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E-mail: silvabalcanica@abv.bg
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RESEARCH ARTICLE

Survival and growth of Common beech (*Fagus sylvatica* L.) provenances in North-Eastern Bulgaria

Krasimira Petkova, Emil Molle, Aysel Mustafova

University of Forestry, 10 "St. Kliment Ohridski" blvd., 1797 Sofia, Bulgaria

Corresponding author: Krasimira Petkova (kpet@abv.bg)

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Abstract
Two provenance tests in North-Eastern Bulgaria have been studied, whose purpose is to test the response of beech provenances from Southern Germany to the drier and warmer climatic conditions in Bulgaria, in order to predict how they would perform in a warming and drying climate. The provenance tests were established in the spring of 2010 in the area of the Varbitza and Kipilovo Forest Services with 2-year-old seedlings in a 2 x 1 m scheme in 3 replications. Four provenances of common beech were studied - 2 German (Silberbach and Ebersdorf) and 2 Bulgarian (Petrohan and Berkovitza). On the 12th year after afforestation, an inventory and measurements of the height and root collar diameter were carried out. The results were processed statistically by applying one and two-factor analysis of variance, as well as Tukey's test for multiple comparisons. A higher survival rate was found in the provenance test in Kipilovo. The Bulgarian provenances Petrohan and Berkovitza were characterized by better growth in height in both provenance tests, and in root collar diameter - provenance Petrohan. Provenance Ebersdorf could be recommended for use in drier and warmer places in Southern Germany.

Keywords
Fagus sylvatica, seedlings, survival rate, height, root collar diameter, provenance test

Introduction

Common beech (*Fagus sylvatica* L.) is a widespread broad-leaved tree species with great economic and ecological importance. In Europe, it occupies an area of about

14 million hectares (von Wüehlisch 2010 according to Ballian and Zukić, 2011), and in Bulgaria it represents 16.5% of the total forested area of the country. It is attached to fresh and moist, medium rich to rich habitats and high air humidity. Because of these ecological features, common beech is threatened by projected climate changes. Its adaptability to changing climatic conditions is the subject of studies in provenance tests, in which the ecological plasticity of different provenances is assessed under changed climatic conditions in place of the provenance test. The first common beech provenance test in Europe was established in 1877 in a botanical garden in Germany (Kienitz 1886 - according to Ballian and Zukić, 2011), but it was not scientifically analyzed. In a common beech provenance test, established by Engler in 1908, it was found that beech provenances from northern areas and higher altitudes grew more slowly than those from lower and southern locations (Burger (1933, 1948) according to Višnjić and Dohrenbusch 2004). A staked experiment with 45 common beech populations in 6 provenance trials in Poland found that provenances from places where common beech is not widespread were characterized by relatively low survival and slow growth rate (Barzdajn, 2002).

Studies of common beech provenances in Slovakia have focused on growth in height and diameter and their seasonal dynamics, as well as spring phenology (Paule, 1982). In the spring of 1998, a provenance test with 38 common beech provenances from 15 European countries was established in Slovenia. At the 10-year age of the seedlings, the highest survival rate was found in the Belgian provenance Soignes – 94%, and the tallest plants – in the local Slovenian provenance (Postojna – Masun) – 242.8 cm. Some provenances Bretagne (France), Urach (Germany), Westfield (UK) were characterized by good adaptability and phenotypic stability, while others were phenotypically unstable (Nizbor and Horni Plana from the Czech Republic) (Ivanković et al., 2008).

In 2007, in Bosnia and Herzegovina, a provenance test with 22 common beech provenances (eight local, four from Germany, three from Serbia, two each from Croatia, Romania and Switzerland and one from Hungary) was established. In the third and thirteenth years after afforestation survival, height growth and root collar diameter were analyzed as well. The fastest and slowest growing provenances, and at the end of the 13th year, the tree shape were determined in order to evaluate their quality. Pearson's coefficient showed that height, root collar diameter, and tree shape are highly correlated. (Ballian, Zukić, 2011; Memišević Hodžić, Ballian, 2021).

The first common beech provenance test in Bulgaria was established in 1974 with provenances from the Training and Experimental Forest Range Petrohan, Etropole Forest Service and "Boatin" reserve and 7 variants of densities (Botev, 1988). There was a tendency to increase seedlings height at higher planting density. It was found that the density affects height growth more than the root collar diameter. From the tested three provenances with the highest growth indicators and as the most promising for the conditions of the Etropole-Lopian section of the Balkan Mountain, the provenance from the Training and Experimental Forest Range Petrohan was outlined (Botev, 1995).

A common beech provenance test from the international network of provenance tests in Europe was established in Bulgaria in the spring of 1994 on the territory of the Tvarditsa Forest Service at an altitude of 1160 m (Alexandrov et al., 2006). It includes 49 provenances, of which 33 from Germany, 5 from Slovakia, 2 each from the Czech Republic, Denmark and France and 1 each from Bulgaria, Estonia, Italy, Poland and Romania. In the first and fifth year after the establishment, a relatively high average percentage of survival is reported - 96.3 and 76.5%, respectively. The following years massive damage from wild animals was observed and the overall 12-year survival rate of the provenances test dropped to just 24.7%. Based on the measurements of the heights and root collar diameters of the seedlings at 1-, 5- and 12-year of the provenance test, the German provenances Herrenberg, Zwiesel and Eisenach were outlined as the most promising for the conditions of the experiment, and the worst results were shown by the Danish provenance Grasten.

The projected increase in mean annual temperature and decrease in annual precipitation has prompted studies to test the possibility of adaptation of common beech provenances from Central Europe to the warmer and drier climate of South-Eastern Europe (Bulgaria) in order to establish how they would play out under projected climate warming and drying. Thus, at the suggestion of the Bavarian Institute for Forest Seeding and Planting in Teisendorf (Germany) at the end of 2009 and the beginning of 2010, provenance tests of common beech of German and Bulgarian provenances were established, the purpose of which was to test the reaction of beech provenances of Southern Germany to the drier and warmer climatic conditions in Bulgaria to determine whether their adaptive capacity would be sufficient to maintain their vitality and productivity without significant changes. Results on phenological traits, as well as survival and height growth, during the first 3 years after the establishment of the provenance tests have been published (Petkova et al., 2017; Petkova et al., 2019). Of interest is the question of the behaviour of provenances 9 years later.

The aim of the work is to analyze the survival and height and root collar diameter growth of 4 common beech provenances in two provenance tests in North-Eastern Bulgaria in the 12th year after the afforestation.

Materials and Methods

The object of the study were four common beech provenances – Silberbach and Ebersdorf from Germany and Berkovitza and Petrohan from Bulgaria, introduced in two provenance tests in North-Eastern Bulgaria - on the territory of the Varbitza and Kipilovo Forest Services. Data on the location of the provenances and the provenance tests are presented in Table. 1 and Table. 2. The provenance tests were established in the spring of 2010 with 2-year-old seedlings under a 2 x 1 m scheme. In general, three replications per provenance were planted, with 50 seedlings each. The afforestation was carried out in slits. During the first 3 years after the establishment of the provenance tests, observations of survival and measurements of seedling heights were carried out, the results of which have been published (Petkova et al., 2019).

Table 1. Data for common beech provenances

Country	Provenance		MAT, °C	MAP, mm	Longitude E	Latitude N	Altitude m a.s.l.
	name	region					
Germany	Silberbach (S)	Oberbayern	6.0	700	12.18	50.13	611
Germany	Ebersdorf (E)	Oberfranken	6.5	900	11.33	50.50	650
Bulgaria	Berkovitza (B)	North Bulgaria	10.4	825	23.09	43.21	850
Bulgaria	Petrohan (P)	North Bulgaria	10.4	1004	23.14	43.15	800

Note: MAT – mean annual temperature; MAP – mean annual precipitation

Table 2. Data for the common beech provenance tests

Site	Longitude E	Latitude N	Altitude m a.s.l.	Exposi-tion	MAT*, °C	MAP*, mm	Soil type	Site index
Varbitza	26.62	42.98	350	NW	11	708	Grey luvisols	$CD_{2,3}$
Kipilovo	26.22	42.88	500	NO	12.4	811	Grey luvisols	$CD_{2,3}$

Note: 1. MAT – mean annual temperature; MAP – mean annual precipitation. 2. In Bulgaria, a system is used to evaluate the site index, consisting of soil richness (A – very poor, B – poor, C – medium rich, D – rich) and a digital index for soil moisture (0 – very dry, 1 – dry, 2 – slightly moist, 3 – moist, 4 – very moist) (Raykov et al., 2011). CD2,3 means medium rich to rich and slightly moist to moist soil.

A survival assessment and measurements of heights and root collar diameters were carried out in the autumn of the 12th year after afforestation (2021)Statistical analysis was conducted after testing the hypothesis of constancy of variance across groups. Constancy of variance was confirmed by Levene's test, allowing analysis of variance (ANOVA) to be applied. The influence of the factors provenance test and provenance on common beech height and root collar diameter, as well as the interaction between them, was verified by applying one- and two-factor analysis of variance. Comparison of differences between the provenances was done by Tukey's method (Molle, 2012).

The data were processed statistically with statistical and graphical functions using environment libraries in the programming language 'R' (Wickham, 2009; R Core Team, 2022).

Results and discussion

Survival

Survival in the autumn of 2021 was compared to that in 2017 (Petkova, 2019).
The average survival rate of the four provenances in the provenance test in Varbitza in the 12th year after afforestation (2021) was 56.8 %. With the lowest percentage of survival was provenance Silberbach - 42%, and the highest - provenance Ebersdorf - 72%. Compared to 2017, there was a drop in the average survival rate from 63.6% to 56.8%. The decrease is from 3% at the Petrohan provenance to 10% at the Silberbach

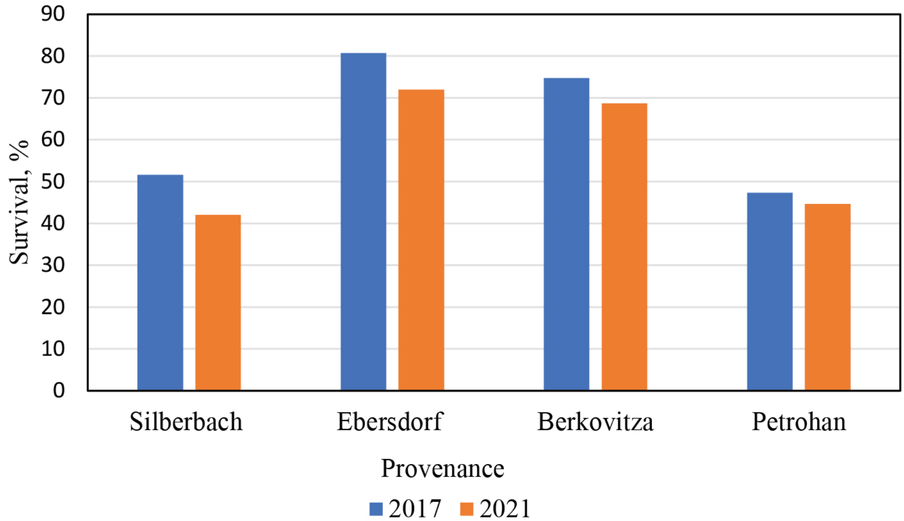

Fig. 1. Survival of the four provenances in Varbitza after the eighth (2017) and twelfth (2021) growth period

provenance (Fig. 1). The differences in the survival rates of the provenances were not statistically significant.

The average survival rate of the four provenances in the provenance test in Kipilovo in the 12th year after afforestation (2021) was 59% i.e. slightly higher than that in Varbitza (Fig. 2). The provenance Silberbach has the lowest survival rate - 48.7%, and the Bulgarian provenance Petrohan - the highest - 68%. It is noteworthy that the provenance Petrohan in this provenance test has significantly fewer losses compared to the same provenance in Varbitza. Compared to the eighth year (2017), here the average survival rate decreased minimally by less than 2%, evenly across the individual provenances, as in the provenance Petrohan, survival was only 0.7% less than in 2017. i.e. the survived individuals at year 8 persisted approximately at year 12. Here, too, the differences in survival rates were not statistically significant.

The higher average survival rate of the provenances in Kipilovo was probably due to the higher annual precipitation (811 mm) compared to Varbitza (700 mm), while in both provenance tests two cultivations were carried out in the first three years after afforestation. The ordering of provenances by survival rate was different in the two provenance tests. While in Varbitza the German provenance Ebersdorf was characterized by the highest survival rate, in Kipilovo the provenance Petrohan was the one with the least losses. From their studies of the provenance trials of 22 European common beech provenances in Bosnia and Herzegovina, Ballian and Zukić, (2011) found that local provenances had the highest survival rate and concluded that the local provenances had better adaptability. In a provenance test in Slovenia the best survival was observed in a Belgian provenance (Ivanković et al., 2008). There was no definite conclusion about better survival of local provenances and in studies in common beech provenance trials in Croatia and Serbia (Stojnić et al., 2015).

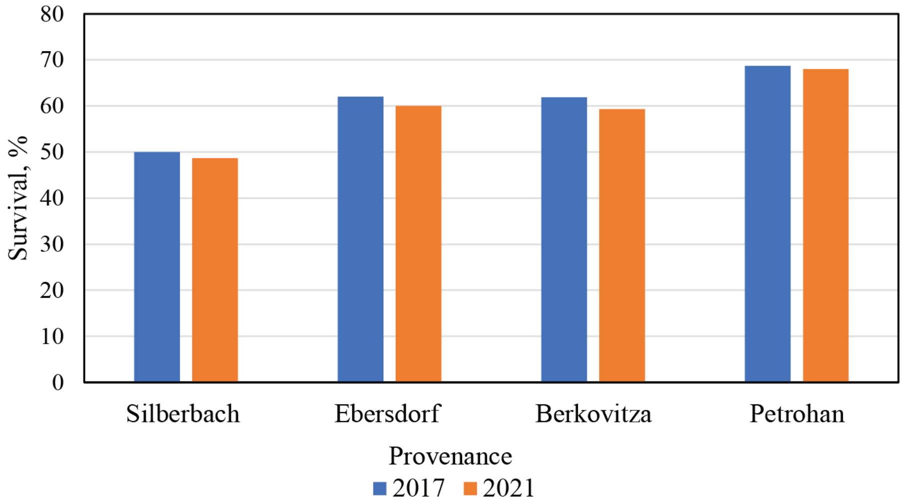

Fig. 2. Survival of the four provenances in Kipilovo after the eighth (2017) and twelfth (2021) growth period

Height growth

The influence of the factors provenance test (PT) and provenance on the height of the beech trees is presented in Figure 3. It could be seen that the provenances differ quite distinctly in height, and in both provenance tests the Bulgarian provenances were taller. The mean height of provenance Petrohan was the highest, followed by provenance Berkovitza. The German provenance Ebersdorf had roughly the same height in both provenance tests. The lowest in both tests was the provenance Silberbach. The mean height of the common beech in the provenance test in Kipilovo exceeds that in Varbitza, but the difference wasn't as obvious as in the provenances.

The result of the statistical test (two-factor analysis of variance, ANOVA) shows (Table 3) that the height of the common beech seedlings wasn't statistically significantly affected by the location of the provenance test (PT), but only by the provenance. There wasn't any statistically proven influence between the two factors – provenance test and provenance.

The mean heights of provenances in the two provenance tests were presented in Figure 4. The mean height of the provenances in Kipilovo was 311.5 cm and slightly higher than that in Varbitza (305.4 cm), as could be seen from Fig. 3 too. With the highest mean height in the 12th year after afforestation was the provenance Petrohan (349 cm in Kipilovo and 336 cm in Varbitza), followed by the provenance Berkovitza, and the smallest - the German provenance Silberbach (240 cm in Kipilovo and 260 cm in Varbitza). The high level of significance of provenances indicated in Tab. 3, allows Tukey's multiple comparison method to be applied.

From the comparison of the mean heights in pairs (Table 4), it was noticeable that the mean height of provenance Berkovitza does not differ statistically significantly

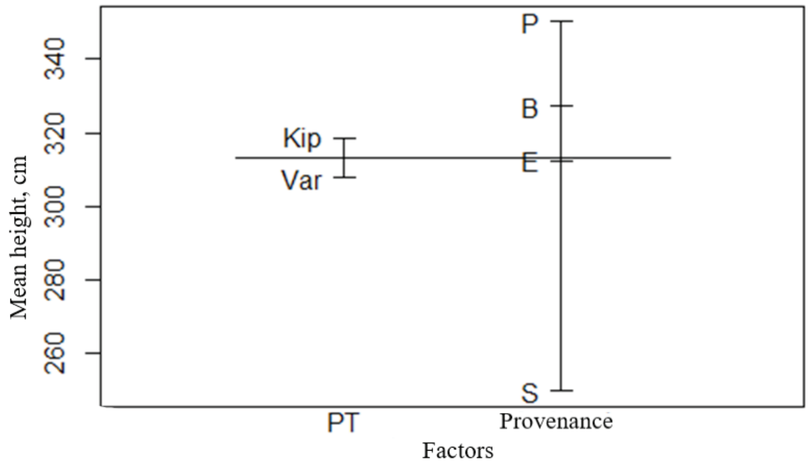

Fig. 3. Mean heights by provenance (S – Silberbach, E – Ebersdorf, B – Berkovitza, P – Petrohan) and provenance trial (PT; Var – Varbitza and Kip – Kipilovo)

Table 3. Results of an ANOVA of heights of 4 provenances at 2 provenance tests (PT)

	DF	Sum Sq.	Mean Sq,	F	*p*
PT	1	20984	20984	1.537	0.215 ns
Provenance	3	810381	270127	19.786	$2.63e^{-12}$ ***
PT x Provenance	3	45999	15333	1.123	0.339 ns
Residuals	680	9283636	13652		

Note: Significance: *** - $p< 0.001$; ns - not significant.

from the height of provenances Ebersdorf and Petrohan, but it exceeds statistically significantly provenance Silberbach. All other comparisons between provenances were statistically significant.

The Bulgarian provenances Petrohan and Berkovitza had better height growth on the 12th as well as on the 8th year after afforestation (Petkova, 2019). One of the reasons was that they originate from the south-eastern part of the beech's natural range and have an earlier development (Petkova et al., 2017). This conclusion is consistent with the studies of other authors (Muhs, 1985; Madsen, 1995; von Wuehlish et al., 1995; Stener, 2002; Matyas et al., 2010), who found that provenances from the eastern and south-eastern parts of the beech range had earlier leaf flushing than those from the western and northern parts. On the other hand, Bulgarian provenances were located in the southern part of the common beech range, and according to Larsen (1985), confirmed by Ballian and Zukić (2011), common beech provenances from the southern part of the range grow faster than those from Northern Europe (Switzerland, Germany, etc.).

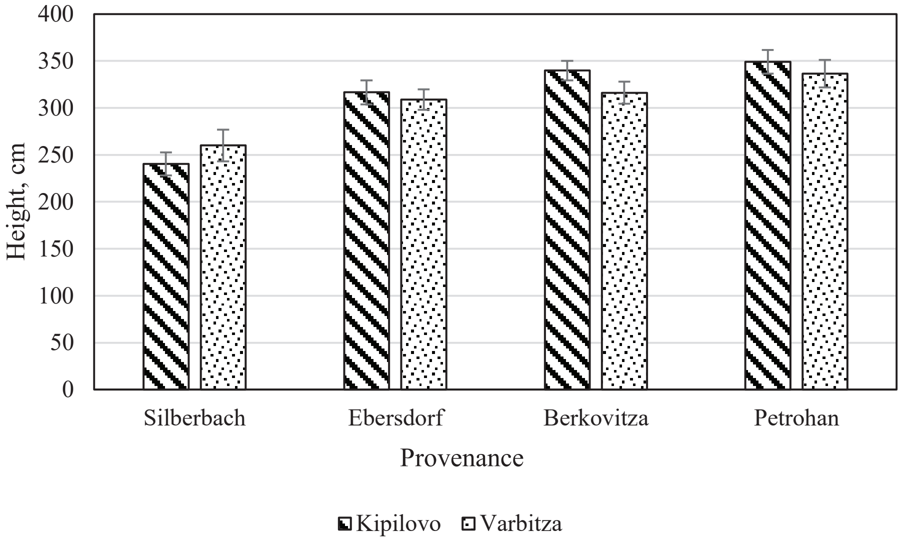

Fig. 4. Mean height of the common beech provenances in the provenance tests in Varbitza and Kipilovo in the 12th year after the establishment

Table. 4. Comparing the differences between the mean heights of the provenances in the two provenance tests by Tukey's method

No	Term	Group 1	Group 2	Null. value	Estimate	Conf. low	Conf. high	p.adj	padj.sig
1	Provenance	B	E	0	-14.7	-45.2	15.8	0.601	ns
2	Provenance	B	P	0	23.2	-8.8	55.2	0.245	ns
3	Provenance	B	S	0	-77.7	-112.0	-43.9	2.88E-08	****
4	Provenance	E	P	0	37.9	6.1	69.7	0.0121	*
5	Provenance	E	S	0	-63.0	-96.7	-29.4	0.0000103	****
6	Provenance	P	S	0	-101.0	-136.0	-65.9	0	****

Note: Significance: **** $p < 0.000$; * $p < 0.05$; ns - not significant

According to Hoffmann (1961), the achieved heights at an early age may not be the measure by which one could accurately determine the growth of particular provenances, or evaluate which provenance has the fastest development, because often there is a change in the growth rate at the late age. Other authors (Vidaković and Krstinić, 1985) consider that more reliable conclusions about the speed of growth in beech provenances can be obtained at the age of 40 years, i.e. for one third of the rotation.

Root collar diameter (RCD)

According to the mean root collar diameter, differences were observed both between the two provenance tests and between the provenances (Fig. 5). In contrast to the height of the seedlings, higher root collar diameter characterized the provenance test in Varbitza, and the difference was of high statistical significance (Table 5). The arrangement of provenances by mean diameter was slightly different compared to their arrangement by height. With the largest mean root collar diameter in both provenance tests, the provenance Petrohan was distinguished, followed by the Ebersdorf provenance. In the third place was provenance Berkovitza. Provenance Silberbach had the smallest root collar diameter in both provenance tests (Fig. 5). The factor provenance also had a statistically significant effect on the root collar diameter. No statistically significant interaction was found between the two factors – provenance test and provenance (Table 5).

The mean diameter of provenances in the two provenance tests was presented in Fig. 6. In Varbitza it was 67.7 mm and was relatively larger than that in Kipilovo (58.5 mm) as could be seen from Fig. 5. With the largest mean diameter was the Bulgarian provenance Petrohan (75 mm in Varbitza and 65 mm in Kipilovo, and the smallest – the German provenance Silberbach (60 mm in Varbitza and 47 mm in Kipilovo). In second place in Varbitza with approximately the same mean diameter were provenances Ebersdorf and Berkovitza, and in Kipilovo - provenance Ebersdorf. The high level of significance of provenance indicated in Table 5 allows applying Tukey's multiple comparison method.

From the comparison of the mean diameters in pairs (Table 6), it was striking that only the provenance Silberbach significantly differs from the others in terms of this

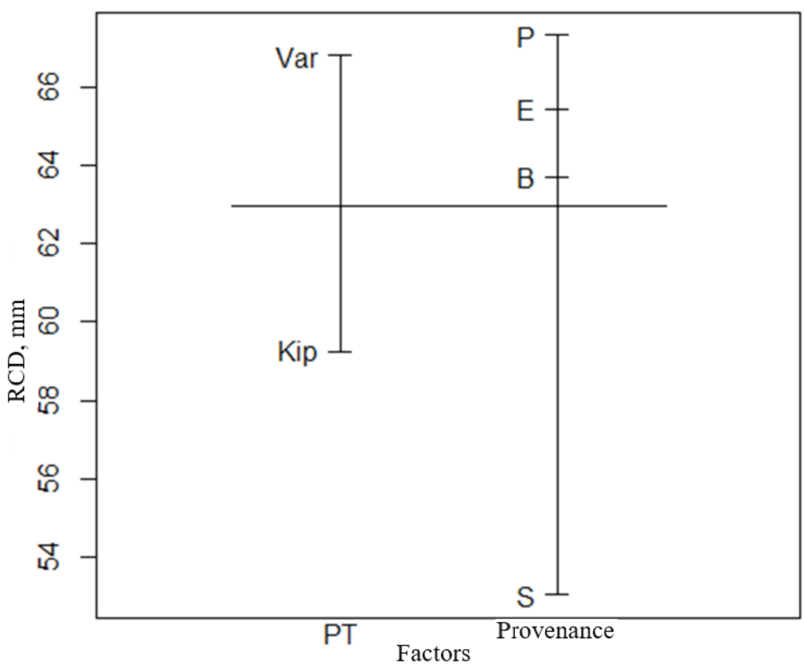

Fig. 5. Mean root collar diameter (RCD) by provenance (S – Silberbach, E – Ebersdorf, B – Berkovitza, P – Petrohan) and provenance trial (PT; Var – Varbitza and Kip – Kipilovo)

Table 5. Results of an ANOVA of root collar diameter (RCD) of 4 provenances at 2 provenance tests (PT)

	DF	Sum Sq.	Mean Sq,	F	*p*
PT	1	9838	9838	16.289	$6.05e^{-05}$ ***
Provenance	3	17624	5875	9.727	$2.73e^{-06}$ ***
PT x Provenance	3	1693	564	0.934	0.424 ns
Residuals	680	410699	604		

Note: Significance: *** - $p< 0.001$; ns - not significant.

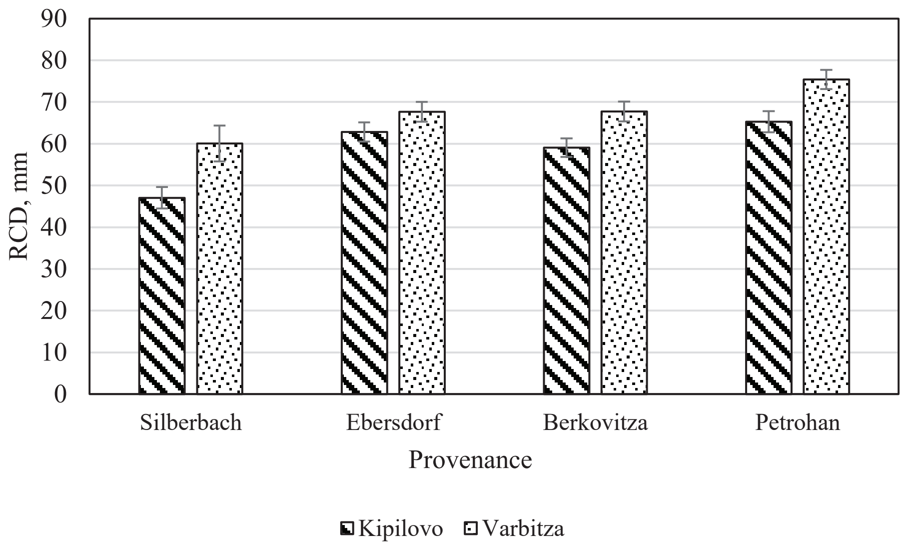

Fig. 6. Mean root collar diameter (RCD) of the common beech provenances in the provenance tests in Varbitza and Kipilovo in the 12th year after the establishment

indicator. The differences between provenances Ebersdorf, Berkovitza and Petrohan were not statistically significant.

The diameter of the seedlings depends not only on the provenance but also on the growth space that is provided when the seedling dyed, because the provenance tests were established under the same scheme. This is probably the reason why the German provenance Ebersdorf was equaled with the Bulgarian one Berkovitza in the provenance test in Varbitza, and in Kipilovo it was displaced.

Provenance Petrohan originated from a place with the largest annual rainfall amount of the four provenances and performs with the best growth and survival in both provenance tests, which were established in places with a relatively drier climate especially in Varbitza. The conclusion of Stojnic et al. (2013), that common beech provenances from wetter locations also perform well in drier continental climate, was confirmed.

Table 6. Comparing the differences between the mean diameters of provenances in the two provenances tests by Tukey's method

No	Term	Group 1	Group 2	Null. value	Estimate	Conf. low	Conf. high	p.adj	padj.sig
1	Provenance	B	E	0	1.7	-4.77	8.2	0.904	ns
2	Provenance	B	P	0	3.6	-3.2	10.4	0.523	ns
3	Provenance	B	S	0	-10.7	-17.9	-3.5	8.07E-04	***
4	Provenance	E	P	0	1.9	-4.88	8.65	0.89	ns
5	Provenance	E	S	0	-12.4	-19.5	-5.25	0.0000547	****
6	Provenance	P	S	0	-14.3	-21.7	-6.85	0.00000561	****

Note: Significance: **** $p < 0.000$; *** $p < 0.001$; ns - not significant

Conclusions

The average survival rate in the 12th year after the establishment of the provenance tests was bigger in Kipilovo (59%) compared to Varbitza (56.8%), most likely due to more rainfall there. The arrangement of the provenances according to this indicator was different in the two provenance tests. In Varbitza, the provenance Ebersdorf had the highest survival rate, and in Kipilovo - provenance Petrohan.

The Bulgarian provenances Petrohan and Berkovitza were with the best height growth in both provenance tests in the 12th year, and in root collar diameter - provenance Petrohan.

The good performance of the Bulgarian provenances shows that, in the event of faster climate changes, we have local provenances with which to support the adaptation of the common beech. It could be recommended for use in drier and warmer places in Germany provenance Ebersdorf, but more definite conclusions about the studied provenances require a longer period of observation.

Acknowledgements

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RESEARCH ARTICLE

Using the EPM method for the estimation of soil erosion in forest territories in the upper part of Dzherman River

Eli Pavlova-Traykova

Forest Research Institute, Bulgarian Academy of Sciences, 132, "St. Kliment Ohridski" Blvd.1756 Sofia, Bulgaria

Corresponding author: Eli Pavlova-Traykova (pavlova.eli77@gmail.com)

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Abstract

One of the most vulnerable to soil erosion parts in Bulgaria is the Struma river watershed. In the past, a lot of erosion control activities have been carried out in this catchment, but the topographic condition and easily prone to soil erosion soils are still redounding to erosion processes.

As a global problem with severe effects on the environment, soil erosion is on the agenda of scientific community. Because of difficult recognition on time, various methods for erosion risk and sediment loss assessment were applied. For mountainous watersheds one of the most appropriate approach is Erosion Potential Model (EPM).

The study aims to evaluate soil erosion and investigate its spatial distribution by applying EPM, also known as Gavrilovic method. The object of investigation is the upper part of the Dzherman river, which is tributary of Struma river. The method was implemented only for forest territories to determine the most vulnerable part of the forest. The results showed that for the forest territories the average value of the coefficient Z is 0.19, which defines erosion as "low" and the average soil loss only for forest areas is 15.28 m3/km2/year. Nevertheless there are territories with more than 100 m3/km2/year.

Keywords

soil erosion, EPM, forest territories, Struma river

Introduction

Soils play an essential role in the balance and preservation of terrestrial ecosystems, however, they are increasingly threatened by many factors (Hara et al., 2022) and are vulnerable to climate change and anthropogenic impact. In just two centuries we have managed to pollute soils with organic and inorganic substances (Malinova et al., 2022), to decrease the topsoil layer due to intensive farming and influence their destruction by allowing unregulated activities in forests and arable lands.

One of the most serious threats to soil is erosion. Soil erosion is a pervasive phenomenon that occurs in all parts of the terrestrial world (Pavlova-Traykova, 2019) and it is a major cause of land degradation. Erosion is a serious environmental concern in the era of worldwide change, natural hazards, and climate problems and it can be considered one of the most serious global issues (Lal, 2017). Global soil erosion rates are estimated to be around 10.2 t ha^{-1} yr^{-1} (Yang et al., 2003), while soil renewal rates are estimated to be considerably slower at less than 0.6 t ha^{-1} yr^{-1} (Branigan et al., 2022). Most of the European soils are affected too. It is considered that 6.6% of the total agricultural area in the EU suffered from severe erosion in 2016 (Panagos et al., 2020). It is estimated that the cost of annual crop productivity loss is 1.25 billion Euro (Panagos et al., 2018). And while some European countries are reducing soil loss rates, in others like Bulgaria it is increased (Panagos et al., 2020). Nowadays soil loss prediction is essential for better management and sustainable silviculture and agriculture practices. For that reason, a lot of models have been used. One of these methods is the Erosion Potential Method, which has acceptable accuracy and has a simple structure. It requires little input data and is also associated with Geographic Information Systems (GIS), which allows the visualization of the most susceptible to erosion areas.

The purpose of the investigation is to determine soil erosion and to investigate its spatial distribution in the forest territories of the upper part of the Dzherman river by applying the EPM method.

Materials and methods

Study area

The upper part of the Dzherman river (fig. 1) includes an area of 111.3 $km^{2,}$ 37.45km^2 of which are forest territories. This part of the river is characterized by steep slopes and active erosion processes. The average altitude is 1297.9 m. The length of the main current is 27.10 km. The density of the hydrographic system isIn this part of the watershed, a lot of erosion control activities have been conducted. For stabilization of steep slopes, the large-scale afforestation are made, mainly with white pine, (Pinus sylvestris L.), black pine (Pinus nigra Arn.), and acacia (Robinia pseudoacacia L.). To strengthen the river bed in this part of the watershed eight hydro-technical facilities have been constructed (Sokolovska et al., 2021). All these erosion control activities led to better soil conditions, stabilization of the territories, and a decrease in the risk of soil erosion and torrential floods. But there are still sights of active degradation processes which, along with climate changes, and with more and more frequent intensive precipitation, this part of Dzherman must be under monitoring.

The Erosion Potential Model (EPM)

One of the methods for estimation of soil erosion, appropriate for our territories is the EPM method, also known as the Gavrilovic method (Gavrilovic, 1988). It is developed for estimating erosion for application in torrential watersheds in southern and south eastern Yugoslavia (present-day Serbia), but it is also widespread and applicable in many other countries (Bazzoffi, 1985; Milanesi et. al., 2014; Efthimiou and Lynoudi, 2016; Pavlova-Traykova, 2021). It this empirical model three descriptive parameters are used, the other variables are quantitative and describe catchments. Gavrilovich determines erosion in 5 degrees (table.1), but for Bulgaria “low” and “very low” (IV and V) degrees of erosion are combined and it is customary to use – “low” erosion. (Marinov, Gruev, 2002; Pavlova-Traykova, 2021).

The annual volume of soil erosion by the Gavrilovich method is determined by the following equation:

$$W_{year}=T.H.\pi.\sqrt{Z^3}$$

In which W is the annual volume of soil erosion (m^3/km^2/year) H is the annual rainfall (mm), Z is erosion intensity, *T* is the coefficient of temperature which is calculated as shown in the following equation:

$$T=\sqrt{\left(\frac{t'}{10}\right)+0,1}$$

Where *t* is the mean annual temperature (°C). The data used to calculate the temperature coefficient of the area and the amount of precipitation are from the Dupnitsa climate station and are for a 39-year period. Climate data are taken from the project Mitigating Vulnerability of Water Resources under Climate Change (2012-2014).

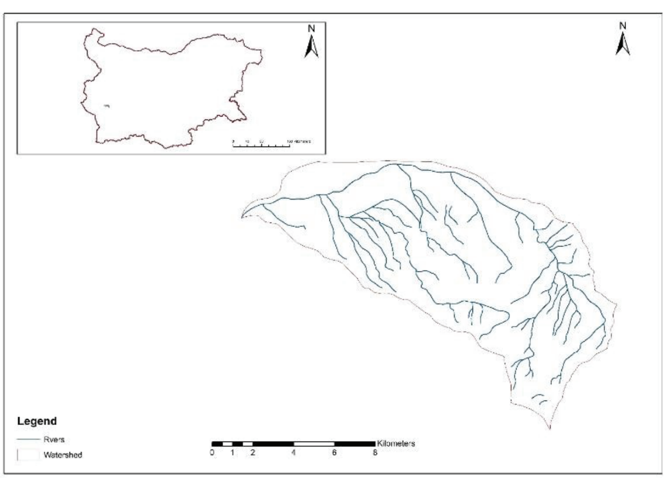

Figure 1. Upper part of Dzherman river

The erosion coefficient (Z) depends on four factors and is calculated as follows:

$Z=Y.Xa.(\varphi+\sqrt{Isr})$

Y is the soil erodibility coefficient, Xa is the soil protection coefficient, φ is the erosion coefficient, Isr is the average slope of the territories (%). These coefficients are determined by the tables which are presented in Pavlova-Traykova, 2021. This method considered the retention coefficient, which is assessed with the following equation.

$$Ru = \frac{\sqrt{O*D}}{0.2*(L+10)}$$

Where, O is the perimeter of the watershed (km), D is the average elevation of the watershed (km) and L is the length of the watershed (km).

The annual amount of transferred (transported) sediment (Gyear) was calculated as:

$Gyear = Wyear \cdot Ru$

In this research, each factor is described by the form of a digital map by using Geographic Information Systems. The digital layers are overlaid in order to estimate soil loss in the forest territories.

Results and disscusion

For forest territories, the average value of the coefficient Z is estimated as 0.19, which defines these territories with "low" erosion. In this watershed, another methodology for assessment actual and potential soil erosion risk was applied and the results showed that the forest territories are with "moderate" potential risk and "low to moderate" actual soil erosion risk (Pavlova-Traykova et al., 2021). From these results, we could make a conclusion that the EPM method underestimates erosion rates. The underestimation of EPM is also found by other authors (Lense et al., 2020).

The calculated soil loss varied a lot but average soil loss is 15.28m^3/km^2/year. This result also defines erosion as "low", which is expected, because the methodology is applied only to the forest territories, but from the spatial distribution (fig.2), there are territories with soil lose more than 100 m^3/km^2/year. These territories are mainly around the tributaries of the river which are the territories with "high" risk from the other applied methodology (Pavlova-Traykova et al., 2021), this is due to the presence of coastal erosion, which both methodologies manage to capture. Although the assessment obtained is lower with EPM, both methods direct our attention to the same forest territories with a high potential of erosion, which shows that EPM also gives relatively good results for our country.

The coefficient of retention Ru was calculated at 0.844, which means that 8.44% of the sediments generated in the forest territories reach the watercourses. According to this, the average annual amount of transferred (transported) sediment from the forest territory is 12.90 m^3/km^2/year, but in this distribution, there is also the presence of sediment of more than 100 m^3/km^2/year. The territories with high quantity of sediment are white pine afforestation and in coppice forest with beech *(Fagus sylvatica* L.*)*

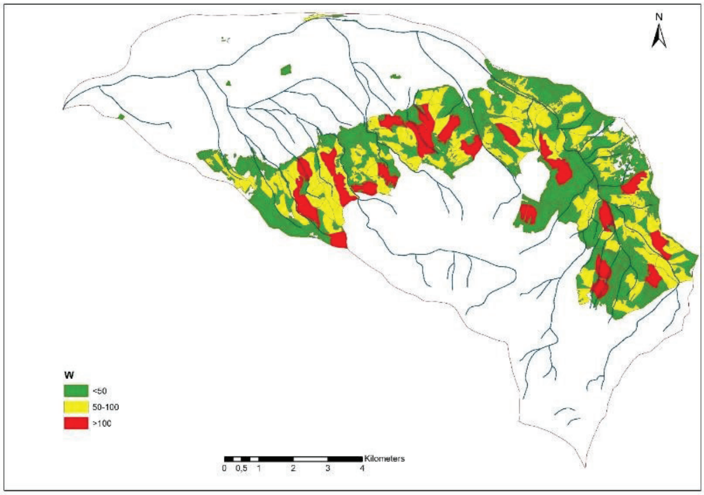

Figure 2. Spatial distribution of W in the forest territories of the upper part of Dzherman river

Table 1 .

Intensity of soil erosion Интензивност на почвената ерозия	Z
Very low Много слаба	<0.19
Low Слаба	0.20-0.40
Moderate Средна	0.41-0.70
High Силна	0.71-1.0
Very high Много силна	>1.0

in the lower part of the forest and in the upper part of the territory with fur (*Abies alba* Mill.) and spruce (*Picea abies* Karst.). They have in common the steep slopes, which are the main factor for soil erosion in the Struma river (Martensson et al., 2001; Malinov et al., 2009) watershed and its tributaries (Pavlova-Traykova et al., 2017; PavlovaTraykova, 2019). In this case it means it is also the main factor for the high quantity of transported sediment in this watershed.

Conclusions

The results for the coefficient of erosion Z and the annual volume of soil erosion present the forest territories in the watershed as areas with “low” erosion. However, there are territories with soil loss of more than 100 m^3/km^2/year. These areas coincide with areas assessed with a „high“ risk of erosion when applying another methodology. This shows that the selected method for erosion assessment is applicable to the conditions of our country and the results are comparable to the results of other methods used in forest areas.

The considerable ability of forest vegetation to protect territories from soil erosion was confirmed with coefficient of retention.

To ensure the future conservation of forests, not only the territories with higher soil loss must be managed cautiously, but sparing silviculture practices must be applied to the whole territories in view of climate change and its consequences.

Acknowledgement

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SILVA BALCANICA

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RESEARCH ARTICLE

Early detection of *Ips typographus* infestations by using Sentinel-2 satellite images in windthrow affected Norway spruce forests in Smolyan region, Bulgaria

Georgi Georgiev[1], Margarita Georgieva[1], Sevdalin Belilov[1], Plamen Mirchev[1], Stanko Deliyanchev[2], Velizar Mladenov[2], Kadir Kropov[2], Sirma Haydarova[3]

[1]*Forest Research Institute – Sofia, Bulgarian Academy of Sciences*
[2]*State Forestry – Smolyan*
[3]*South Central State Enterprise – Smolyan*

Corresponding author: Georgi Georgiev (ggeorgiev.fri@gmail.com)

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Abstract

Strong winds uprooted more than 100 thousand m^3 of coniferous trees in natural forest stands nearby the town of Smolyan (the Western Rhodopes) in January 2018. Although damaged trees were quickly removed from the stands, the European spruce bark beetle (*Ips typographus*) attacked the healthy Norway spruce trees near the windthrow areas in August 2020. Our hypothesis was that the trees were infested by the pest in previous years when no symptoms of attacks were observed. This study was conducted in three spruce stands, located near the windthrow areas and attacked by *I. typographus*, and in three control (healthy) stands located 5-10 km from the affected areas. We used satellite images captured by Sentinel-2 in September 2017-2020. It was established that in September 2017 (a year before the windthrow), the mean values of the Normalized difference vegetation index (NDVI) in the attacked stands were concentrated between 0.60 and 0.75 (with a maximum at 0.70), indicating that the trees were in good health. During the period 2018-2020 the distribution of mean values of NDVI was stretched between 0.35 and 0.75, which is an indication of evidence of pest attacks on the individual trees. The detail comparison of pixel values of the NDVI in the attacked and control sample plots was made on the base of images captured on 27.06.2020. The mean NDVI values in the three control plots (0.74-0.79) were much higher than the mean values in the sample plots attacked by the pest (0.57-0.65). These results showed that the values of NDVI based on satellite remote sensing data of Sentinel-2 can be used for early detection of *I. typographus* infestations in spruce stands around the windthrows. These data are important for rapid planning and implementing the sanitary feelings that reduce the pest population.

Keywords
Ips typographus, spruce forests, windthrow damages, satellite images, NDVI, Western Rhodopes, Bulgaria

Introduction

The State Forestry Smolyan is located in the Western Rhodopes at a territory of 28368.3 ha with mountainous landscape, different climatic characteristics and plant species biodiversity. Coniferous stands occupy 75.4% of the forested area with main tree species Norway spruce (*Picea abies* (L.) Karst.) – 35%, Scots pine (*Pinus sylvestris* L.) – 27%, Austrian pine (*Pinus nigra* Arnold) – 8%, and European silver fir (*Abies alba* Mill.) – 5%.

Natural disturbances caused by abiotic factors periodically occur in mountain forest ecosystems. Severe damages from wet snow were recorded in Scots pine plantations in the region of Smolyan in 2015. In 2018 strong winds brought down more than 100 thousand m^3 of coniferous trees in natural forest stands nearby the town (Belilov et al., 2022). The damaged trees were removed in less than one year from the affected stands. Nevertheless, the presence of fresh food substrate (stumps and stem residues) contributed to the multiplication of the European spruce bark beetle (*Ips typographus* Linnaeus, 1758) (Coleoptera: Curculionidae, Scolytinae) attacking healthy Norway spruce trees near the windthrow area. The first visible symptoms of the pest infestations were observed in 2020.

The application of remote sensing data based on images captured by satellites or unmanned aerial vehicles (UAV) has consistently increased for assessment the health status of forest ecosystems. Despite the appearance of new equipment and methods, satellite-borne multispectral sensors are the most commonly used technology for monitoring and assessment of the forest health condition (Torres et al., 2021). An integrated approach including the use of RGB orthophotos, multispectral data and terrestrial verification has been successfully applied in Bulgaria for mapping the bark beetle spots of *Ips typographus* (Dimitrov et al., 2019; Georgiev et al., 2022) and of *Ips acuminatus* (Gyllenhal, 1827) (Georgieva et al., 2022).

The aim of this study was to investigate the possibility of using the satellite images for early detection of *Ips typographus* infestations in Norway spruce stands around the windthrow areas in Smolyan region.

Material and Methods

The study was conducted in three spruce stands infested by *Ips typographus* near the windthrow areas (SP), and in three control (healthy) stands (CP) with similar structural characteristics, located 5-10 km from the damaged areas. The main characteristics of the sample plots are shown in Table 1.

Table 1. Main characteristics of the studied Norway spruce stands

N	Forest unit	Geographical coordinates	Altitude, m	Forest species* (Relative share, %)	Age, years
		Control (healthy) plots			
CP 1	98-f	41.599969°N, 24.694839°E	1420	Pa (90%), Ps (10%)	110
CP 2	2038-c	41.680688°N, 24.775218°E	1380	Pa (70%), Ps (10%), Aa (20%)	100
CP 3	3136-b	41.653501°N, 24.750588°E	1160	Pa (80%), Pn (20%)	100
		Attacked sample plots			
SP 1	163-g	41.559110°N, 24.704345°E	1220	Ps (40%), Pa (60%)	90
SP 2	165-x	41.558201°N, 24.691020°E	1330	Pa (60%), Ps (30%), Aa (10%)	90
SP 3	194-f	41.544936°N, 24.619699°E	1460	Pa (80%), Ps (20%)	100

* Aa – *Abies alba*; Pa – *Picea abies*; Pn – *Pinus nigra*; Ps – *Pinus sylvestris*

Satellite images captured by Sentinel-2 of the European Space Agency in September 2017-2020 were used to assess the earliest infestation of the pest in the studied spruce stands. Sentinel-2 has a multispectral instrument of a passive type, recording sunlight reflected from the Earth's surface with a spatial resolution of 10 m for visible and near-infrared bands, and 20 m and 60 m for short wave infrared bands. Imaging is performed in 13 spectral bands in the visible and near-infrared part of the electromagnetic spectrum (VNIR from 400 to 1100 nm) and short-wave infrared part (SWIR from 1100 to 3000 nm). The recording frequency is 5 days for the equator and 3 days for the other latitudes. The data is freely accessible. The images were acquired using the application Earth Explorer of US Geological Survey. Raster image processing was performed with QGIS-3 – a professional open source GIS application.

Pre-processing of the used images was carried out in order to remove the influence of water vapor and other particles located in the atmospheric layers above the studied objects. Shape files of the surveyed spruce stands were created.

Based on the spectral characteristics of the registered multispectral images, the Normalized difference vegetation index (NDVI) was calculated, which is the main indicator of the health status and vitality of the vegetation. NDVI is a mathematical combination between the red band (B4) and the nearinfrared (NIR) band (B8) that produces values between -1 to +1, according to the following expression:

$$NDVI = \frac{B8-B4}{B8+B4}$$

where B_8 is a spectral band of Sentinel-2 with a wavelength of 665 nm; B_4 – with a wavelength of 842 nm.

The comparison of pixel values of NDVI in the attacked and control plots was made by satellite images captured on 27.06.2020. Extraction of the investigated raster images was performed with subsequent raster analysis of all pixel values in each raster layer.

Statistical evaluation of NDVI values was performed using descriptive statistics of Statistica 12.0 for

Windows (StatSoft). The results were cited together with their standard error. T-test for independent samples was applied to compare the means.

The terrain verification of *Ips typographus* attacks was performed in the sample plots on 06.08.2020.

Results

The first visible infestations by *Ips typographus* in the healthy Norway spruce stands near the windthrow sites were observed in late July – early August 2020. The main symptoms of the pest development were observed: discoloration of tree crowns (Fig. 1A) and the preliminary fall of needles on the ground. The development of *I. typographus's* second generation under the bark of stems was also established (Fig. 1B).

The presence of *I. typographus* infestations in the spruce stands adjacent to the windthrow in August 2020 was a reason to hypothesize that the same trees were infested by the pest in previous years, when no symptoms of attacks were observed.

In September 2017 (before the windthrow), the mean values of NDVI in attacked stands were concentrated between 0.60 and 0.75 (with a maximum of 0.70), indicating good vitality of spruce stands (Fig. 2). In next years (September, 2018-2020), the main distribution of mean values of NDVI was between 0.35 and 0.75), which is an indication of pest attacks on individual trees.

The NDVI models of the studied areas on the base of satellite images captured on 27.06.2020 (before the appearance of visible symptoms of *I. typographus* attack) showed that in the control plots that were away from the windthrow the spruce stands were in good health status (Fig. 3 A-C), in contrast to the sample plots close to the damaged areas (Fig. 3 D-F).

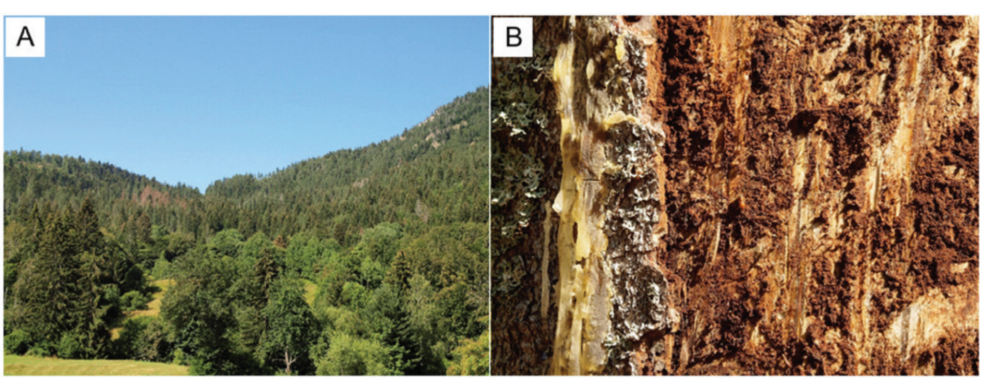

Figure 1. *Ips typographus* attacks (06.08.2020): A – attacked spruce stands; B – galleries and emerged adults of *Ips typographus* under the bark of attacked tree

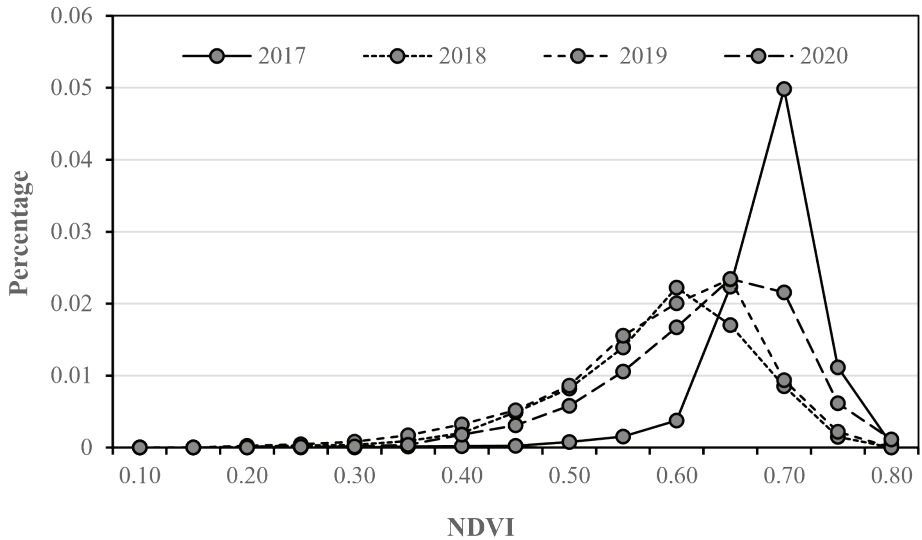

Figure 2. Distribution of mean NDVI values in three attacked spruce stands in the period 2017-2020

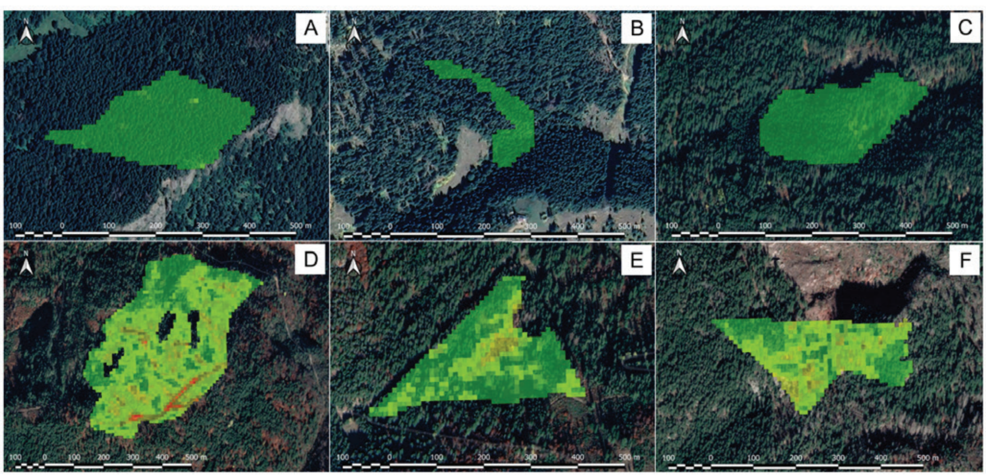

Figure 3. NDVI models of studied areas (27.06.2020): A – Control plot 1 (98-f); B – Control plot 2 (2038-c); C – Control plot 3 (3136-b); D – Sample plot 1 (163-g); E – Sample plot 2 (165-x); F – Sample plot 3 (194-f)

The mean NDVI values in the three control plots (CP1=0.74±0.02; CP2 and CP3=0.79±0.03) were much higher than the mean values in the sample plots with pest attacks (SP1=0.57±0.09; SP2=0.65±0.05; SP3=0.59±0.05) (Fig. 4).

The differences in the mean NDVI values from three control plots without *I. typographus* attacks (CP1 – CP3) and the sample plots attacked by the pest (SP1 – SP3) were statistically proven (p<0.001).

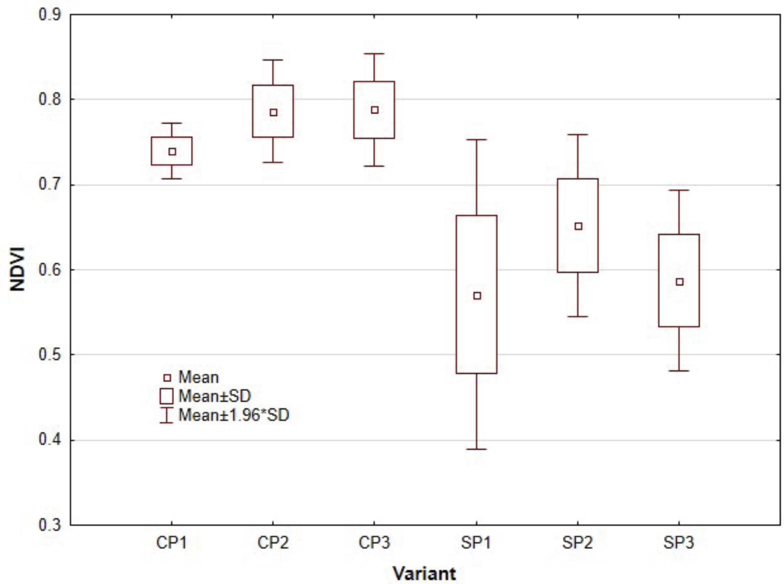

Figure 4. Pixel values of NDVI in the captured areas (27.06.2020): A – Control plot 1 (98-f); B – Control plot 2 (2038-c); C – Control plot 3 (3136-b); D – Sample plot 1 (163-g); E – Sample plot 2 (165-x); F – Sample plot 3 (194-f)

Discussion

Ips typographus is one of the most destructive xylophagous insect pests of Norway spruce species in Europe (Kaminska et al., 2021). Its outbreaks are usually caused by disturbances or extreme weather conditions (Wermelinger, 2004). Several outbreaks of the pest were recorded in the 20th century in various parts of Europe where over 100 million m^3 of spruce trees were killed (CAB International, 2021).

In Bulgaria, *I. typographus* does not usually cause strong damage to the managed spruce forests because of the intensive sanitary and control measures. Conversely, in protected areas, the pest develops on fallen and broken fresh trees, increases in number and attacks healthy stands. In 2001, a tornado affected mature spruce stands on 62 ha in Bistrishko Branishte Biosphere Reserve in Vitosha Mountain, after which *I. typographus* population first developed in windthrown timber, and from 2003 to 2005, spruce trees on over 200 ha were killed by the pest near the windthrow in the reserve (Rossnev et al., 2005).

In the Smolyan region, it was found that the use of NDVI from multispectral UAV and satellite data is not suitable for long-term monitoring of windfall forest areas due to the overgrowth of damaged stands with grass and shrub vegetation (Belilov et al., 2022).

It is well known that the symptoms of the advanced stages of bark beetle infestation (i.e. red attack), can be observed using the visible part of the electromagnetic spectrum (400 to 700 nm), but the detection of early stage symptoms (i.e. green attack) is more effective using sensors in near-infrared (700 to 1300 nm) and shortwave infrared (1300 to 2500 nm) spectrum (Abdullah, 2019).

In the Polish part of the Białowieża Forest, *I. typographus* outbreak was estimated by mapping dead spruce stands on a tree level using airborne hyperspectral and laser scanning data obtained from HySpex VNIR-1800 camera and Riegl LMS-Q680i scanner (Sterenczak et al., 2019, 2020). Satellite optical and thermal data of Landsat-8 and Sentinel-2 were successfully used to investigate the early stage of *I. typographus* infestation in the Bavarian Forest National Park in Germany (Abdullah et al., 2018, 2019). The authors established that the majority of spectral vegetation indices calculated from Sentinel-2, particularly red-edge dependent indices (NDRE 2 and 3) and water-related indices (SR-SWIR, NDWI, DSWI and LWCI) are able to discriminate healthy from infested plots. In addition, satellite images of WorldView-2, Pléiades 1B, and SPOT-6 were also used for detection of early stage of pest infestation in the Czech Republic (Abdollahnejad et al., 2021). The authors determined that identifying physiological stress in earlier stages could be more feasible, with higher reliability and accuracy, using hyperspectral sensors in wavelengths that multispectral sensors cannot cover.

Multispectral UAV-based imagery is capable of classifying tree decline during a bark beetle infestations in Scots pine (Georgieva et al., 2022) and Norway spruce (Junttila et al., 2022). Recent studies of spruce bark beetle attacks using Sentinel-2 multispectral data and different vegetation indices (including NDVI) in the Italian Alps show that the two stages of the epidemic (i.e. early and late) can be detected with an overall accuracy of 83.4% (Dalponte et al., 2022).

In conclusion, the present study showed that periodic observations and analyzes based on NDVI from satellite data of Sentinel-2 can serve reliably for early detection of *I. typographus* infestations in spruce stands around windbreak and windfalls in mountain areas. From a management point of view, the possibility to detect the attack of the European spruce bark beetle at an early stage using freely available satellite data is very important for rapid planning and implementing of sanitary measures in order to reduce the pest attacks.

Acknowledgments

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SILVA BALCANICA

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RESEARCH ARTICLE

European brown hare (*Lepus europaeus* Pall.) testes weights from different seasons and ages from Bulgaria

Chavdar Zhelev[1,2], Nino Ninov[3]

[1] *Southwest State Forest Enterprise, Blagoevgrad, Bulgaria*
[2] *Forest Research Institute – Bulgarian Academy of Sciences, Sofia, Bulgaria*
[3] *University of Forestry, Sofia, Bulgaria*

Corresponding author: Chavdar Zhelev (chavdar.d.zhelev@gmail.com)

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Abstract

The testes weights of 315 European brown hare from different ages were measured during a whole year in Bulgaria. The results indicate that the active reproductive season finishes at end of August and the beginning of September, whereupon follows a period of calm when the testes weights are at their lowest. In September, October, and the beginning of November, the weights of the testes are low. The first indications for the start of the new reproductive season were shown in November, with the gradual growth of the testes weights. In January the testes weights reached high levels, as the highest weights were measured in May-June, with slightly lower values in July and August. Low weights followed after this, when the calm period started in September and the testes growth is reactive in December. All adult males (above 1 year old, determined by dry eye lens weights, $n = 160$), had high significant values ($p<0.0001$) of testes weights during the whole year, compared to all the young ones (under 1 year old, determined by dry eye lens weights, $n = 155$). The results showed a normal reproductive cycle with periods of activity and calm in male European brown hares from Bulgaria. The distribution of testes weights, compared to the various ages, follows the same sequence, as the sperm density (we assigned sperm quantity for each individual in the epidydimides to five classes: 1 – no sperm, 2 – very little, 3 – moderately present, 4 – high amount, 5 – massive amount). In view of the fact that the density of sperm is defined by the tail of the epididymis, and the weights were measured from the testes, the connection between them proves the existence of a normal reproductive cycle with stages of activity and standstill. The heaviest testes had the biggest quantity of sperm in the epididymis, regardless of the season. We determined that the quantity of sperm and the weights of the testes were in direct dependency ($p < 0.0001$), directly following the line of activity and standstill in the seasons.

Keywords
testis weight, brown hare, sperm density, testicular activity

Introduction

The last 3-4 decades saw a decline in the brown hare population density in the places, where it occurs on the European continent. Some authors (Tapper, Parsons, 1984; Hutchings, Harris, 1996; Marboutin et al., 2003; Smith et al., 2005) state various reasons (change in habitats, intensive agriculture, reproductive problems, low survivability, the climate, the poaching, over-use, predators, diseases and low genetic diversity) for this, but there is no definite opinion on the issue. All researchers agree, however, that the reasons are complex. The decreasing number of brown hares has led to a change in their statute in the last decade. The species has been included in the Red List of the Endangered Species IUCIN in the category Least Concern (LC) (Smith, Johnston, 2008). The hare is listed in Application III of the Bern Convention (Vaughan et al., 2003, Smith et al., 2005). In Great Britain, it is classified as a 'priority species with conservation significance' (Smith et al., 2005), and Switzerland has included the species in its National Red List (Pfister et al., 2002).

Despite the declining tendency of the population in Bulgaria (Botev et al. 1985), the brown hare remains one of the most numerous local hunting species in the country. So much meat was obtained from it in the past that it was equal to the total remaining game. The yearly yield of brown hare skins (over 250 thousand pcs. in 1962) made up about 60 % from the total yield of game skins. (Ruskov, Petrov, 1968, Ruskov et al., 1972). During the years when its number exceeded 1 million individuals, the brown hare was a subject of trade. The peak in export was reached in 1968-1969 - over 40 thousand pcs. (Botev et al., 1985). The number of the brown hares in Bulgaria has been on a progressive decline from 1970 onward, but it has been more apparent since 1994. The official censuses report number within 370 to 420 thousand pcs. За последните 20 години броят на кафявия заек намалява до нивата на отстрел през 1970 г. After the high number and shooting from the 60s to the 80s, at present its number is at its lowest levels since 1952. Since 1995, the shooting has also began to decrease significantly, especially in 2003 (13 334 brown hares shot in total), when it reached its lowest point since 1933 (Zhelev, 2015; Zhelev et al., 2013). There are no official data about the shooting after 2009, but in 2012 and 2013, it did not exceed more than 5 thousand brown hares yearly (Zhelev, 2015).

Hunting of brown hares during 2012 occurred in 54 Hunting and Fishing Units (HFU) in the country, out of a total of 140 (HFU) in the structures of the National Association of Hunters and Anglerism - NAHA (without the members of Bulgarian Union of Hunters and Anglers - BUHA). In 2013, there were already 48 HFU, where 6 HFU free willingly denied themselves from hunting (Zhelev, 2015).

Studies about the reasons leading to the low number in the whole country have not been made in the last 30 years. A research on reproduction was made to determine the reasons for the decreasing hare population. We research the testicle weight of the European brown hares from Bulgaria of various ages, obtained from different months of the year in order to get an overview of the normal sequences of the morphological changes in the gonads during the year.

Materials and methods

For the time period from 2009 to 2014, 315 European brown hares form different ages underwent year-long testes weight measurements, and testicular activity was studied (Table 1 and Table 2). The samples were collected from 121 hunting grounds around the country under 600 m a.s.l. From all testes, 55 pcs were taken outside of the hunting season, in the period January – September, from 43 hunting grounds. The IBM SPSS Statistics, 19 (2010) (IBM corporation) software was used for the calculation of t-test at the various analyses. All weights were measured with an electronic scale Sartorius L 1000S, with an accuracy of up to 0.01 g. Their diameter was measured with a digital gauge IDF, L – 300 mm, with an accuracy of up to 0.1 mm. The age was defined according to the weight of the eye lens, described by Suchentrunk et al. (1991) and also from skull characteristics (Cabon-Raczynska, 1964; Pepin, 1973; Suchentrunk, Davidovic, 2004) and the Stroh (1931) method. Four classes of age for juvenile hares (up to 1 year of age) were identified regardless of the fact, that some of them were born at the end of the previous year (1 – up to 3 months, 2- from 4 to 6 months, 3 – from 7 to 9 months and 4 – from 10 to 12 months). Three classes were defined for adult brown hares (up to 1 year of age): 5 – from 1 to 2 years, 6 – from 2 to 3 years, and 7 – over 3 years. In order to compare the sequence on the testes weights distribution to the various ages with sperm density, we assigned sperm quantity (concentration of the spermatozoa) for each individual in the epididymis by binocular stereoscope (Carl Zeiss Germany) with a categorization into five classes by Hubenov (1974): 1 – no sperm, 2 – very little, 3 – moderately present, 4 – high amount, 5 – massive amount.

Results and Discussion

We determine (Table 1) that there is a significant difference in the testes weights from age class 3 up to age class 7 between the periods (active and inactive). This is normal due to the fact that in the 7-th month the brown hare is already physiologically mature. We observe similar results with the sperm classes (Table 2), where the significant differences between the periods have already started at age class 2, with the exception of age class 3.

The results of a study by Lincoln et al. (1976) showed that juveniles reach puberty only during the breeding season of adults. The age at which puberty is reached varies with the date of birth. Males born before May reach puberty and become sexually mature at 2-3 months of age. Puberty is delayed for several months for those born between May and July, and who reached physiological maturity in the autumn, in the inactive reproductive period. The third group, born after July, resemble those of the first group. They show strong reproductive tract growth at 3 months of age, which coincides with the start of the new breeding season. The delay of puberty in male hares is dictated by the oppressive photoperiodic conditions of autumn. The development of the reproductive tract begins at a normal age, but unfavourable environmental conditions delay sexual maturation until the start of the new breeding season.

The results show (Fig. 1) that the active reproductive season finishes at the end of August and the beginning of September, after which follows a period of calm when the testes weights were at their lowest. In September, October and the beginning of

Table 1. Testes weights distributed by age classes during the whole year for the research period 2009-2014 and statistical significance on the testes weight differences between the periods, compared with t-test

Age class	*p*	Active reproductive period (January – September)							Inactive reproductive period (October – December)						
		N	Range	Min	Max	Mean	SE	SD	N	Range	Min	Max	Mean	SE	SD
1	0.795	2	0.1	0.1	0.2	0.2	0.0	0.1	6	1.8	0.2	2.0	0.5	0.3	0.7
2	0.222	3	0.3	0.3	0.6	0.4	0.1	0.1	26	5.4	0.3	5.7	1.1	0.2	1.2
3	0.009**	8	13.3	0.9	14.1	7.3	1.6	4.6	71	7.9	0.3	8.3	3.2	0.3	2.2
4	0.010*	7	14.7	1.7	16.3	8.7	1.6	4.3	30	9.6	1.2	10.8	3.9	0.4	2.3
5	0.000***	8	7.2	7.2	14.5	10.7	0.9	2.5	39	10.8	0.8	11.6	4.5	0.4	2.6
6	0.000***	25	13.0	1.7	14.7	9.7	0.8	3.8	81	10.0	1.4	11.4	4.7	0.3	2.4
7	0.020*	2	2.8	10.4	13.2	11.8	1.4	2.0	7	19.6	3.6	23.2	9.0	2.5	6.6

Note: N – number individuals; statistical significance: *p < 0.05, ** p < 0.01, ***p < 0.001

Table 2. Testes weight distributed by sperm classes during the whole year for the research period 2009-2014 and statistical significance on the testes weight differences between the periods, compared with t-test

Age class	*p*	Active reproductive period (January – September)							Inactive reproductive period (October – December)						
		N	Range	Min	Max	Mean	SE	SD	N	Range	Min	Max	Mean	SE	SD
1	0.557	2	0.4	0.2	0.6	0.4	0.2	0.3	23	4.7	0.2	5.0	2.2	0.3	1.5
2	0.019*	5	1.0	0.1	1.1	0.6	0.2	0.4	84	6.7	0.2	6.8	2.2	0.2	1.4
3	0.068	9	8.7	1.7	10.4	5.9	1.2	3.7	117	11.3	0.2	11.4	4.0	0.2	2.2
4	0.022*	26	8.7	6.0	14.7	10.2	0.5	2.5	22	20.7	2.5	23.2	7.9	0.9	4.0
5	0.002**	13	9.6	6.7	16.3	11.6	0.9	3.2	14	8.0	3.1	11.1	7.7	0.6	2.2

Note: N – number individuals; statistical significance: *p < 0.05, ** p < 0.01, ***p < 0.001

November, the weights of the testes were low. The first indications for the start of the new reproductive season were shown in November, with the gradual increase of the testes weights. In January the testes weights reached high levels, as the highest weights were measured in May-June, with slightly lower values in July and August. After this follows a low weight spell, when the calm period starts in September, and the testes growth is reactive in December. Similar results are also recorded by Lincoln (1974), Blottner et al. (2000) and Simeunovic et al. (2000). All adult males (above 1 year old, n=160), had high significant values (p<0.0001) of testes weights during the whole year (see Table 1), compared to all the young ones (under 1 year old, n=155). The results showed a normal reproductive cycle, with periods of activity and calm in male European brown hares from Bulgaria.

Lincoln (1974) studied the reproductive physiology of 760 hares shot throughout the year to explain seasonal changes in behaviour and the so-called 'March Madness'. After the autumn rest period, the first indications of the new reproductive season appear in November, with the increase in weight and activity of the testicles. This trend continues from December to February. Reproduction in females begins most often in January with the first ovulation. In March and April, hares show full reproductive activity and almost all the females are pregnant, most often with three or more embryos. During these months ('March Madness') the breeding process is at its peak and many male hares are close to depleting their sperm reserves in the epididymis. In May, June and July, females continue to be highly fertile. In males, there is a decrease in the synthesis of testosterone in the testicles. The reproductive period declines and

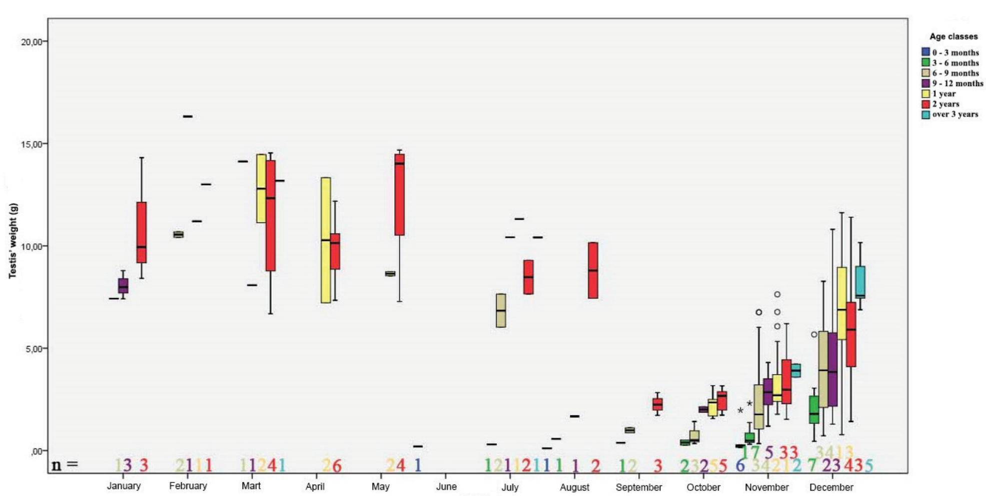

Fig. 1. Distribution of the testes weight from all individuals (n=315) during the whole year according to different age classes. For each class of age, coloured in different colours, the number of individuals belonging to it was also pointed bellow. Each month can have a maximum class of age seven (e. g. November) and minimum one (e. g. June), due to the lack of samples

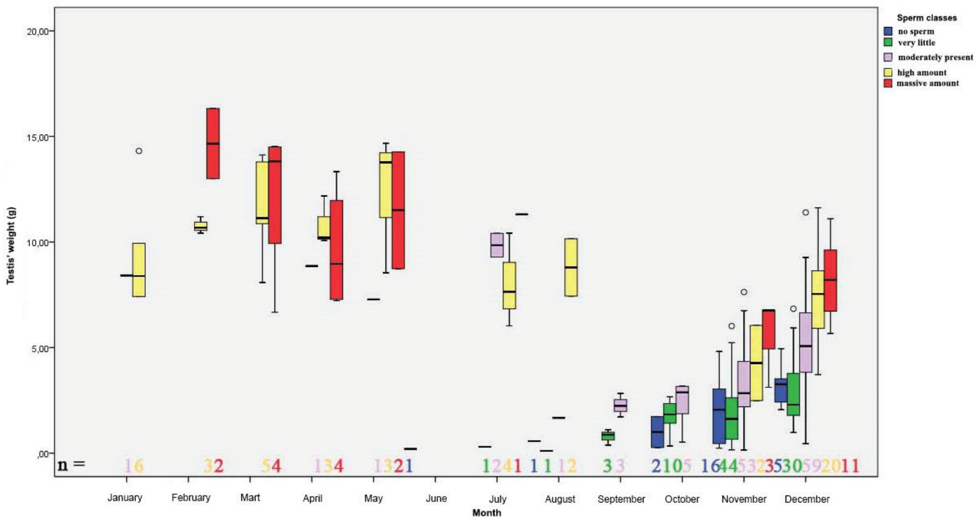

Fig. 2. Distribution of testes weight from all individuals (n=315) during the whole year according to different sperm classes. For each class of sperm, coloured in different colours, the number of individuals belonging to it was also pointed out below. Each month can have a maximum class of age seven (e. g. November) and minimum one (e. g. June), due to the lack of samples

ends in late July and early August. In the testes, there is a rapid regression in August and sperm production is constant (no peaks) until September. The sperm reserves in the epididymis are gradually depleted and the sperm count is reduced by October. In females, the number of births from one birth is also reduced and pregnant individuals are rare after September.

The distribution of testes weights, compared to the various ages, follows the same sequence as the sperm density. In view of the fact that the density of sperm is defined by the tail of the epididymis, and the weights were measured from the testes, the connection between them proves the existence of a normal reproductive cycle with stages of activity and standstill. The heaviest testes had the biggest quantity of sperm in the epididymis (Fig. 2), regardless of the season (see Table 2). We determined that the quantity of sperm and the weights of the testes were in direct dependency ($p<0.0001$), directly following the line of activity and standstill in the season, which confirms the results by Blottner et al. (2000, 2001).

The results related to the condition of the reproductive possibilities of hares in Bulgaria show that there is a normal sequence of the morphological changes in the gonads during the year. The reproduction of hares was completely normal, and the reproductive parameters were within the accepted ones for the areal of the species. That is why the notion that the probable reason for the low number is related to an impaired reproductive process can be dismissed with a high degree of certainty. Problems in reproduction were not observed, and the reason for the declining numbers of the species can be searched in other factors and reasons.

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SILVA BALCANICA

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RESEARCH ARTICLE

New data on the distribution of ground beetles (Coleoptera: Carabidae) in Kenya

Vladimir Sakalian[1], Georgi Georgiev[2]

[1]*Institute of Biodiversity and Ecosystem Research, Bulgarian Academy of Sciences, 1 Tzar Osvoboditel Blvd., 1000 Sofia, Bulgaria*
[2]*Forest Research Institute, Bulgarian Academy of Sciences, 132, "St. Kliment Ohridski" Blvd.1756 Sofia, Bulgaria*

Corresponding author: Georgi Georgiev (ggeorgiev.fri@gmail.com)

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Abstract

New data on the distribution of 12 species and subspecies of ground beetles (Coleoptera: Carabidae), which belong to 9 genera, 6 tribes and 5 subfamilies (Anthiinae, Carabinae, Cindelinae, Dryptinae and Panagaeinae) in Kenya are reported.

Keywords

Carabidae, Anthiinae, Carabinae, Cindelinae, Dryptinae, Panagaeinae, distribution, Kenya

Introduction

During the period 2003-2006, the first author collected many different coleopteran insect species in Kenya, mainly Buprestidae (Curletti, Sakalian, 2007, 2009; Sakalian, Georgiev, 2013; Bílý, Sakalian., 2014), but also Cerambycidae (Sakalian, Georgiev, 2011) and Tenebrionoidea (Ferrer et al., 2016). Among the other coleopteran material, some taxa belonging to Carabidae family were established.

The family Carabidae numbers more than 40,000 species worldwide. The fauna of the best studied area in the Ethiopian zoogeographical region – South Africa includes over 1,400 species (Schoeman et al., 2018), but its actual number in this country, as well as that of the Ethiopian region as a whole, is undoubtedly greater due to the still insufficient knowledge about ground beetles in the tropics and subtropics. A part of the carabid samples were identified by Dr. Augusto Vigna-Taglianti.

This note reports new data on the distribution of 12 carabid taxa belonging to 9 genera, 6 tribes and 5 subfamilies in Kenya.

Materials and Methods

The ground beetles were collected by traditional entomological methods: hand collection on the ground and attracting to lamp light.

The current status, synonyms and combinations concerning Kenyan taxa are reported according to Lorenz (2005). The names of the subfamilies, tribes and species and subspecies are listed in alphabetical order.

The studied material is deposited in the Scientific Fund of Institute of Biodiversity and Ecosystem Research of Bulgarian Academy of Sciences (Sofia, Bulgaria).

Results and Discussion

Subfamily Anthiinae Bonelli, 1813
Tribe Anthiini Bonelli, 1813

***Anthia (Anthia) artemis* Gerstaecker, 1884 (Fig. 1A)**

Elmentaita Lake, 00°28′31″S, 36°15′46″E, 1820 m, 14-15.04.2006, 1 ex., V. Sakalian leg.

***Anthia (Termophilum) hexastictum hexastigmum* (Gerstaecker, 1866) (Fig. 1B)**

Voi Wildlive Lodge, 600 m, 04-06.11.2005, 2 ex.; 27-28.04.2006, 1 ex., V. Sakalian leg.

***Chilanthia cavernosa* (Gerstaecker, 1866)**

Voi Wildlive Lodge, 600 m, 04-06.11.2005, 1 ex.; Kipepeo Farm near Malindi, 24.04.2006, 1 ex., V. Sakalian leg.

***Cypholoba chanleri* (Linell, 1896)**

Lower Tana River, Gamba Guest House, 25-27.10.2005, 2 ex.; 20-23.04.2006, 4 ex., V. Sakalian leg.

***Cypholoba cinereocincta alluaudi* (Sternberg, 1907)**

Voi Wildlive Lodge, 600 m, 04-06.11.2005, 2 ex.; 27-28.04.2006, 4 ex., V. Sakalian leg.

***Cypholoba sparthulata* (Gerstaecker, 1866)**

Lower Tana River, Gamba Guest House, 25-27.10.2005, 2 ex.; 20-23.04.2006, 1 ex.; Voi Wildlive Lodge, 600 m, 27-28.04.2006, 1 ex., V. Sakalian leg.

***Cypholoba tetrastigma tetrastigma* (Chaudoir, 1848)**

Voi Wildlive Lodge, 600 m, 27-28.04.2006, 1 ex., V. Sakalian leg.

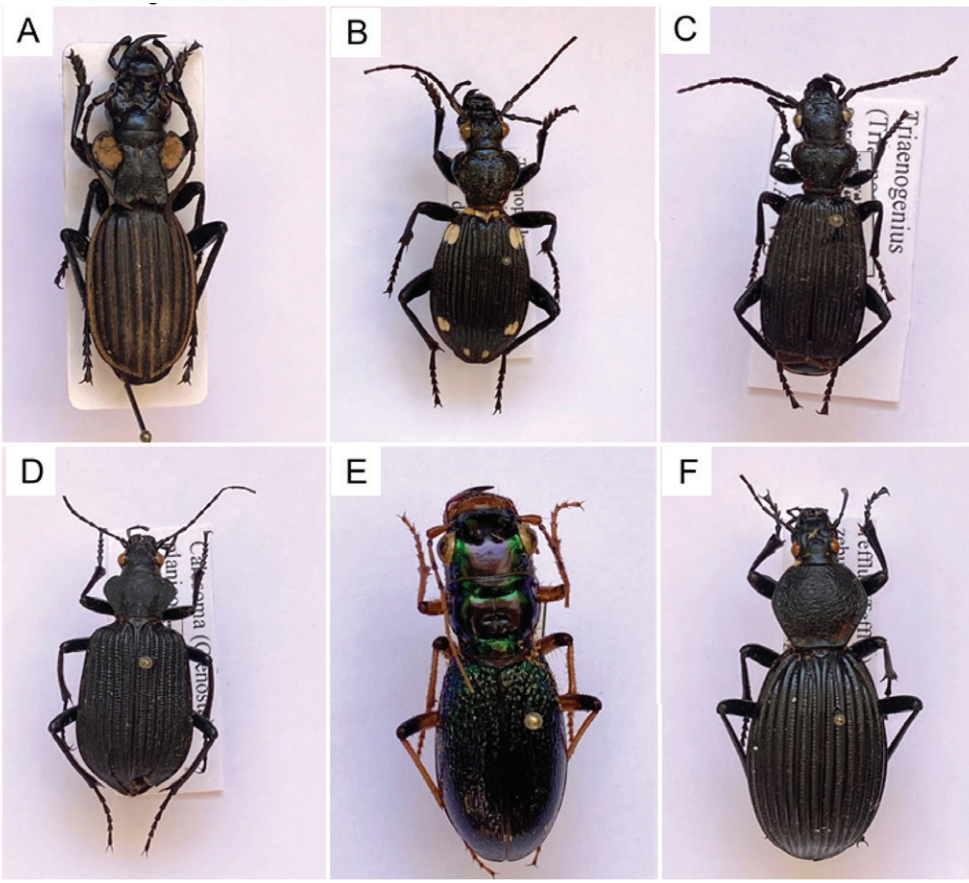

Figure 1. Ground beetles collected: A – *Anthia artemis*; B – *Anthia hexastictum hexastigmum*; C – *Triaenogenius gerstaeckeri*; D – *Calosoma planicolle*; E – *Megacephala regalis excelsa*; F – *Tefflus zebulianus transitionis*

Tribe Helluonini Hope, 1838

***Triaenogenius (Triaenogenius) gerstaeckeri* (Chaudoir, 1877) (Fig. 1C)**

Voi Wildlive Lodge, 600 m, 04-06.11.2005, 2 ex., V. Sakalian leg.

Subfamily Carabinae Latreille, 1802

Tribe Carabini Latreille, 1802

***Calosoma (Ctenosta) planicolle* Chaudoir, 1869 (Fig. 1D)**

Voi Wildlive Lodge, 600 m, 27-28.04.2006, 1 ex., V. Sakalian leg.

Subfamily Cindelinae Latreille, 1802

Tribe Megacephalini Laporte, 1834

***Megacephala regalis excelsa* Bates, 1874 (Fig. 1E)**

Kipepeo Farm near Malindi, 24.04.2006, 2 ex., V. Sakalian leg.

Subfamily Dryptinae Bonelli, 1810

Tribe Galeritini Leconte, 1853

***Galerita (Galerita) angustipennis* Gerstaecker, 1867**

Lower Tana River, Gamba Guest House, 20-23.04.2006, 1 ex., V. Sakalian leg.

Subfamily Panagaeinae Bonelli, 1810

Tribe Panagaeini Bonelli, 1810

***Tefflus* (*Tefflus*) *zebulianus transitionis* Kolbe, 1903 (Fig. 1F)**

Voi Wildlive Lodge, 600 m, 27-28.04.2006, 1 ex., V. Sakalian leg.

We consider that this short list is only a small contribution to a better understanding of the species diversity of the Kenyan Carabidae. We expect a lot of new data to be established to improve our knowledge on the very interesting fauna of this country.

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We would like to express our gratitude to the late famous entomologist Dr. Augusto Vigna-Taglianti (Rome, Italy) for determining of our material.

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RESEARCH ARTICLE

Study on the level of operational reliability of diesel engines for backhoe loaders

Svetozar Madzhov

Forest Research Institute, Bulgarian Academy of Sciences, 132, "St. Kliment Ohridski" Blvd.1756 Sofia, Bulgaria

Corresponding author: Svetozar Madzhov (smadjov@gmail.com)

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Abstract

In the present study the main numerical characteristics of the reliability indicators for the Komatsu SAA4D104E-1 engines of the KOMATSU WB93R-5 backhoe loader have been determined, and the laws of resource allocation have been established.

To study the level of reliability of machines, a methodology for experimental research has been developed, where the complex, comparative and formal methods, as well as the systematic, cybernetic and statistical approach have been used. It has been found that increasing the level of reliability of the engine elements can be improved by increasing the quality and timeliness of the repair and maintenance activities and compliance with the rules of operation.

This study is a continuation of a study conducted by the author.

Keywords

reliability, units, assemblies, systems, engines, excavators, maintenance, repair

Introduction

In the current stage of economic development, especially relevant is the problem of increasing the efficiency of machinery, used as the active part of the main production assets, and determining the production capacity of the business organization.

As the technical level of the machines increases, their complexity and productivity increase, as well as the price (Kozlovsky et al., 1998; Mirotin, 2000; Chervonyi et al., 1972). The main trend, however, is the clear relative share of the service complex in the overall balance of productive forces that is constantly growing.

Significant reduction of costs in the service complex can be achieved by optimizing the structure and parameters of the system for maintenance and repair of equipment with different methods and models. This requires studying the numerical characteristics of the reliability indicators of the elements of machines / units, parts and assemblies / in order to develop an effective system for maintenance and repair, ensuring efficient use of machines.

The aim of the research is to determine the main numerical characteristics of the reliability indicators of the engines of KOMATSUWB93R-5 backhoe loaders. This study is a continuation of our previous study (Madzhov, 2019), which in the future will track how the reliability characteristics of engines change with age.

Materials and methods

To study the characteristics of reliability indicators, a methodology for experimental research was developed, which used the complex, comparative and formal methods, as well as the systematic, cybernetic and statistical approach (Mihov et al., 2012; Spiridonov et al., 1981; Skovorodin et al., 1990; Lukinsky, 2000; Mirotin et al., 2000; Mikhovet al., 2012;).

The methodology of the experimental research (Fig. 1) is based on active and passive methods of conducting the experiment.

Monitoring planning means the selection of the site, the conditions for conducting operational observations and the monitoring plan (establishing the number of monitoring sites and the duration of the monitoring).

According to the research plan, the latter are divided into the following main groups: [NUN]; [NUT], [NUr], [NRT], [NRr]; where U means a plan in which failed objects are not replaced by new “Unrepaired”, R - means a plan in which failed objects are replaced by new or repaired “Repaired”.

Within the limits of this classification, the following plans are also used: [1*RT*] – object of testing is one product, which, in case of refusal, is replaced with a new or repaired for fixed production Ti;

[1*RT*] - the object of testing is one product which, if it fails, is replaced by a new one or repaired up to a fixed number of failures r;

[*NUT* (r=0)], [*NRT* (r=0)]– the object of the test is N products, and the ones that have been replaced or not during production T no failures have been registered.

The process of occurrence of failures and change of the state of the elements of the object of study has a random (stochastic) nature. To assess the level of reliability of the elements, specific and complex indicators are used, which are based on statistical information. Obtaining the statistical characteristics of the indicators is based on methods of probability theory and mathematical statistics. The systematic approach is applied to choose the best solution in the presence of several possible options.

The study was performed in the conditions in which the machines operate: a set of natural, climatic, production, technical, economic, organizational and social factors

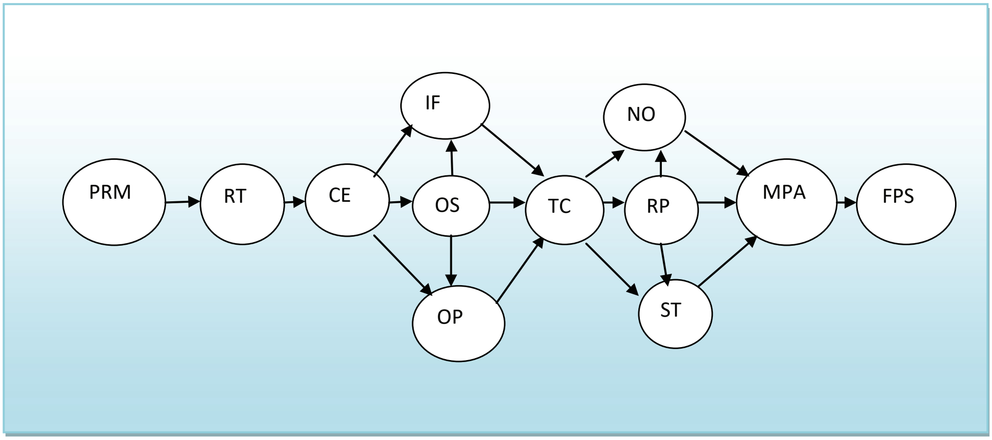

Figure 1. Structure and interrelationship of the elements of the methodology for the experimental study of the level of reliability of the machines: PRM - purpose of the research methodology; RT - research tasks; CE-criteria evaluation of the condition of the site; OS - object of study; IF- input factors; OP - output parameters; TC - testing conditions; RP - research plan; NO - number of objects; ST - study time; MPA-methods for processing and analysis of test results; FPS - form of presentation of study results.

influencing the intensity of changes in the parameters of their condition. The survey was conducted for the territory of the Republic of Bulgaria with excavator loaders of the company “Kirov” AD in Sofia and Sofia region. The object of study were: 180 excavator loaders, working all year round, and the nominal working fund is 1896 hours per year; monthly - 158 hours. The study was conducted for 2 years in the period 2014 – 2015.

The object of research are the same 180 excavator loaders, studied in the previous 4 years for the period 2010 – 2014. Therefore, the aim of this study is to supplement the information on the reliability of the site and to increase the reliability of indicators and numerical characteristics of the reliability properties (Madzhov, 2019). A student test was used to prove the statistical significance of the main numerical characteristics of the indicators of reliability of research for both periods.

The following four main stages can be identified in each test: test planning; conducting the test; processing of the test result; analysis of the result and choice of solution (Lukinsky, 2000; Mihovet al., 2012; Spiridonovet al., 1981; Skovorodinet al., 1990; Howard et al., 1998)

In this study we will focus mainly on the analysis of research results and proposals for theory and practice.

Basic information on SAA4D104E-1 engine malfunctions of KOMATSU WB93R-5 backhoe loaders is classified according to the following main features: origin, cause of occurrence, complexity of removal, type of elements, consequences of refusals, the nature of manifestation and manner of removal.

The information received is from direct observations and information maps from January 2014 until December 2015. The data were collected according to the developed methodology of the experimental study, classified by elements and grouped according to the following classification features, properties and reliability indicators.

Results and discussion

Distribution of refusals by reasons of occurrence (quality of workmanship; construction) active defects, violated rules of exploitation, prolonged exploitation. The wear and tear, the quality of the repair are shown in Table 1.

Table 1. Percentage distribution of failures by reason of occurrence

Causes of failures	**Percentage,%**
Duration of operation	44.25
Natural wear	8.25
Quality of workmanship	6.36
Structural deficiencies	3.24
Violation of the rules of operation	26.25
Quality of repair	11.65

From the analysis of the types of refusals due to their origin, we found that the highest number of refusals due to long-term operation is 44%. Secondly - 26% are failures due to non-compliance with the rules for using the machines.

From the analysis of the information on the reliability of the engine elements of the KOMATSU WB93R-5 excavator backhoe loader, we have concluded that the highest percentage is those of failures of the elements of the fuel system. Tables 2 and 3 give the distribution of the failures of the elements of the fuel system. The distribution of the refusals according to the external manifestation is shown in Table 2, and by units and aggregates - in Table 3:

It has been established that the share of malfunctions of the elements of the fuel system on the level of reliability of the engine is different and this is more substantial after an engine overhaul, given the different degrees of recovery of their resource.

Investigation of the faultlessness of the elements of the fuel system of the excavators

The reliability of the fuel system of the engines was evaluated according to the indicators: workmanship among the failures and the flow of refusals and characteristics: average number of refusals $\overline{m}$ (t); parameter of failures flow *w(t)* and the work between the failures $\bar{t}_i$.

Table 2. External manifestation of failures

№	Rejected elements and external manifestation	% of refusals
A	**Disclaimer of details and assemblies**	
1.	Camshaft bearing	24.22
2.	Violation of the tightness of the sealant	12.06
3.	Fuel supply pump	3.25
4.	Spring on the leaking valve	3.29
5.	Pusher spring	2.89
6.	Regulator connector	2.39
B	**External manifestation of failures**	
7.	Increasing the inequality of supply	15.08
8.	Reducing the minimum cycle rate	14.23
9.	Reduction of the frequency of rotation and the beginning of the activation of the regulator	6.35
10.	Decrease in the degree of enrichment	16.24

Table 3. Breakdown of combustion system failures by units and unit*s*

Units and aggregates	**Number of engine failures**	
	to major repairs	**between major repairs**
Fuel pump	0.32	0.57
Nozzles	0.66	0.68
Fuel line for high pressure	0.50	0.48
Fuel line for low pressure	0.74	1.68
Filter for rough cleaning of fuel	-	0.09
Filter for fine cleaning of fuel	0.29	0.13
All on the engine	2.46	3.23

The values of the numerical characteristics of the indicators are given in Table 4. The analysis of the data shows the level of reliability of the elements of the fuel system up to overhauls about 2 times higher than between repairs.

The workmanship between the orders is divided according to Gauss's law. The hypothesis of Gauss's law is not rejected as a level of significance $\alpha = 0{,}0$ and degree of freedom k = 2. The main numerical characteristics of the production among the failures are $\bar{t}_i$ = 858.7 moto hours; σ = 284.35; ϑ = 0.18. This means that this evidence can be used in further research and to model the processes of maintaining the performance of the studied backhoe loaders.

Table 4. Characteristics of the combustion system reliability

Characteristic of impunity	Designation	Values	
		up to an overhaul	between the overhauls
Average number of failures per 3000 motorcycle hours	$\overline{m}$	3.70	7.80
Response flow parameter, 1/-hour x10^{-5}	$w(t)$	119	230
Work between failures, moto hours	$\bar{t}_i$	858.7	439.4

Table 5. Main numerical characteristics of the operation until combustion system elements failure

№	Description	Main numeric characteristics moto h.		
		$\bar{t}.0^{3}$	$\sigma.0^{3}$	ϑ
1	High-pressure fuel line	145.1	31.0	0.21
2	Pipe line outlet nozzle, kit	45.9	12.0	0.26
3	Pipe pipeline overflow, kit	58.9	13.1	0.22
4	Pipe to the filter, kit	49.0	6.0	0.12
5	Pipe to the pump, kit	28.9	6.0	0.21
6	Fuel filter for rough cleaning	46.6	14.0	0.30
7	Fuel filter, kit	38.7	10.0	0.01
8	Fuel filter spring	28.4	3.0	0.10
9	Bolt on the rotating knee	31.1	4.1	0.13
10	Sealing ring	10.5	2.50	0.24
11	Filter with console	89.9	22.0	0.25
12	Reflector	0.86	0.20	0.23
13	Filtering element	0.98	0.40	0.41
14	Winged profile, kit	19.5	9.2	0.47
15	Needle on the blow hole	10.5	1.30	0.12

Table 6. Basic numerical characteristics, parameters, and resource distribution laws of Komatsu SAA4D104E-1 elements of Komatsu WB93R-5 Backhoe Loaders

№	Elements	Estimates of the main numerical characteristics and parameters		
		top	σ	V
1	Engine	20708	11920	0.472
2	cylindrical head	22398	7330	0.33
3	Nozzle	14259	6830	0.48
4	Fuel Pump	24787	12740	0.51
5	fuel injection pump	24927	9420	0.38
6	Oil Pump	42359	14828	0.35
7	Water pump	21488	12044	0,56
8	Radiator	27838	8524	0.31

Table 7. Gamma percentage resource elements in Komatsu SAA4D104E-1

№	Elements	80% gamma- resource, l
1.	Engine	13344
2.	cylindrical head	18970
3.	Nozzle	7892
4.	Fuel Pump	19955
5.	fuel injection pump	17858
6.	Oil Pump	29785
7.	Water pump	10784

Table 8. Characteristics of the combustion system durability

Durability characteristic	Designation	Values	
		up to an overhaul	between the overhauls
Resource, moto hours	T	5428	1375
Gamma percentage resource, moto hours	$T_{y\text{-}0.80}$	4889	1070
Exploitation period, yearly	T_e	8,45	4,08
Gamma percentage exploitation term, yearly	$T_{ey\text{-}0.80}$	7,80	2,54

Table 9. Timing for the replacement of Komatsu SAA4D104E-1 engine elements on KOMATSU WB93R-5Backhoe Loaders

№	Elements	Average discharge	Number of workers	Standard Replacement Time man-hours t_{cp}		Replacement time according to experts		
						σ	V_x	
1	*Engine*	3.5	2	3.80	(7.50)	11.0	3.0	0.27
2	*Cylindrical head*	3.3	2	3.78	(7.55)	4.0	1.2	0.3
3	*Nozzle*	3.6	2	0.38	(0.76)	0.25	0.1	0.4
4	*Fuel pump*	3.5	2	3.80	(7.50)	1.6	0.7	0.44
5	*Fuel injection pump*	2.5	1	0.27	(0.27)	0.3	0.2	0.67
6	Oil Pump	2.5	1	0.18	(0.18)	2.0	0.8	0.4
7	*Water Pump*	2.7	2	2.31	(4.62)	2.2	0.7	0.32
8	*Radiator*	3.4	2	1.93	(3.86)	3.0	0.5	0.17

Numerical characteristics and parameters of the laws of distribution of expression up to the failure of elements of fuel system are presented in Table 5.

The main numerical characteristics of the parameters of the laws for distribution of resources of The Komatsu SAA4D104E-1 engine units and components of the KOMATSU WB93R-5 backhoe loader are determined according to the experimental method. The total study and are given in Table 6, and the gamma percentage resource at γ = 80% - Table persons 7.

The analysis of the data in Table 7 shows that 80% of the engine's life up to overhaul is smaller than the normative value about 1.5 times and between overhauls - 9.5 – 10 times.

Investigation of the main indicators of repair of the elements of the engine elements Komatsu SAA4D104E-1 backhoe loader KOMATSU WB93R-5.

Investigation and determination of the time for replacement of the elements of the tractors under conditions The work of partial mechanization of repair and maintenance work was carried out according to methods, given in the methodology for experimental research, and the basics. These numerical characteristics and conditions for replacement of units and units of the engine are given in the Table 9.

Conclusions

It was found that the predominant number of failures 44% of the fuel system of Komatsu SAA4D104E-1 engines on KOMATSU WB93R-5 backhoe loaders are due to prolonged operation of the machines or violation of operating rules - 26%.

The law of distribution of the resource of the main elements of the Komatsu SAA4D104E-1 engine has been established. Pearson's criterion confirms that it is distributed according to Gauss's law of distribution, which is also confirmed by the values of the coefficient of variation of the studied reliability indicators.

Increasing the level of reliability of the engine elements can be improved by improving the quality and timeliness of the repair and maintenance activities and compliance with the rules of operation.

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RESEARCH ARTICLE

Work productivity assessment of small forwarders in forest operations: An international review

Mohammad Reza Ghaffariyan

Forest Industries Research Centre, University of the Sunshine Coast, Locked Bag 4, Maroochydore DC, Queensland

Corresponding author: Mohammad Reza Ghaffariyan (mghaffar@usc.edu.au; ghafari901@yahoo.com)

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Abstract

There are two types of forwarders available in the practice including conventional forestry forwarders and farm tractors equipped with a trailer/grapple loader that operate as a forwarder. Forwarders loading capacity can vary depending on the machine size. This paper aims to review the work productivity of small size forwarders (payload<10 tonnes and engine power<120 HP) to create an overview of their performance for small scale operations within the small-scale forestry/plantations management or agroforestry systems. According to the review, small forwarders were mainly used for harvesting small trees over gentle slopes. Main machine types include light tractor-trailer and purpose-built forwarders. The reported productivity by international scholars ranged from 3.4 to 19.2 m^3/PMH_0. Main variables impacting the productivity of small forwarders included forwarding distance, load volume, piece volume, number of logs per turn, season, operator skills and harvesting intensity. This report has summarised recommendations from literatures on the proper application of small forwarders to improve harvesting efficiency, which can be of use to the forest industrial and academic users for practical and research purposes.

Keywords

Forest harvesting, Small forwarder, Productivity, Time study, Load volume

Introduction

Sustainable forest management as a dynamic and evolving concept aims to maintain and enhance the economic, social and environmental value of all types of forests, for the benefit of present and future generations (UN, 2008). In this context "sustainability" means harvesting wood resources in a way which produces materials with low operation cost, high product quality, low environmental impact, and high social benefits for the community. Timber harvesting is a key part of a sustainable forest/plantation management. Timber harvesting deals with several activities from stump to the mill gate such as forest road planning, road maintenance, tree felling/processing, timber extraction, loading, transportation and unloading (Conway, 1982). Timber extraction is one of the most difficult jobs within the timber supply chain as forest terrains are often rough or steep and timber sizes are large. Industrial revolution introduced the farm tractors to the farms. Consequently, most of the forest growing and contracting companies around the world started using tractors into the forest operations (Johansson, 1996). One of the early studies was reported by Boe (1963) that referred to the application of a D-8 tracked bulldozer to skid the large logs from old-growth redwood forests (*Sequoia sempervirens*) located in California (USA). Over time, forest engineers and logging planners realized that skidders and tractors can only skid a limited mass of timber per each turn in a short cycle time. Skidding logs/trees on the ground also led to heavy soil and site disturbance (Ghaffariyan, 2020). Considering the above-mentioned limitations with skidders/tractors, a new machine called forwarder was invented and introduced to the forest industry in the early 1960s in Sweden (https://magnetawanlibrary.ca). The forwarder that was (often) equipped with a grapple to load timbers (logs or trees) onto a bunk to forward the timbers to a roadside/landing. A forwarder usually works in combination with harvesters within a cut-to-length operation. Forwarding helps increase the load mass per turn (e.g. up to 20 tonnes in the case of a large forwarder). Unlike with skidding, the forwarded logs/trees have no contact with the soil on their way to the landing. There are two types of forwarders available in the practice including conventional forestry forwarders (Kellogg and Bettinger, 1994; Nurminen et al. 2006; Ghaffariyan et al. 2007, 2012, 2015) and farm tractors equipped with a trailer/grapple loader that operates as a forwarder (Stańczykiewicz et al. 2016). The loading capacity of a forwarder can vary from 5 to 25 tonnes (t). These machines can extract up to 25 m^3 per each working cycle (https://magnetawanlibrary.ca). Several scholars have extensively studied the performance of medium and large size forwarders worldwide in North America, Europe, Asia and Oceania (Kellogg and Bettinger, 1994; Hossain and Olsen, 1998; Hanell et al. 2000; Spinelli et al. 2002; Turner and Han, 2003; Nurminen et al. 2006; Rottensteiner et al. 2008; Berg et al. 2018; Ghaffariyan et al. 2019; Gagliardi et al. 2020;). However, there are fewer published scientific reports on work studies of small forwarders. Thus, this paper aimed to review the work productivity of small size forwarders (payload<10 tonnes and engine power<120 HP (90 kW)) to create an overview of their performance for small scale operations within the small-scale forestry/plantations management or agroforestry systems. The other objective of this research was to identify the main variable impacting the work productivity and main reasons for delays during the small forwarder operations. The final study objective was to summarise the international knowledge on how to improve the work productivity of small forwarders.

Materials and Methods

Work productivity for small forwarders

The typical work cycle of small forwarders includes travelling empty to the sites, loading the timber, travelling loaded to the landing and unloading (Kellogg and Bettinger, 1994). The work productivity is calculated using time study method where forwarding time (including productive and delay times) and work output (volume of forwarded wood) are measured (Griliches, 1998 cited in Heinimann, 2021; Magagnotti et al. 2012). Different factors can impact the productivity of a forwarder such as forwarding distance, piece size, load volume, operator skill, slope of skid trail, harvesting intensity etc. which are taken into account during time studies (Kellogg and Bettinger, 1994; Spinelli et al. 2002; Gagliardi et al. 2020). Productivity studies can help improve work performance, enhance work design (Heinimann, 2021), schedule the production, prepare a harvesting budget and compare different equipment and working systems (Murphy, 2005; Magagnotti et al. 2012).

To find the required literatures (in English language) for this review the following keywords were used; productivity, time studies, timber harvesting, forwarding, mini forwarder and small forwarder. The electronic search engines such as Google Scholar, Scopus and Web of Science, Research Gate and Academia were used. The review results were classified based on their region/country with a brief description of the work method and productivity outputs. Important concluding remarks made by international scholars were all summarised in the conclusion section of this review article to provide an overview of the most important conclusions for the readers.

Results

America

Canada

A case study was conducted by Meek (2001) in a thinning operation of a softwood plantation (species not reported) in New Brunswick in Canada. The terrain was flat and DBH ranged from 10 to 14 cm (average volume was 0.1 m^3). Average skidding distance was 150 m. Trees were felled and processed by a harvester-processor. Then a purpose-built forwarder (Figure 1) was used to extract the short logs. The forwarder was made using a Versatile 276 tractor attached with a Hardy 1700 boom and a Patu trailer (capacity of 5 tonnes). The study yielded a productivity of 8.2 m^3 per productive machine hours (m^3/PMH_0) (Table 1).

Figure 1. A purpose-built forwarder tested in Canada (Meek, 200)

Asia

Australia

According to McCormack et al. (2000) in small scale forestry, farmers and small-scale forest/plantation owners are included in the management that requires adaptation of both farming and forestry techniques to match with the requirements. As farm forestry has started increasing in Australia the farmers equip their tractors with suitable trailers to extract the timber. A farmer planted pine seedlings (*Pinus radiata*), which can be grown up to 40 years where farmers conduct first, second, third thinning and final cuts during the management period to mainly produce pulpwood in Victoria. Plantation size was about 20 ha and terrains were flat. Trees were felled and processed to short logs. Logs were first skidded by a large farm tractor then were loaded into a forwarder which was a combination of Fiat 6066 4WD farm tractor and trailer with the capacity of 6 tonnes. The trailer was equipped with a grapple and crane to load and unload. The productivity of this machine was not reported.

Japan

In Japan, small forwarders are used in the thinning or final cuts. Suzuki et al. (2017) studied an IWAFUJI U-3C forwarder (engine power not reported, capacity of 3 tonnes) in the Kochi region which was used to extract the short logs produced by a manual feller using chainsaw. The stand was composed of Japanese Cedar with the age of 40 years. The slope was gentle and maximum extraction distance was 300 m (average of 150 m) that resulted in an average productivity of 3.5 m^3/PMH_0. A small tracked-based forwarder (Figure 2) was applied to extract the logs in steep terrains within thinning and final cut operations in Tochigi area (Japan) (Aruga et al. 2017). The main species were Japanese Cedar and Japanese Cypress. The slope varied from 1% to 58%. Piece volume – from 0.3 m^3 to 1.0 m^3. The forwarding distance varied from 139 to 590 m. Trees were felled manually by chain saw then bunched using a grapple loader. Then a processor machine processed the trees into short logs to be extracted by the tracked-based forwarder to the roadside. The average forwarding productivity in thinning operations was 5.7 m^3/PMH_0 (note that the author of this review assumed a productive working time of 6 hours per day to obtain this value from this case study). Study results indicated that shorter skidding distances and larger thinning areas contributed to larger work productivity (Aruga et al. 2013). The forwarder in clear cut achieved higher productivity (6.5 m^3/PMH_0) than the one in thinning operations (5.7 m^3/PMH_0).

Figure 2. Small track-based forwarder tested in Japan (Aruga et al. 2017)

Iran

Small farm tractors are used to extract timber on gentle slopes from the Iranian mountainous forests located near the Caspian Sea (Gilanipoor et al. 2012). The loaded farm tractors in Iran can travel over a maximum slope of 15% during uphill forwarding. A study was reported by Mousavi and Naghdi (2014) in a clear-cutting a mixed stand of Alder (*Alnus glutinosa*), Caucasian walnut (*Petrocarya fraxinifolia*), Chestnut-leaved Oak (*Quercus castaneifolia*), Persian ironwood (*Parrotia persica*). Slope ranged from 0 to 5%. Average tree volume was 0.6 m^3. Felling and processing was carried out using a chain saw operator. Then a worker loaded the short logs manually into a trailer attached to the 8502 four wheels drive tractor (engine power of 75 HP). The forwarding distance averaged at 167 m. The study yielded an average forwarding productivity of 3.6 m^3/PMH_0 which was 2.3 times higher than the skidding productivity in the study area. Collecting and loading the logs took the longest time among the elements making up 40.2% of the total work time. The unloaded travel was the shortest element, consuming 3.5% of the time. Other work elements included travelling loaded and unloading. The time spent for work delays accounted for 3.8% of the total work time. Load volume and number of logs per turn significantly impacted the productivity based on the regression model developed by Mousavi and Naghdi (2014).

Europe

Czech Republic

The Czech Republic is a country that applies forwarders in the harvesting of 72% of all its forest area (Dvoˇrák et al. 2021). A study was conducted in two sites mainly covered by coniferous species (species were not reported). Trees were felled and processed by a harvester-processor; then the logs were collected and extracted by three forwarders. One of the forwarders was Novotný LVS 5 with the engine power of 55 kW and bunk capacity of 5 t. The tree volume and forwarding distance averaged at 0.11 m^3 and 389 m respectively. The terrain was mainly flat. The average productivity was reported to range from 3.5 to 5.8 m^3/PMH_0 (Table 1) (Dvoˇrák et al. 2021). The forwarding cost did not differ significantly from larger forwarders such as John Deere 1010 (engine power of 82 kW) and John Deere 1010E (engine power of 115.5 kW).

Ireland

Mini-forwarders are equipped with roll-over protection systems (ROPS). The productivity of these machines can be competitive with conventional large forwarders especially in small and non-uniform thinning practices. One of the small tractors is Vimek Minimaster101 with the engine power of 16 HP that is equipped with a tailer to extract the timber in British forests (Russell and Mortimer, 2005).

Italy

An Italian mini-forwarder was tested in thinning operations by Spinelli and Magagnotti (2010). The machine was Entracon Loglander LL85 with the engine power of 67 HP (50 kW) and loading capacity of 4.5 t. The plantation was based on a flat ex-farmland consisting of three hardwood species including walnut (*Juglans regia L.*), southern alder (*Alnus cordata Loisel.*) and ash (*Fraxinus ornus L.*) with an average DBH of 11.7 cm. The second study site consisted of Austrian pine (*Pinus nigra J.F. Arnold*) with an average ground slope of 15% and DBH of 14.8 cm. In both study sites trees were felled by a chainsaw operator and processed into short logs which were manually stacked into small piles. The mini-forwarder achieved an average productivity of 3.1 to 3.8 m^3/PMH_0 for both sites when the forwarding distance averaged at 400 m. In this case study the load size and forwarding distance did not change much, thus the speed of the mini-forwarder was mostly influenced by the slope of the ground. In the steeper site, the operator drove 20-40% slower than the flat site which reduced the work productivity. Longer forwarding distances resulted in lower machine productivity due to an increase in travelling time (including travelling loaded and empty). Spinelli and Magagnotti (2010) added that their reported productivity for the Entracon Loglander LL85 mini-forwarder was higher than the productivity of a mini-forwarder ranging from 1 to 2.5 m^3/SMH reported in Japan by Shishiuchi (1993) that had smaller engine power and load capacity operating on shorter forwarding distances.

Poland

Manual felling is a common practice in Polish forest operation as 80% of the operations is carried out by manual felling. Grzywinski et al. (2018) studied the impact of seasons on harvesting work productivity. Early thinning of young alder stands (*Alnus glutinosa Gaertn.*) was performed by chain saw operators who felled and processed the trees. After felling and processing, the logs were manually loaded into a farm tractor (Zetor 7045 (with engine power of 65 HP), equipped with a trailer. Mean DBH was 15 cm. Forwarding distance averaged at 545 m. The statistical analysis confirmed that the forwarding productivity in winter (3.8 m^3/PMH_0) was significantly lower than in summer (5.7 m^3/PMH_0) due to the longer time required to perform similar tasks (Grzywinski et al. 2018).

Another similar case study tested a farm tractor attached with a trailer in thinning Scots pine stands (*Pinus sylvestris*) (Leszczynski et al. 2021). The stands were 25 years old, and were felled and processed by a small harvester-processor. Then MTZ Belarus 952.2 farm tractor (engine power of 90 HP) equipped with FAO FAR 842 Logging Trailer with 3264 Crane (loading capacity of 8 t) was used to extract timber to the roadside. The tree volume averaged at 0.08 m^3 and the average forwarding distance was 500 m under flat terrains. The average productivity of the forwarding was 4.1 m^3/PMH_{15} (note PMH_0 was not reported). The forwarding distance was the main variable, impacting the productivity of forwarding, based on a linear regression model developed by Leszczynski et al. (2021).

Spain

Eucalypt plantations are one of the forest resources in Spain, Southern Europe. Forwarders have been in use to harvest these types of plantations (Spinelli et al. 2004). Two types of small capacity forwarders were tested by Spinelli et al. (2004) in clear-cut operations of an even-aged *Eucalyptus globulus* plantation in Northern Spain. The slope averaged at 23%. The average DBH was 12 cm. The average tree mass was 122 fresh kg (assuming conversion factor of 1:1 this is equal with 0.1 m^3). The purpose built forwarder in use was Deutz 913 (6× 6 wheel drive), with the engine capacity of 119 HP (89 Kw) and loading capacity of 8.5 t. The other forwarder was a farm tractor-trailer type (4 × 4 wheel drive) with a Sisu Diesel 20 engine (power of 109 HP (81 kW)). The purpose-built forwarder yielded an average productivity of 17.6 m^3/PMH_0 (mean forwarding distance of 693 m), while the tractor-trailer one produced an average productivity of 19.2 m^3/PMH_0 (mean forwarding distance of 174 m). The shorter forwarding distance resulted in higher productivity gained by the tractor-trailer forwarder. Loading and travelling loaded took the longest time during the operations of small forwarders. The other work elements included: travelling empty, manoeuvre, move, unload and others. Delays consumed less than 15.3% and 9% of the total work time for the tractor-trailer and purpose-built forwarder respectively. According to a regression analysis, the productivity of the purpose-built forwarder was significantly impacted by forwarding distance, load weight per turn (payload) and piece volume, while the tractor-trailer's productivity depended on forwarding distance and load weight per turn.

Figure 3. Purpose-built forwarder tested in Spain (Spienlli et al. 2004)

Sweden

The farm tractors have been used in Swedish timber harvesting especially for early thinning and clear cutting of small size trees. Johansson (1996) tested a Ford 276 Versatile frame farm tractor that was equipped with a small felling head at the front, a crane to load/unload and a trailer at the back. The machine was first used to fell and process the trees to short logs. The engine power was 116 HP. The stands were a mix of pine and spruce (species not mentioned in the report by Johansson (1996)), and were thinned for first time. The soil was frozen, covered by 10-40 cm of snow, and tree volume averaged at 0.14 m^3. Product types in this study included sawlogs and pulpwood. In the case of the sawlog, the average driving distance during loading travelling loaded distance, and travelling empty, the distance was 313 m, 253 m and 352 m respectively. The average load volume per turn was 9.2 m^3 (average log length of 4.60 m). Sawlog forwarding productivity averaged at 11.2 m^3/PMH_0. In the pulpwood recovery site the average driving distance during loading, travelling loaded distance and travelling empty, the distance was 303 m, 288 m and 370 m respectively. The average load size was 8.5 m^3 (average log length of 4.25 m) which resulted in average work productivity of 9.4 m^3/PMH_0 (Johansson, 1996). The longer forwarding distance and smaller piece volume resulted in lower work productivity in pulpwood production.

Early thinning can produce small size timber that can be used for bioenergy production. Wang (1999) indicated that one of the common Swedish mini forwarders was Vimek 606D which could fit with the small size tree harvesting operations. This machine had a low power of 20 HP and loading capacity of 0.3 t. The advantages of this small machine included its simple design, high work productivity and low fuel consumption rates, compared to other similar machines (Wang, 1999). Over time, more powerful types of Vimek forwarders were introduced in Swedish forestry. Lazdins et al. (2016) tested a small-scale harvesting system consisting of a Vimek harvester-processor and forwarder. The study was conducted in two spruce stands (*Picea sp*.). Trees were felled and processed into short logs by the harvester-processor then extracted to the roadside by a forwarder. The harvested tree volume ranged from 0.04 to 0.06 m^3. The average forwarding distance was not noted in this study report. The terrain was flat. Vimek 610 had an engine power of 60 HP and loading capacity of 5 t which was more powerful than earlier models e.g., Vimek 606D. The average work productivity was 10.5 m^3/PMH_0 (note that this value was calculated by the author of this review article, based on the percentages of travelling time reported by Lazdins et al. (2016) as they only reported loading and unloading productivity). The work elements of this time study included travelling empty, travelling loaded, reaching to logs for loading, locating the head while loading, unloading and arranging while unloading. Travelling empty and travelling loaded took the longest time among the work elements, accounting for 24.3% of the total cycle time.

South Africa

A small-scale harvester-processor/forwarder technology has been tested by Ackerman et al. (2022) to recover from a low volume and lowquality *Pinus patula* plantation located in the Highveld region of Mpumalanga during the winter season. The machine model was Malwa 560C that had a combination of harvester-processor and forwarder. The engine power was 74 HP with the loading capacity of 5.5 t. The stand age was 10 years and the tree volume averaged at 0.2 m^3. The terrain was flat. Trees to be removed, as part of the thinning regime, were marked prior to harvesting. Trees were felled and processed to short logs (pulpwood and sawlogs) by the harvester-processor. Then the logs were loaded to the bunk of the forwarder and extracted to the roadside. The forwarding cycle included travelling empty, loading, travelling loaded and unloading. During the time study, the average forwarding distance and load size were 219 m and 2.8 m^3 respectively. This study yielded a mean forwarding productivity of 5.0 m^3/PMH_0. According to the multiple regression model developed by Ackerman et al. (2022) the forwarding distance and load volume had significant impact on the productivity of forwarder. The larger load volume and shorter skidding distances resulted in lower forwarding productivity. Table 1 provides a summary of selected time study results on mini-forwarders around the world.

Table 1. Summary of productivity studies on farm tractors equipped with trailer

Continent/ country	Operation	Machine type	Power (HP)	Payload (t)	Forwarding distance (m)	Slope (%)	Piece Volume (m^3)	Average productivity (m^3/PMH_0)	Reference
America/ Canada	Thinning	Versatile 276 (farm tractor)	116	5	150	0	0.1	8.2	Meek (2001)
Asia/ Japan	Thinning	IWAFUJI U-3C	n/a	3	150	0	n/a	3.5	Suzuki et al. (2017)
Iran	Clear-cut	8502 4WD (farm tractor)	75	5	167	2.5	0.6	3.6	Mousavi and Naghdi (2014)
Europe/ Czech Republic	Thinning	Novotný LVS 5	74	5	389	0	0.11	3.5-5.8	Dvoˇrák et al. 2021
Italy	Thinning	Entracon Loglander LL85	67	4.5	400	0-15	0.06-0.08	3.1-3.8	Spinelli and Magagnotti (2010)
Poland	Thinning	Zetor 7045	65	n/a	545	0	n/a	3.8-5.7	Grzywinski et al. (2018)
	Thinning	MTZ Belarus 952.2 (farm tractor)	90	8	500	0	0.08	4.1	Leszczynski et al. 2021
Spain	Clear-cut	Deutz 913 Sisu Diesel 20 (farm tractor)	119 109	8.5 8	693 174	11 9	0.1 0.1	17.6 19.2	Spinelli et al. (2004)
Sweden	Thinning	Vimek 610	60	5	n/a	0	0.05	10.5	Lazdins et al. (2016)
	Thinning	Ford 276 Versatile (farm tractor)	116 116	5 5	306 320	0 0	0.44 0.27	11.2 9.4	Johansson (1996)
Africa/ South Africa	Thinning	Malwa 560C (combined harvester-forwarder)	74	5.5	219	0	0.2	5.0	Ackerman et al. (2022)

Table 2 presents the descriptive statistics of main parameters such as machine power, payload, forwarding distance, slope, piece volume, and work productivity of international case studies mentioned in Table 4. Within the reviewed time studies on small forwarders, the reported productivity by international scholars ranged from 3.4 to 19.2 m^3/PMH_0. Engine power did not exceed more than 199 HP while the lowest engine power was 30 HP for small forwarders. The engine power and load capacity consequently influenced the payload which ranged from 3 to 8.5 t with an average of 5.6 t that is much less than conventional forwarders. The maximum forwarding distance within the data base of this review was less than 700 m while the average value was 334 m. This is an important consideration to be used by logging planners to select suitable and optimal spacing among the forest road segments. An important observation is that the tested small forwarders were all limited to slopes less than 11%. The average slope of 2.3% indicates that internationally these types of machines are applied in flat to moderate slopes. The range of piece volume and its average value (0.2 m^3) indicates that small forwarders are mostly used for small tree size harvesting operations mostly in early thinning or in clear cutting of stands with small tree size.

Table 2. Descriptive statistics for the time study data

	Minimum	Maximum	Mean
Engine power (HP)	60	119	90.1
Payload (t)	3.0	8.5	5.6
Forwarding distance (m)	150	693	334.4
Slope (%)	0	11	2.3
Piece volume (m^3)	0.05	0.6	0.2
Productivity (m^3/PMH_0)	3.4	19.2	8.1

Conclusions

Meek (2001) suggested maintaining a high utilisation rate for the small-scale harvesting machines to achieve a cost-effective operation. Appropriate planning should include night shifts; applying proper maintenance regimes and allocating suitable stands for harvesting could be potential alternatives. According to Aruga et al. (2017) forwarders can work more efficiently in clear cuts, rather than in thinning operations which could be due to the larger harvesting intensity and piece volume. Dvǒrák et al. (2021) pointed that the application of small forwarders can sometimes result in similar range of forwarding costs per unit, thus the application of larger machines does not necessarily reduce the costs. In this sense proper planning should be made to achieve higher machine utilisation and productivity to reduce the costs.

Spinelli et al. (2004) suggested using a light tractor-trailer type for shorter forwarding distances and as a complement to the current timber extraction. For longer forwarding distances (<1 km) the purpose-built forwarder would be a more suitable option from economic perspective. According to Ackerman et al. (2022), the forwarding distance and load volume are the two most significant variables impacting the forwarder productivity.

Regarding the mini-forwarder's performance in steep terrains, Spinelli and Magagnotti (2010) mentioned that although these machines have high manoeuvrability due to their narrow width and good ground clearance, the operators should only drive them straight along the grade because of low machine stability.

Spinelli and Magagnotti (2010) concluded that mini-forwarders can carry smaller loads than farm tractor-based forwarders and their loading and unloading efficiency is also lower due to weaker grapple loader. Mini-forwarders should be limited to an extraction distance of 1 km and a proper and optimal forest road network can be helpful for the application of mini-forwarders. The Swedish experience indicated that a suitable work pattern is to combine mini-forwarders with harvester-processors in thinning operations so that they can follow the path of the harvesters to pick up the stacked short logs (Lazdins et al. 2016). An early Swedish study confirmed that forwarding sawlogs could result in higher machine productivity, compared to pulpwood recovery, due to the larger piece size in the case of sawlog production (Johansson, 1996). The other general conclusion was that the application of small farm tractors equipped with trailers is a low-cost option with good work productivity and proper ergonomic performance.

The season has a significant impact on the productivity of mini forwarders that needs to be considered in harvesting planning. Thick snow and cold temperatures during winter can reduce the machine's productivity (Grzywinski et al. 2018). Future research could test new mini-forwarders in more diverse forest types (small scale native and plantation forests), terrain conditions (including various slopes and soil conditions), and product types (sawlog, pulpwood, biomass and integrated biomass production). This will create a more comprehensive overview of the machine's performance to be useful for decision making purposes.

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REVIEW ARTICLE

Microbial cellulose: an alternate source for plant cellulose

L. Sarvananda[1*], P.R.M.K. Fernando[2], P.A.D.S. Palihaderu[3], Amal D. Premarathna[4]

[1]*Department Botany, University of Peradeniya, Sri Lanka, P. O. Box 20400,*
[2]*Department of Animal Science, Faculty of Agriculture, University of Peradeniya, P. O. Box 20400 , Sri Lanka.*
[3]*Department of Basic Veterinary Sciences, Faculty of Veterinary Medicine and Animal Science, University of Peradeniya, P.O Box. 20400, Sri Lanka.*
[4]*School of Natural Sciences and Health, Tallinn University, Narvamnt 29, 10120 Tallinn, Estonia*

Corresponding author: L. Sarvananda (sarvacool18@gmail.com)

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Abstract

In the contemporary generation, rapid urbanization, industrialization, and declining woodland lead to global weather modifications. The massive scale of deforestation for firewood, constructions, paper products, textile, and plenty of different packages are steadily enforcing a critical poor impact on the surroundings. Inherently, plant cellulose has restrained utility because of the presence of hemicellulose and lignin. Consequently, studies in the discipline of microbial cellulose display many benefits over plant cellulose. It possesses numerous crucial and unique properties compared to plant cellulose, including high purity, better absorptivity, excellent polymerization, crystallization, in-situ mold potential, biodegradability, biocompatibility, and plenty of others. This assessment looks into a potent cellulose producer to develop an economically feasible manner for huge-scale production of microbial cellulose therefore, it may replace some of the requirements where plant cellulose has been currently in use.

Keywords

deforestation, microbial cellulose, polymerization, global warming

Introduction

"Biopolymers" are natural substances that consist of macromolecules. They are made from monomeric subunits covalently linked in a repeating pattern. (Klemm *et al*., 2005). Biopolymers are created from renewable sources and are easily biodegradable because of the oxygen and nitrogen atoms found in their structure. Biodegradation converts them to CO_2, water, biomass, vapor, and different herbal substances. These biopolymers were mainly recycled naturally through organic processes (Gross and Scholz, 2001). Biopolymers play vital roles in preserving genetic expression data, catalysis of reactions, storage of essential elements such as carbon (C), nitrogen (N), phosphorus (P), and different nutrients, and avert harmful effects of other cells and protecting from harmful environmental factors. Furthermore, biopolymers act as mediators for adhesion to surfaces of other organisms, and communicators with the environment and other organisms. (Steinbuchel, 2003; Steinbuchel and Doi, 2005).

Cellulose $(C_6H_{10}O_5)_n$ is the most abundant naturally occurring carbon-based polymer, which is most commonly found in plants. Out of all constituents in plant structures, approximately 30% is comprised of cellulose making it the most abundant organic substance on earth. Nevertheless, the cellulose content varies significantly depending on the plant species (Klemm *et al*, 2005). It is the building block of plant cell walls, algae, and oomycetes (fungus-like eukaryotic microorganisms). This polysaccharide which is made of long linear chain of β (1-4) linked D-glucose units (Updegraff, 1969; Crawford, 1981), plays a pivotal role in the modern-day industry. It is used as a structural ingredient for cellulose-based products such as paper, textiles, and construction substances. Moreover, a variety of cellulose derivatives: spinoff (cellophane), rayon, and cellulose acetate are also used at the industrial level (Saxena and Brown, 2005; Peng *et al.*, 2011). However, the presence of lignin and hemicellulose along with cellulose has become a major challenging factor in using plant cellulose to provide the needs in many industrial approaches. Moreover, the plant resources cannot cater to the growing demand for cellulose with the quickly diminishing woodland sources, decreased agricultural land, and other environmental concerns.

The difficulty of isolating cellulose from hemicellulose and lignin from plant-based sources has paved the way for a discussion about an alternative source. (Brown, 2004). Similarly, the scale of deforestation with the aim of harvesting plant cellulose has a negative effect on the ecological balance. Therefore, the necessity of locating an alternative for plant cellulose was due. Microbial cellulose (MC) has shown the signs of a feasible substitute for plant cellulose. MC is free from lignin and hemicellulose, and it also has a higher degree of polymerization, gadget-driven capacity, excessive level of crystallinity, high purity, high water-absorbing capacity, in-situ moldability, biodegradability, and biocompatibility (Iguchi *et al.*, 2000; Brown, 2004; Torres *et al.*, 2012).

Due to these physical and chemical properties, MC emerged as a flexible biopolymer in multi-industries including textile, paper, cosmetics, audio products, and the medical area. (Brown *et al.*, 1992; White and Brown *et al.*, 1989). Some microorganisms can produce cellulose where its commercial uses are possible, for instance, *Acetobacter*, *Agrobacterium*, *Rhizobium*, *Pseudomonas,* and *Sarcina* (Chawla *et al.*, 2009). Among those microorganisms, *Sarcina* is one of the most prominent green cellulose producers in the presence of oxygen and glucose (Chawla *et al.*, 2009). Furthermore, this bacterium is a non-photosynthetic organism that can procure glucose, glycerol, or different natural substrates from others and which could convert into natural cellulose (Brown, 1976).

Overall, the application of this MC as an alternative for plant cellulose can be of utmost importance for both industrial avenues and eco-protective approaches.

Cellulose and its derivatives

Cellulose is often considered the most abundant macromolecule on earth consisting of dozen to several thousands of monosaccharide units (Brown, 2004; Lavanya *et al*, 2011). The main occurrence of cellulose used to be existing lignocellulosic material in forests which ultimately made the most vital source of cellulose (Ummartyotin and Manuspiya, 2015). Various plant fibers such as cotton and vascular plants have cellulose as an essential constituent (Myasoedova, 2000; Gross and Scholz, 2001). Apart from this main plant cellulose resources, many industries additionally utilize algae, the slime mold *Dictyostelium*, a variety of bacterial species (including the cyanobacteria), and tunicates in the animal kingdom (Saxena and Brown, 2005). Cellulose was first identified in 1839 from green plants by Anselme Payen, a French chemist (Purves, 1946). He found that cellulose has the same structure as starch, but exhibits differences in dimensions with physical and chemical properties. But the amount of cellulose and its extraction varied from plant to plant, the environment, and the life span of the plant.

Cellulose ether derivatives

Cellulose ethers are high molecular weight compounds produced through changing the hydrogen atoms of hydroxyl groups in the anhydrous glucose units of cellulose with alkyl or substituted alkyl groups. Cellulose ether derivatives have their special properties such as solubility, viscosity in solution, surface activity, thermoplastic film characteristics, and stability towards biodegradation, heat, hydrolysis, and oxidation. Examples of the most used cellulose ethers are Methyl Cellulose (MC), Ethyl Cellulose (EC), Hydroxyethyl Cellulose (HEC), Hydroxypropyl Cellulose (HPC), hydroxypropylmethyl cellulose (HPMC), Carboxymethyl Cellulose (CMC) and Sodium Carboxymethyl Cellulose (NaCMC) (Shokri and Adibki, 2013).

Cellulose ester derivatives

Cellulose esters are generally water-insoluble polymers with good film-forming characteristics. Hence, it is widely used in the pharmaceutical industry. Cellulose esters are categorized into two different groups: organic and inorganic groups. Most of the natural cellulose has been used in industrial merchandise or pharmaceutical investigations such as Cellulose acetate (CA), Cellulose acetate phthalate (CAP), Cellulose acetate butyrate (CAB), Cellulose acetate trimelitate (CAT), and Hydroxupropylmethyl cellulose phthalate (HPMCP), (Heinämäki et al., 1994). Cellulose nitrate and Cellulose sulfate are examples of inorganic cellulose esters.

Microbial cellulose as an alternative

Cellulose exists in the cell components of a notable variety of organisms, from microorganisms (*Cyanobacteria*), prokaryotes (*Acetobacter*, *Rhizobium*, *Agrobacterium*) to eukaryotes (fungus, amoebae, green algae, freshwater, and marine algae, mosses, ferns, angiosperms, gymnosperms). It is additionally produced through some animals, the tunicates (urochordates), individuals of the subphylum *Tunicata* in the *Chordata* phylum (Nobles, 2001; Kimura and Itoh, 1998).

The feature of cellulose in these specific groups of organisms reflects the various roles related to this easy structural polysaccharide. Whereas it is feasible for some of these organisms, specifically bacteria, to live on in the absence of cellulose synthesis, it might also no longer be real for most vascular plant cells to continue to exist in the absence of cellulose synthesis (Saxena and Brown, 2005). Production of cellulose from *Acetobacter xylinum* was once first stated in 1886 by A.J. Brown (Brown, 1886). He observed that the resting cells of Acetobacter produced cellulose in the presence of oxygen and glucose. When it comes to the molecular characteristics, MC is equal to that of plant cellulose; however, possesses unique physical and chemical characteristics (Yoshinaga et al, 1997).

Why Microbial cellulose is preferred over plant cellulose?

The benefit of MC used to be associated with the purity of the product as it can be acquired in greater purity and is well-known for its greater degree of polymerization and crystallinity index (Shoda and Sugano, 2005). Cellulose prepared from microorganisms was free from wax, lignin, pectin, and hemicelluloses, which used to be regularly existing in cellulose derived from plants. In addition, microbial cellulose has greater tensile power and water-conserving potential than that of plant cellulose, making it more than appropriate for the production of excessive-constancy acoustic speakers, excellent paper, and dessert meals (Shoda and Sugano, 2005). Moreover, cellulose originating from bacteria should be efficiently managed on its repeating unit and the molecular weight in the fermentation process. However, from the perspective of industrial commercialization, the value of cellulose from bacteria was high. The use of microbial cellulose-based fabric for sustainable power was consequently restricted if any mass manufacturing was to be persisted (Ummartyotin and Manuspiya, 2015).

Characteristics of microbial cellulose (MC)

MC produced by some microbes has unique physical, functional, structural, and chemical properties. Cellulose is an unbranched polymer, β (1→4) linked to D-glucopyranose residues. The chemical structure of plant and MC is identical. However, the degree of polymerization differs from about, 13,000 to 14,000 for plants and 2,000 to 6,000 for MC (Jonas and Farah, 1998). Additionally, microbial cellulose stands apart from its plant counterpart with the utilization of high crystallinity index (above 60%). Native microbial cellulose takes place in two specific crystalline structures, particularly cellulose Iα and cellulose Iβ (Yoshinaga et al., 1997). These two sorts of crystalline structures show up to be separately disbursed in the microfibril of cellulose with exception of tunicin (sea squirt cellulose) which is pure Cellulose Iβ.

Cellulose Iα is dominant in microbial cellulose whilst cellulose Iβ is dominant in plant cellulose. Moreover, the content material of cellulose Iα is about 60% in microbial cellulose whilst it is solely about 30% in the greater plant cellulose, cotton, and ramie. In contrast, Cellulose Iβ is the essential element in plant cellulose (Sugiyama et al., 1991).

The structural aspects of microbial cellulose differ by the way of life conditions in which it has been produced and the subcultures used. The crystallinity and cellulose I content are decreased in an agitated culture compared to in a static culture. Similarly, the degree of polymerization in cellulose molecules is additionally decreased in agitated subculture prerequisites (El-Saied et al., 2004).

A xylinum cellulose consists of ribbons of microfibrils generated at the surface of the microbial cell. The dimensions of the ribbons are 3–4 nm thick and 70–80 nm wide. The structure of the microbial cellulose sheet looks to be maintained by hydrophobic bonds. It is stated that the inter and intramolecular hydrogen bonds initially take place in every cellulose sheet, and then the cellulose crystalline shape is formed with the improvement of hydrogen bonds between cellulose sheets (Bielecki et al., 2005).

Microbial cellulose is water-insoluble and due to its giant community of fibers, it has a massive surface area. MC fibers have around 200 times the surface region of fibers compared to that of plant cellulose. Due to the special nano-morphology coupled with its capability to structure hydrogen bonds which debts for their special interactions with water, microbial cellulose can take in up to 200 times its dry mass of water. When microbial cellulose is used in suspension, it shows pseudoplastic thickening properties. Moreover, microbial cellulose shows amazing elasticity, and conformability (Czaja et al., 2006; US Congress, 1993).

Mechanism of cellulose synthesis and purification

Acetobacter xylinum (A. xylinum) has been substantially used as a model for the investigations of cellulose due to its functionality to synthesize high numbers of polymers from a huge range of carbon and nitrogen resources. Two techniques are usually employed for the manufacturing of microbial cellulose; particularly the stationary subculture and the agitation (Watanabe et al., 1998). In the static cultivation, also known as the stationary subculture method, the microbial cellulose is produced as a gelatinous membrane on the surface of the medium, whilst in the agitated culture method, the microbial cellulose is gathered in dispersed suspension as irregular masses, such as granule, stellate, and fibrous strand. The agitated culture technique is commonly utilized for industrial manufacturing of microbial cellulose (El-Saied et al., 2004).

Acetobacter or *Gluconacetobacter xylinus* require glucose or sucrose as their major carbon sources since the precursor in cellulose synthesis is uridine diphosphoglucose. The biosynthesis of cellulose from different carbon sources, such as 5- or 6-carbon monosaccharides, oligosaccharides, starch, alcohol, and natural acid has additionally been reported. Moreover, fructose and glycerol are additionally used as carbon sources and result in nearly comparable yields of microbial cellulose as that from glucose whilst the usage of galactose and xylose yields smaller. The microbial cellulose yield from sucrose is half the yield from glucose. The use of D-arabitol as the carbon source was six times more effective than that of the D-glucose. A nitrogen source is also required for the cellulose-producing strain. Most of the media used for the manufacturing of microbial cellulose utilizes yeast extract and peptone as nitrogen sources. A few amino acids, e.g., methionine and glutamate, have also been used for this purpose. Vitamins such as pyridoxine, nicotinic acid, p-aminobenzoic acid, and biotin stimulate cell growth and cellulose production (El-Saied et al., 2004).

The microbial cell development and cellulose manufacturing are extensively affected by the pH of the culture broth; therefore, the management of the pH is crucial. The conversion of glucose to gluconic acid leads to a sizable drop in the pH of the medium in the batch culture. The ideal pH varies for cellulose production with the species. Provided, the *A. xylinum* requires a pH of 4±6, whilst some researchers (Oikawa et al., 1995; Delmer and Amor, 1995) confirmed pH 4±7 as optimum. In addition to the pH of the nutrient broth, the yield of microbial cellulose is temperature-dependent. The optimal temperature for cellulose production is 25± 30 °C. The cellulose synthesis generally takes place at the air/cellulose pellicle interface, and hence oxygen is a vital element for cellulose production. The manufacturing rate and the yield of microbial cellulose are proportional to the oxygen transfer rate (OTR) and oxygen transfer coefficient (KLa). The providence of excessive oxygen is stated to result in the reduction of the MC productiveness due to a loss of substrate by direct oxygen (El-Saied et al., 2004). After fermentation, the microbial cellulose is typically harvested from the culture medium through centrifugation or filtration. Then those are observed through washing with distilled water and undergoing re-centrifugation or filtration again. At some stage the microbial cells are eliminated from the microbial cellulose in a warm caustic treatment that destroys them. The suspension is then filtered, and the filter cake is washed completely with distilled water to eliminate the traces of sodium hydroxide. The microbial cellulose is ultimately freeze-dried.

The industrial production

Industrial scale production of microbial cellulose

Culture medium plays a vital role in MC production. It provides essential nutrients for microbial growth and extensively influences the structure and yield of the MC as well (Jozala et al., 2016). At the very least, a general growth medium consists of a carbon source, a nitrogen source, and other nutrient elements such as phosphorus, potassium, sulfur, and magnesium (Andriani et al., 2020). The major drawback is the high production cost of the commercial process of MC. A techno-economic analysis (TEA) of industrial-scale production of MC has been performed using SuperPro Designer software (Dourado et al., 2016). The software estimated the manufacturing cost of MC is around US$ 7.4 million per year whereas, the net profit is US$ 3.3 million per year. However, producers and research scientists have been working to find the new ways to reduce the production cost through increasing the production efficiency of MC (isolation of high strain yield and optimization of fermentation reactors) and discovering the economical sound nutrient sources as the substrate (Rivas et al., 2004; Ul-Islam et al., 2020). In recent years, the possibility of using alternative culture media was heavily explored as the bacteria can be fed with diverse array of carbon and nitrogen sources. Coconut water has been used as the prominent nutrient source for commercial production of MC (Hainan Yeguo Foods Co., Ltd, 2020). Nevertheless, the huge market for coconut water makes it scarce, consequently causing its price to increase. The isolation of cellulose-producing bacteria was carried out from rotten fruits and vegetables (Rangaswamy et al., 2015). Specifically, from pomegranate, sweet potato and potato. Based on the biochemical properties, bacterial strains were identified as *Gluconacetobacter* sp. RV28, *Pseudomonas* sp. RV14, and *Enterobacter* sp. RV11. The findings of the study conclude that the improvement of cellulose synthesis by these strains, with the involvement of bioengineering to produce cellulose at an industrial scale, is possible. Furthermore, other agricultural and industrial wastes such as molasses i.e. sugarcane and beet (Bae and Shoda, 2005; Premjet et al., 2007; Kusano Sakko Inc, 2020), dairy waste i.e. sour whey waste (Nguyen et al., 2021), waste beer yeast (Lin et al., 2014), dry oil mill residue (Gomes et al., 2013), corncob, alcohol waste liquor, pineapple peel, citrus juice, and apple juice (Zhong, 2008),achieve a comparable MC yield with the fermentation of nitrogen and phosphorous supplements. In addition, MC production through agricultural waste alleviates environmental pollution associated with improper disposal of industrial wastes (Gomes et al., 2013).

Potential applications of microbial cellulose

Microbial cellulose is a new useful material for a broad variety of purposes even in areas where the use of plant cellulose is limited. Since microbial cellulose has traits like excessive purity, an excessive degree of crystallinity, excessive density, suitable form retention, excessive water binding capacity, and a greater surface region in contrast to the plant cellulose, it can be utilized in distinct industries such asthe cloth, paper, food and pharmaceutical industries, waste treatment, broadcasting, mining, and refinery (Czaja et al, 2006; Legge, 1990; Shah and Brown, 2005). The essential industrial uses of microbial cellulose can be concluded as follows.

Uses in the food industry

Microbial cellulose has essential functions in diverse meal formulations due to its structure. The excessive stage of purity, change in color, alternate in flavor, and vast possibility to strengthen a range of shapes and textures, makes MC a suitable candidate for the food industry (Gallegos et al., 2016). MC has been categorized as "generally identified as safe" (GRAS) (Badel et al. 2011). The first use of MC in the food industries used to be in nata de coco (fermentation product of the bacteria, *Acetobacter xylinum*) in the Philippines. The gel-like properties of MC, blended with its entire indigestibility in the human intestinal tract, made this a fascinating food base (Budhiono et al., 1999).

It has a plasma cholesterol-lowering impact and has many different fitness advantages such as the protection against bowel cancer, atherosclerosis, and coronary thrombosis, and prevents the increment of glucose in the urine. In 1992, Chinese Kombucha or Manchurian Tea used to be produced via developing yeast and Acetobacter in a medium containing tea extract and sugar, is additionally a famous microbial cellulose-containing food product. (El-Saied et al., 2004).

Future potential uses consist of pourable and spoon-able dressings, sauces, and gravies; frostings and icings; bitter cream and cultured dairy products; whipped toppings and aerated desserts, and frozen dairy products. The use of microbial cellulose, mixing with different agents such as sucrose and carboxymethyl cellulose improves the dispersion of the product. It is also a low-calorie additive, thickener, stabilizer, and texture modifier, and can be used in pasty condiments and ice cream (Khan et al., 2007).

Uses in paper and paper products

The pulp and paper enterprise procedures demand huge portions of cellulosic substances each year (Manda et al. 2012). With an increasing demand for paper and improvements in processing science (Singh et al. 2012), paper can be produced from many unique cellulosic materials, including MC. Microbial cellulose consists of very small clusters of cellulose microfibrils. Therefore, it increases tremendously the energy and durability of pulp when converted into paper. Microbial cellulose is also a precious factor of artificial paper since nonpolar polypropylene and polyethylene fibers offer insulation, warmth resistance, fire-retarding properties, and the inability to form hydrogen bonds. The quantity of wooden pulp in this kind of paper is typically from 20% to 50% to obtain excellent quality (El- Saied et al., 2004). According to Shah and Brown, (2005), much of the research has been directed to produce a digital paper that consists of MC with a digital dye between electrodes. Furthermore, this technology could be a basis for electronic books, wallpapers with modifications patterns, bendy digital newspapers, and dynamic paper.

Application in the biomedical industry

Microbial cellulose is a prominent constituent that finds a range of biomedical applications, from usual wound dressing to tissue engineering. The biomedical purposes of MC have already been reviewed and documented in the latest literature (Fu et al. 2013; Rajwade et al. 2015). The technique of burn tissue recovery includes each generation of the dermis and restoration of the dermis resulting in the formation of scar tissue (Balasubramani et al., 2001). There is still a need for improvement of wound care dressing material, which should sufficiently defend wounds from contamination or excessive loss of fluid. Due to the latest advances in the subject of biomedical materials, scientists have developed a range of herbal and artificial polymers that can be used for wound closure, drug transport systems, novel vascular grafts, or as scaffolds for the advent of tissue-engineered constructs. As microbial cellulose is a highly porous material, it facilitates the practicable transfer of antibiotics or different drugs into the wound, whilst at the same time serving as an eco-friendly bodily barrier towards any exterior infection. It satisfies the necessities of current wound dressing material (Czaja et al., 2006). Furthermore, due to its special nanostructure and unique bodily and chemical properties, MC has been identified as a key for many scientific functions such as synthetic blood vessels, scaffolding for tissue engineering of cartilage, and a wound dressing fabric for chronic wounds (Ring et al., 1986; Fontana et al. 1990; Klemm et al. 2001; Alvarez et al. 2004; Svensson et al. 2005).

Conclusion

There is a necessity for the conservation of forests that reduce the emission of environmental pollutants because of the rapid industrialization, declining forests, and global climate changes, by using microbial cellulose. Microbial cellulose has the potential to provide a solution for the issues associated with the usage of plant cellulose. Also, microbial cellulose can be used as a superior alternative with extra sturdiness and better performance than plant cellulose. However, packages of biopolymers are reliant on the cost and scale of manufacturing. It would not be feasible to directly shift to microbial cellulose in the current arena. Therefore, studies should be carried out on economically possible processes for large-scale production of microbial cellulose where it would be able to replace at least a portion of the cellulose requirements. Knowing the significance of microbial cellulose, it is advisable to put more focus and effort into manufacturing and developing commercially feasible techniques for cellulose production.

Consent for publication
We certify this manuscript has not been published elsewhere and submitted to another Journal.

Competing interests
The author(s) declare that they have no competing interests.

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