Latitudinal variability of the radiation microclimate in artificial forest gaps in Poland – the modelling perspective

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Abstract. The aim of the study was to characterize latitudinal changes in the radiative microclimate of small forest openings (artificial gaps) under Polish conditions. The global, direct and diffuse radiation on the forest floor in gaps was modelled using the Solar Radiation tool in ArcGIS 10.2 Esri. The gaps were modelled as holes of elliptical shape (60 m x 40 m diameters) in flat terrain and with a depth of 20 to 30 meters to mimic the height of a surrounding tree stand. The range of global radiation diversity on an open and flat surface predicted by our model was comparable with findings of empirical studies. Theoretically, the investigated gaps in the northern-most part of Poland receive only 82% of global solar radiation, 74% direct and 90% of diffuse radiation compared to gaps in the most southern part of the country. The comparison with empirical data indicates that local values of the transmittance parameter of the atmosphere may have a large influence on the actual values of solar radiation and may partially mask the latitudinal impact. Nevertheless, the model constitutes a valuable tool for characterising solar radiation diversity in a gap and supports silvicultural decision-making.

Keywords: radiation conditions, diffuse radiation, direct radiation, modelling, artificial gap, latitude

1. Introduction

Gap cutting is regularly used in practice, both as main regeneration cutting mode of as a part of more complex cutting systems. Important factors that influence the radiation microclimate in artificial gaps include the dimensions of the gap as well as their relation to surrounding stand height. The radiation microclimate, including light conditions in the artificial gap can be influenced to some extent by geographic latitude. In the same season of the year, the sun in its apparent motion in the sky takes higher position at sites located at lower latitudes (closer to the equator) than in those located further from the equator. The higher the position of the sun over the horizon, the larger portion of the forest floor within the artificial gap receives direct solar radiation.

The radiant energy emitted from the sun that reaches the top of the Earth's atmosphere, comprises approximately 50% of the infrared region (near and far) (> 0.7 μm), about 40% of the visible region (0.4–0.7 μm), and about 10% of the UV region (< 0.4 μm) (Fu 2003). Increased accessibility of direct solar radiation to any section of the forest floor within the gap denotes higher availability of thermal energy. The latter influences air and soil temperature within the gap (Tomanek 1958; Carlson, Groot 1997; Prévost, Raymond 2012) as well as can indirectly affect soil humidity inside the gap (Gray et al. 2002; Ritter et al. 2005).

Variability of growth conditions (temperature and humidity of upper soil layers), caused by solar radiation availability, can result in spatial variability of the density of natural regeneration (Minckler et al. 1973; Bolibok, Andrzejczyk 2008) or variability of the height of planted trees (Gray, Spies 1996; Bolibok et al. 2011).

Determination of latitude effects on the radiation microclimate within forest artificial gaps - important in view of improving techniques of gap regeneration cutting – is a task empirically difficult to achieve. All the methodological pro-

blems could not be solved, even if it was possible to establish experimental gaps with the same shape and area within forest stands identical in terms of the species composition and height, and at the same time - situated at a range of geographic latitudes. In Poland, one of the unavoidable problems would be altitudinal variability of the country. A part of solar radiation energy is reduced when passing through the atmosphere. Theoretically, forest openings formed at higher elevations at the same latitude, should be expected to receive more solar radiation when compared to those at lower elevations. In Poland, spatial variability of elevation a.s.l. makes it impossible to establish experimental forest openings in the conditions comparable in terms of altitude but different in terms of latitude. A helpful solution could be advanced models describing light conditions in the forest floor which can take into account the shade casted by the surrounding forest stand (Bolibok et al. 2013). Rich et al. (1995) showed how modelling could be used to study the effects of various parameters describing artificial gap's localisation and shape (geographic latitude, gap size, surrounding stand height) on light conditions inside a given forest opening. The influence of surrounding stand height, terrain configuration (slope and aspect) on the radiation microclimate in forest openings under the conditions of central Poland was presented using such a model in the study of Bolibok at al. (2015).

The aim of the present study is to analyse potential differentiation of the radiation microclimate within elliptical artificial forest gaps, located at a range of latitudes in Poland, in view of available data on long-term insolation variability. As a tool for modelling of the radiation microclimate, there was used Solar Analyst software developed as an extension of ArcView Esri geographic information system software (Fu, Rich 2002). The analyses were performed with the implementation of Solar Analyst model, called in ArcMap ArcGIS 10.2 Esri as Solar Radiation tool.

2. Methods

The concept of Solar Analyst originated from the computer program CANOPY, developed by Rich (1989) for determination of light conditions under tree canopy with the use of hemispherical photography. A hemispherical photograph depicting the canopy of a forest stand seen from a forest floor after accurate alteration can be used as a source of information concerning which parts of hemisphere are masked by tree crowns that get in the way of direct and diffuse solar radiation (Bolibok 2010). It could be assumed that Solar Analyst model generate for specified locations on forest floor in gap virtual hemispherical images of the sky showing which fragments of hemisphere are obstructed by crowns of trees surrounding given artificial gap. The

calculations were based on the digital terrain model (DTM), which described the artificial gap as a hollow in the terrain. Solar Analyst modelled the path of the sun on the sky, which allowed for determination of time intervals when tree crowns were not in the way of sunlight, in other words – the periods of time when direct radiation was available at a given spot within the gap. Generally the availability of diffuse radiation to a given spot on the forest floor is proportional to the part of unobscured hemisphere which which could be observed from this very spot. On the basis of aforesaid virtual hemispherical image also is possible estimation of the part of sky area which was not masked by tree crowns, thus determination of diffuse radiation availability.

Basically, Solar Analyst software was developed for modelling relationships between land topography and the amount of available solar radiation. The model uses raster data and computes the values of solar radiation available at given pixel. The size of raster pixels can be adjusted according to the user's needs. In the present study, light conditions within forest artificial gaps were analysed on 200 × 200 m plots, with 0.5 m-long basic pixels. The gap was defined as a hollow designated in the centre of the plot, with the depth equal to the height of the surrounding stand. In such convention the modelled surface refers to upper canopy surface, thus the used model could rather be described as digital surface model (DSM).

At the same time, it was assumed that both artificial forest floor in artificial gaps and the surface of upper canopy (land cover) were levelled horizontally (had no slope, and consequently – no aspect). There was made a that no solar radiance could either access the gap through the crowns of adjacent trees or be reflected from the trees toward the forest floor within the gap. This assumption was necessary because the algorithm used was not able to take into account the correction for light reflection and penetration within the canopy. Some of the measurements conducted in forest openings (Chen et al. 1993) showed that reflected light could amount to 12–17% of diffuse radiation registered within the gap. Solar radiation-transparency of tree crowns is complex phenomena and depends, among others, on the species and age of trees (Canham et al. 1994; Astrup, Larson 2006; Lefrançois et al. 2008) as well as weather conditions (Johnson, Smith 2006). Taking into consideration all of mentioned factors could hinder the assesment the effect of latitude on the radiation microclimate in the forest artificial gap. Moreover, the used model also assumes that no solar radiation reflected from far-away elements of topography (e.g. mountains covered with snow) reach the gap floor.

The analyses were performed on DTM representing forest artificial gaps situated at a range of latitudes in Poland (from 49°N to 55°N). All DTM described forest artificial gaps of the ecliptic shape, with E-W oriented longer axis. The ratio between the lengths of ellipse longer and shorter axes was 3:2

(60 to 40 m, respectively), that is, likewise in real managed forest stands. In all the DTM, the same gap altitude (190 m a.s.l.) was assigned. The presumed height of the surrounding stand was 20 m or 30 m. Although in Poland, 190 m a.s.l. altitude is never observed (either along the seacoast or in the mountainous regions), the assumption of this value was important in view of radiation microclimate modelling (Bolibok et al. 2013), beacause to some extend evens the length of solar radiation path (optical depth of the atmosphere) to the gap foor. This assumption did not cancel out the path elongation connected with the change of angle at which the sun's rays strike the Earth's surface at higher latitudes. Generally speaking, all the parameters of the gaps included in modelling were unified, exclusive of latitude coordinates of gap location. Hence only this variable will be responsible for the observed differences between locations.

The first step in model development was determination of the amount of solar radiation available at the open area in studied localisation. Solar radiation striking the atmosphere comprises the major part of electromagnetic radiation spectrum and is conventionally referred to as the solar constant S – the total solar electromagnetic radiation per unit time and per unit area on a plane perpendicular to the rays, at the mean distance from the sun to the Earth. Even though S value slightly fluctuates, for the purpose of this study, in Solar Radiation tool it was specified as a default value 1367 W / m². The developed model also required inclusion of the value describing solar radiation absorbed during passing through the atmosphere. In the present study, the coefficient of solar radiation transmittance (quotient of global radiation striking the Earth divided by global radiation striking the upper layer of the atmosphere) was determined as 0.4, in accordance with the value defined for Warsaw (Bogdańska, Podogrocki 2000).

Solar Analyst model provided information on global solar radiation energy available to selected points on the forest floor within the gap without specifying the amount of energy carried by the different ranges of the radiation spectrum, but estimates how much of this energy is carried by the direct solar radiation coming from the solar disk, and how much by the diffused radiation reaching from the sky. In open area total solar radiation energy is sum of energy carried by direct and diffused radiation. In Poland, the share of diffuse radiation in global radiation is 50% (Woś 1996). This share was assigned as a default value for each localisation analysed in the present study. Based on this information the computer program computed the values of potential amounts of direct and diffuse solar radiation. During the analysis of the radiation microclimate in the gap, program calculations took into account time intervals when elements of topography (forest stand surrounding the gap) masked the sun, and accordingly reduced the values of potential amounts of direct radiation. The energy carried by diffuse radiation, coming down from each sector of sky hemisphere, and its va-

riation of intensity depends mainly on the cloud cover and the angular height of the sun above the horizon.

Diffuse radiation availability in the forest gap is also affected by the surrounding stands that overshadow some parts of horizon. When modelling it was summed that the diffused solar radiation reaching the gap floor from different sky hemisphere sectors has varied intensity described by SOC (Standard overcast sky) model.

In the model, the value of direct and diffused solar radiation energy are derived from solar constant - S and its value refers to the instantaneous density radiant flux expressed in W / m². The model calculated the energy of various types of radiation in the indicated period, expressed in kWh / m². Calculations were carried out for growing season. The beginning, end and duration of the growing season depend on the location of given area, therefore, taking the real length of growing season into consideration for selected locations would be an additional source of variation for results modifying effect of latitude. Thus, for all assumed locations, there was specified the same length of growing season. The starting point were the parameters of the growing season from the area Rogów (Łódź Province), that is, from the beginning of 2 April and the end of 2 November (Chojnacka-Ożga 1999). Finally, to simplify the calculations it was assumed, that the growing season cover the period from 1 April to 31 October inclusively.

3. Results and Discussion

The results of modelling of solar radiation availability to open flat areas at different latitudes in Poland are presented in Figure 1. In view of input parameter values, the model predicts that in the vegetation season, global solar radiation striking the open area ranges from 771.0 kWh / m² at the latitude 49°N to 879.5 kWh / m² at 55°N. The model predicts that global solar radiation at gaps situated in the north of Poland will be lower than that in the south of the country - in total by 12%. In the model obtained, direct solar radiation is more reduced when compared to diffuse radiation (by 15 and 9%, respectively). The obtained results on global solar radiation reaching the open area are comparable to those obtained by Bogdańska and Podogrocki (2000). The authors reported that in Poland, from 1 April to 31 October, global solar radiation ranged from 783 to 922 kWh / m². These values were obtained based on data gathered by 8 meteorological observatories established throughout the country (from Gdynia by the Baltic Sea to Kasprowy Wierch in the Tatra Mts.).

The model (Figure 1) predicts gradual reduction of solar radiation with increasing geographic latitude. This is due to ever-increasing length of the path of solar radiation that passes through the atmosphere to reach the more northerly locations. An additional factor taken into account by the
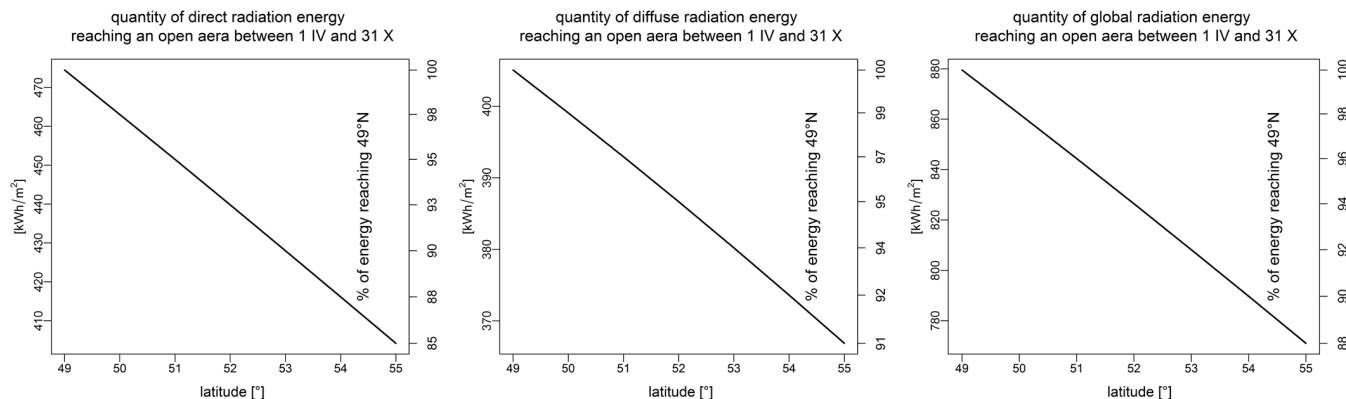
Figure 1. The outcome of modelling of latitudinal changes in supply of different kinds of solar radiation received by open area in different localisations between 49°N and 55°N

model is the length of the day. In the northern parts of Poland, annual daytime lasts 20 hours longer when compared to the southern regions, and these differences are more evident during summer months (Bogdańska, Podogrocki 2000).

Empirical data indicate that in Poland, geographic latitude is not the major factor affecting solar radiation availability to open areas. Figure 2 presents spatial variability of solar radiation supply to the open area in the period 1 April -31 October in Poland. The figure was prepared based on data (a set of 1983–2005 monthly averages for selected measurement points) provided by the EUMETSAT Satellite Application Facility on Climate Monitoring (CM-SAF). These are the results of the analysis of satellite data, performed based on methodology by Mueller et al. (2009). Spatial variability of global solar radiation accessibility presented in Figure 2 is analogous to the yearly averages of global solar radiation reported by Miara et al. (1987) for the period 1956–1975. Solar Analyst model predictions are to some extent similar to spatial variability of global solar radiation currently observed in Poland. In general, with some exceptions, the northern part of the country (especially western parts of Poland's Pomerania) receive less solar radiation when compared to southern Poland's regions (Lublin Upland).

The areas situated close to the Baltic Sea and those in mountainous regions show opposite trends. Relatively more solar radiation accesses coastal areas when compared to the mountains. On the scale of the whole country, there can be observed visible reduction of solar radiation along the East–West gradient. This is connected with spatial variability of another important factor - definite sunshine duration, that is, the number of hours when the sun is not covered by clouds. The comparison of variability of global solar radiation and that of definite sunshine duration observed in Poland (Koźmiński, Michalska 2001) shows that the effect of definite sunshine duration at a

local isolation (reliant upon spatial and time cloudiness variability) is stronger than that of geographic latitude.

The differences between the outcome of modelling and the results obtained empirically do not call into question the use of Solar Analyst model, but rather highlight the importance of input of appropriate parameteres for computation. Indisputably, more matching results could be obtained with better adjusted values of the parameters used in the present study to local conditions, as the transmission coefficient value as well as the proportion of diffuse radiation are strongly related to local sunshine duration. Proper selection of model parameters is even more important when model outcom is used for interpretation of natural phenomena (eg. survival seedlings) in a particular growing season. In a given locality, there can occur significant quantitative differences in availability of global solar radiation, depending on the vegetation season. In incidental years, spatial variability of global solar radiation availability is contradictory to that observed on a regular basis (Figure 2, the years: 1987 and 2005). The above considerations are important in silvicultural practice. Owing to great spatial and time variability of definite sunshine duration received within Poland's area, no forest artificial gap - even if it is supposedly of the most favourable size - can guarantee the optimum light and thermal conditions for forest regeneration. Nonetheless, the pursuit to optimise the parameters of forest artificial gaps increases chances to form the optimum radiation microclimate.

The effect of latitude on the total amount of solar radiation reaching the forest floor within the artificial gap is presented in Figure 3. The graph shows that with increasing geographic latitude, solar radiation available to the forest floor within the gap is reduced more rapidly when compared to the open flat area. This is associated with the effect of surrounding tree stand.
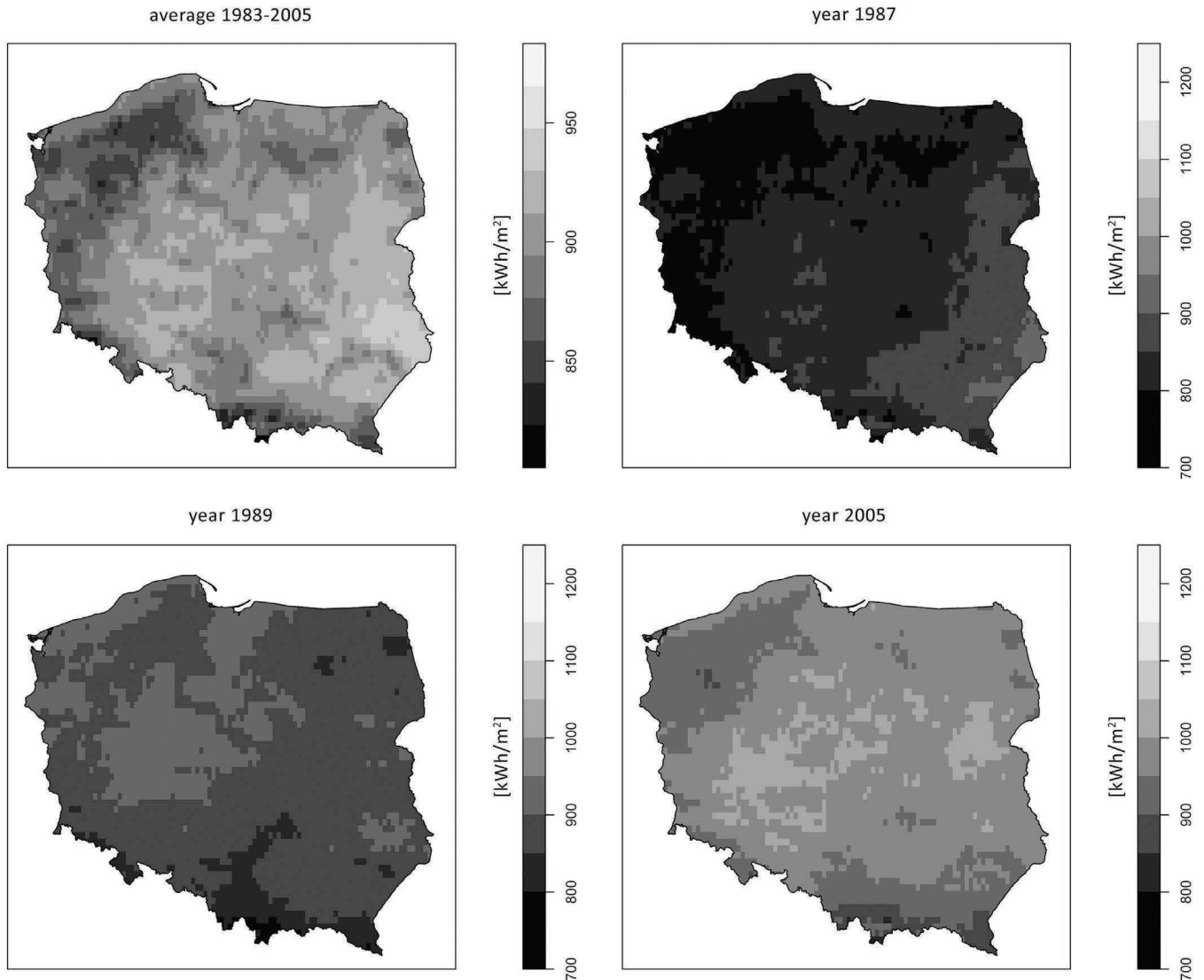
average 1983-2005

year 1987

year 1989

year 2005

Figure 2. Spatial diversity of global solar radiation intensity calculated on the basis of month averages (April to October) from years 1983–2005. Data on month averages for specific localisations (SIS METEOSAT 3, Monthly Mean, Version 001 © (2013) EUMESAT) were prepared by EUMETSAT Satellite Application Facility on Climate Monitoring.

The largest solar radiation amount reaches the gap surrounded by 20-m-high tree stands, situated at 49°N, and solar radiation availability decreases with increasing latitude. Within artificial gaps located at 55°N, available direct solar radiation is 82% of the reference value for the gap at 49°N. The reduction of diffuse radiation availability is lesser when compared to that of direct radiation, and at 55°N, it is up to 90% of the reference value.

The amount of direct radiation decreases the most (down to 74%). There are two reasons behind the observed reduction of direct radiation. The first mechanism is connected with the angular height of the sun above the horizon, which decreases with increasing latitudes. The lower is the sun position, the longer is the path of solar radiation through the atmosphere, and consequently solar radiation reaching the Earth's surface is reduced (Bolibok et al. 2013). The second reason is associated with the effect of tree stand surrounding the artificial gap. At higher geographic latitudes, even at noon, the sun is comparatively closer to the horizon line, and then the shadow of the trees growing on the southern edge of the gap is somewhat longer. This results in a decrease of the proportion of the area with highest insolation within the gap, that normally receives
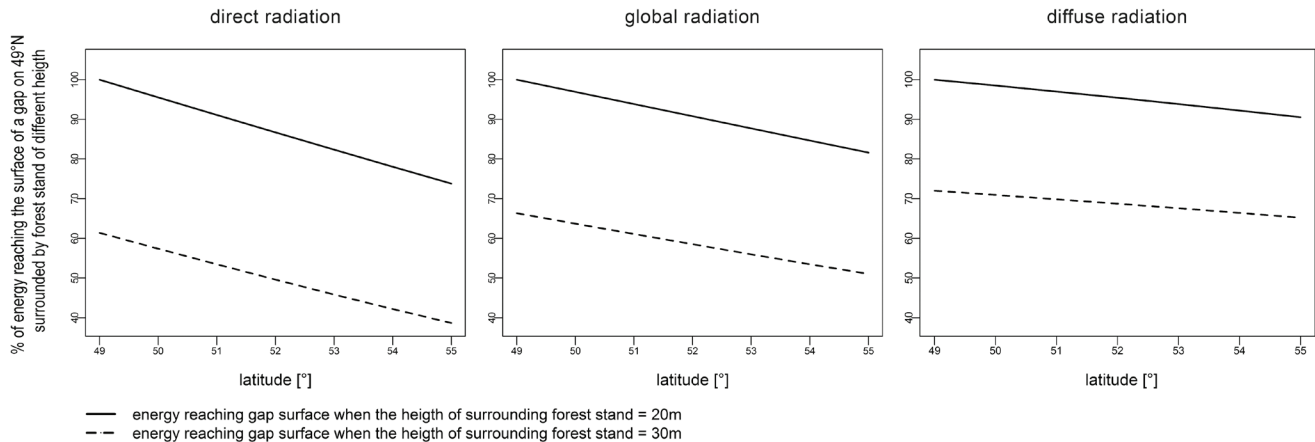
Figure 3. Modelling outcome of potential latitude influence on diversity of supplies of different kinds of solar radiation on elliptical artificial gaps with axes length 60 and 40 m, located between 49°N and 55°N and surrounded by tree stand of height 20 and 30 m. The figures show how changes the sum of solar radiation energy received by a gap in the period between 1st April and 31st October expressed as a percent of energy received by the gap placed on 49°N.

from 80 to 100% of direct radiation available at the open area at a given latitude (Figure 4).

The reduction of the proportion of the area with the best sunlight conditions (from 18.38 % down to 10.7%), indicates that this sunny spot becomes smaller and smaller, and shifts northerly (Figure 5). Occasionally, it can move beyond the gap limits, and this can potentially affect the growth of young regeneration under the canopy situated north of the gap. In the case of small gaps, this can also indicate that most of direct solar radiation connected with the gap, actually does not get to the forest floor within the gap, and only reaches the canopy north of the gap (Canham et al. 1990). For silviculture practice this means, that in northern Poland, the forest floor under the canopy placed north of the gap will have better sunlight conditions when compared to southern regions of the country.

Northerly shift of the most insolated gap part with increasing geographic latitude, is important in view of the growth of tree seedlings within the gap. According to Lieffers et al. (1999), as a result of the shift, two definite gap zones, that is, that with better sunlight and that with better water and nutrient availability overlap to a lesser and lesser degree. The central position of the zone with higher water and nutrient availability is somewhat attributable to competitive effects of surrounding trees (Bolibok 2009), and it is hardly susceptible to changes of latitude. With increasing latitude, there increases the proportion of the most shaded part of the gap, (from 23.2% up to 30.9%), which receives less than 20% of direct solar radiation reaching the open area at a given latitude (Figure 5). This could be a beneficial factor for the soil with low water contents (Bolibok, Andrzejczyk 2008; Bolibok et al. 2011).

In case of decline in the availability of diffused solar radiation acts only the mechanism associated with increasing radiation path through the atmosphere, and therefore the relative decrease in the energy content of the solar radiation is significantly smaller (Fig. 3) and is about 10%. Taking into account this value, there can be estimated that at the latitude 55°N, 26% of relative reduction of direct radiation in the gap comprises 16% of the reduction linked to the longer tree shade and 10% – to the effect of enlarged optical depth of the atmosphere.

Increasing geographic latitude has no effect on the area share of gap sections which that receive certain proportion of diffuse radiation reaching the open area. Both, at 49°N and 55°N, the model showed no gap sections receiving less than 20% or more than 80% of diffuse solar radiation available at the open area. Regardless of geographic latitude, the model showed that within elliptical artificial gaps (60 and 40 m axes) surrounded by 20-m-high tree stands, 58% of the gap area received from 41 to 60% of diffuse solar radiation observed in the open area (Figure 5).

4. Conclusion

The main goal of the present study was to determine the effect of geographic latitude on the radiation microclimate within the forest artificial gap. Two series of analyses, carried out on the gaps surrounded by 20 m- and 30 m-high tree stands showed that the distinctive size of the gap (diameter/ stand height ratio) had a substantial effect on the radiation climate in the gap. Geographic latitude indicated the lesser, however, distinctive effect. Latitude influence can be
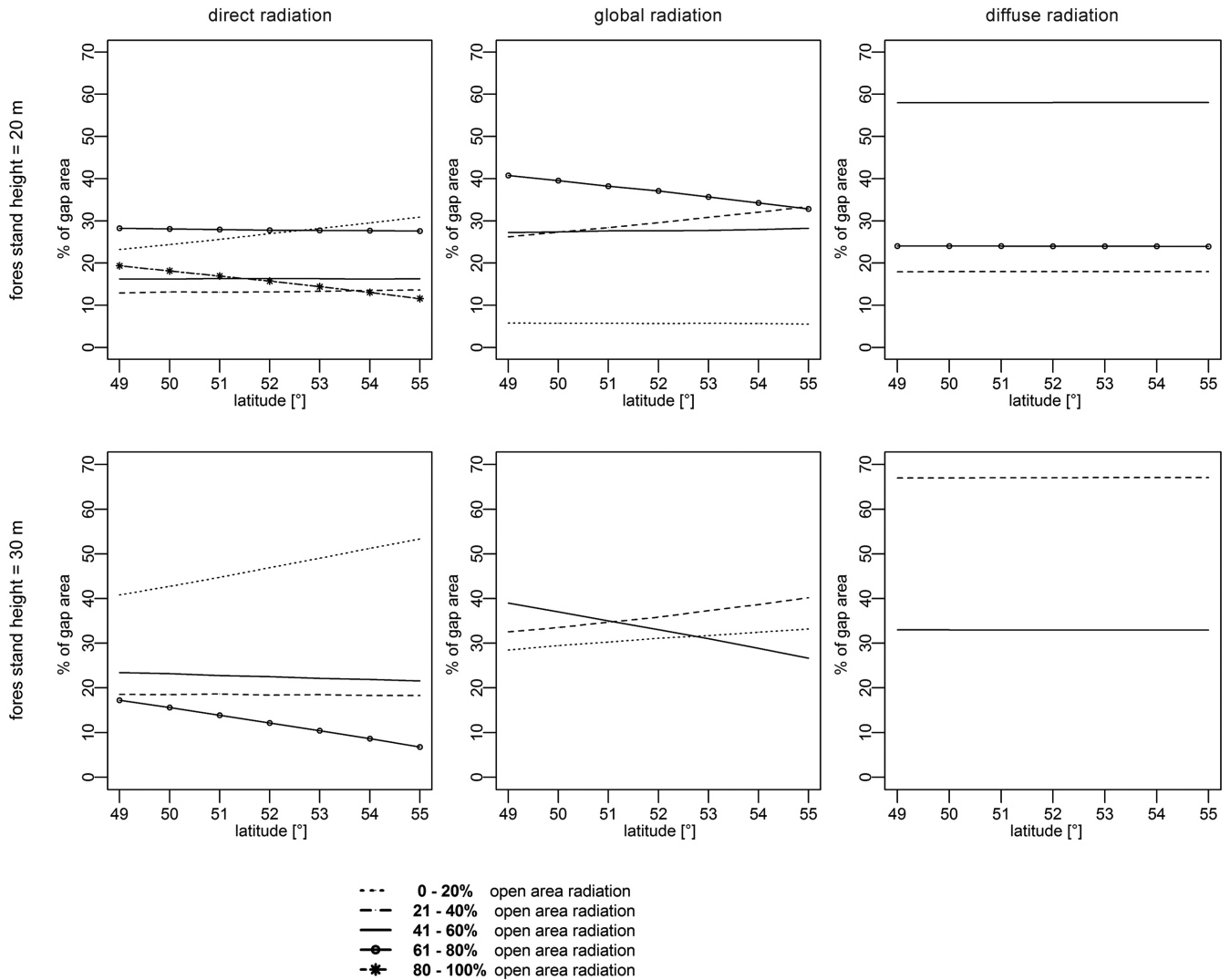
Figure 4. Modelling outcome of different kinds of solar radiation supplies on elliptical artificial gaps with axes length 60 and 40 m located between 49°N and 55°N and surrounded by tree stand of height 20 and 30 m. The figures show changes in the share of gap gap area receiving different levels of solar radiation. The levels are described as the percent of solar energy received by open space in given localisation.

significantly reduced by adequate delineation of the size of the artificial gap. Nonetheless, in view of obtainable data on time and spatial variability of solar radiation availability under Poland's conditions, in practice, there will always be present some risk. Fortunately, the repetitiveness of sunshine conditions is relatively stable in certain regions of Poland. The Solar Analyst model developed can serve as a tool for depiction of theoretical variability of solar radiation conditions within forest artificial gaps. At the same time, the model could support decision making on silvicultural practices, pertinent to specific parameters of gaps at given forest localisations.

Conflict of interest

The authors declare no potential conflict of interest.

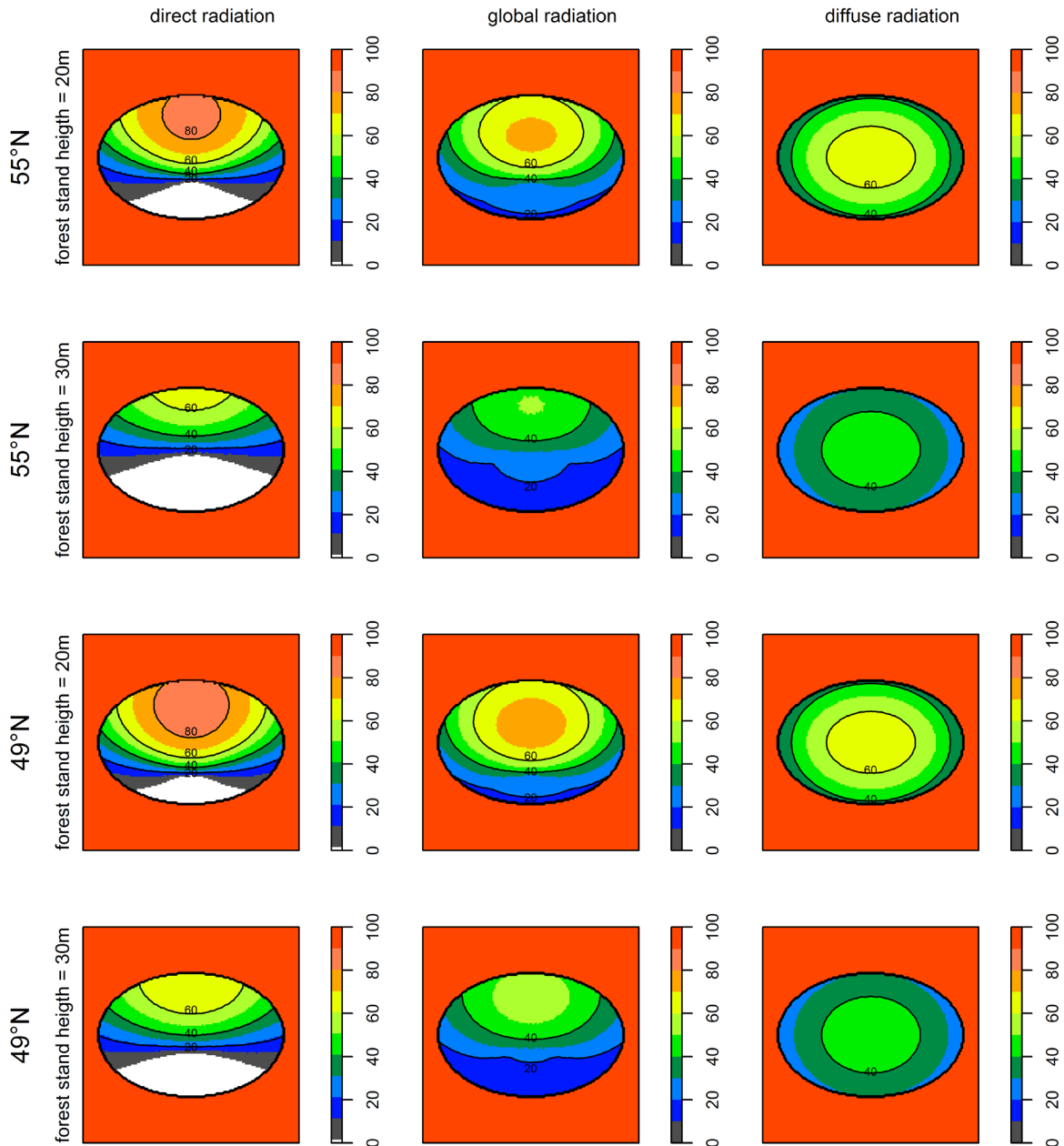## Acknowledgements and source of funding

Figure 5. Modelling outcome of spatial diversity of different kinds of solar radiation supplies on elliptical artificial gaps with axes length 60 and 40 meters, located between 49°N and 55°N and surrounded by tree stand of height 20 or 30 meters. The figures show how changes the share of gap area receiving different levels of solar radiation. The levels are described as the percent of solar energy received by open space in given localization in the period between 1st April and 31st October.

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Authors' contribution

L.B. – study concept, data analyses, manuscript preparation;
M.B., S.D., H.Sz. – data analyses, manuscript preparation.

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