account road and rail transit. The total energy consumption by tourists staying at camping sites was not taken into account either. In addition to electricity, included in the analysis, and gasoline for vehicle propulsion, they consume liquefied petroleum gas (LPG) to prepare meals. However, these are small amounts compared to the energy consumption for living purposes and economic activity carried out by permanent residents of the municipality.

Despite the above reservations, indices expressing the relationship between the amount of damaged foliage and the corresponding amount of carbon dioxide not assimilated by forest stands and CO_2 emissions from the economic sector seem nevertheless to be good indicators of the damage to nature caused by windstorm events over large areas covering considerably large forest ecosystems and quite numerous human settlements with large local populations.

Basing the analysis of estimating post-hurricane losses in forest ecosystems on the amount of CO_2 not absorbed by the damaged tree assimilation apparatus allows for a stronger link between the natural losses incurred and economic processes, and for them to be compared with carbon dioxide emissions from the technosphere and considered in relation to the objectives of the state environmental policy implemented by economic, administrative and local government systems at different levels.

Analysing the amount of unabsorbed CO_2 in relation to the prices of a tonne of greenhouse gas, used under the European Emissions Trading Transfer (EU ET), makes it possible to assess post-hurricane losses in forest areas in financial units.

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Appendix

Table A.1. Conversion factors of biomass and assimilation of trees applied in calculations

Taxon	Density of wood	Longwood biomass	Biomass of branches	Biomass of leaves	Gross assimilation	Net assimilation
	t/m^3	%	%	%	$t\ CO_2/t_{leaves}$/year	$t\ CO_2/t_{leaves}$/year
Pinus sylvestris	0.430	81.89	14.70	3.41	14.13	0.47
Picea abies	0.380	83.18	11.89	4.93	16.48	
Larix decidua	0.450	66.15	27.96	5.89	12.30	
Pinus strobus	0.340	81.39	16.72	1.89	22.71	
Pseudotsuga menziesii	0.450	87.84	8.61	3.55	19.32	
Abies alba	0.370	85.21	9.59	5.20	14.62	
Pinus nigra	0.430	82.97	14.26	2.77	12.14	
Pinus banksiana	0.400	80.31	15.91	3.78	16.14	
Betula pendula	0.520	89.00	9.00	2.00	27.91	
Alnus glutinosa	0.417	85.00	13.00	2.00	25.88	
Fagus sylvatica	0.570	84.52	13.10	2.38	19.04	
Quercus robur	0.550	77.09	21.31	1.60	15.14	
Populus tremula	0.360	72.00	24.00	4.00	23.95	
Tilia cordata	0.440	75.68	22.66	1.66	26.47	
Quercus rubra	0.560	67.68	29.88	2.44	19.19	
Carpinus betulus	0.650	70.54	27.37	2.09	18.33	
Acer platanoides	0.500	73.36	24.26	2.38	26.07	
Robinia pseudacacia	0.660	80.18	17.84	1.98	21.13	
Fraxinus excelsior	0.570	67.05	29.68	3.27	15.74	
Salix spp.	0.356	74.17	21.69	4.14	15.72	

Source: author's own work