

## Modeling light conditions on the forest floor

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**Abstract.** Contemporary models of light conditions on the forest floor can be divided into two categories: under-canopy models that allow the light conditions in a stand under the canopy to be simulated, and models that take into account shielding from the side.

Under-canopy models precisely estimate the availability of wavelengths of light spatially distributed under the canopy of stands: however, these models require a large amount of data on the spatial structure of forest stands.

The other class of models describe the light conditions on a particular open surface. These incorporate shielding from the side and are easier to use as they require less data than under-canopy models. In practice, in forest conditions, such models require data on the size, shape and geographical location of surveyed surfaces (e.g. gaps and cut areas) and on the height of the surrounding stand. Often, these data are available in databases, such as the State Forest Information System (SKP), or can otherwise be obtained relatively easily (and inexpensively).

Compared to under-canopy models, these models provide a cheap way to obtain useful information on variation in the light environment that affects the microclimate for regenerating plants on clearcuts and canopy gaps.

**Key words:** light conditions, diffuse light, direct light, gaps, modeling

### 1. Introduction

For a long time, determination of light conditions on the forest floor has been of interest for researchers and foresters practitioners, especially in the context of providing appropriate light conditions for forest regeneration (Wagner 1923, Dengler 1930) but also in other applications e.g. in the estimation of flood control or soil-protecting functions of forest, or studies of phytocenosis. All methods of the modeling of light access to the ground must take into account its source, and both types of solar radiation: direct and diffuse. The oldest methods of modeling were limited to the calculation, with the use of astronomical tables, of the length of the shadow cast by a stand on the adjacent open space. The progress of calculation techniques facilitated laborious calculations and allowed for the

modeling of light conditions under-canopy of varying closure degree.

Contemporary models of light conditions on the forest floor may be divided into two categories: under-canopy models that allow the light conditions in a stand under the canopy to be simulated, and models that take into account shielding from the side and limitations in light access resulting from the stand adjacent to the studied space. Current under-canopy models are able to precisely estimate the availability of different kinds of light in any fragment of forest floor; however, these models require a large amount of data on the spatial structure of forest stands. Gathering such data is time-consuming, which significantly constrains the usefulness of these models for practical applications. Before progress in remote sensing and data processing changes the status quo, it is worth paying attention to the

not fully exploited potential shown by an existing class of models that describe the light conditions on the given open surface incorporating shielding from the side. In practice, in forest conditions, such models require data on the size, shape and geographical location of surveyed surfaces (e.g. gaps, and cut areas) and on the height of the surrounding stand. Often, these data are available in databases, such as the State Forest Information System (System Informatyczny Lasów Państwowych), or can otherwise be obtained relatively easily (and inexpensively). In comparison with under-canopy models, these models provide a cheap way of obtaining useful information on variation in the light environment that affects the microclimate for regenerating plants on clear-cuts and canopy gaps.

In forestry practice, there is a long-standing rule that you can expect the side shield protection from light in a distance which equals no more than one height of surrounding stand adjacent to the south, east or west. It works well in a flat terrain, on standard rectangular clear-cuts, but in a terrain with diversified slope and exposure or a typical shape it may be insufficient. When a digital terrain model is available (or at least information on the slope and exposure), models of light conditions on the open surface incorporating shielding from the side may prove very useful. Relatively easy visualisation of the results of such models against existing stand map may be a valuable guideline while planning gaps shape or considering locations on clear-cuts of admixture of species demanding frost protection.

## 2. Modeling solar radiation which reaches the canopy

Regardless of whether the aim of modelling is to determine under-canopy light conditions or amount of heat reaching the bottom of a gap, the starting point is usually to determine the amount of solar radiation reaching a certain open surface in the surveyed location. In the context of forestry research, it is about determining the amount of solar radiation reaching from above crowns of trees in stand. If a surveyed stand is located in the vicinity of a meteorological station which records changes in direct and diffuse solar radiation, it is possible to use this information. As these data are not very common, in most cases modeling is based on additional assumptions concerning such phenomena as the amount of light absorbed by the atmosphere, as well as the ratio of the energy carried by direct and diffuse radiation at a given location. When using software

modeling the supply of solar energy, it is necessary to pay attention to default values of the discussed variables proposed in the model, as they may strongly affect the modeling results.

Solar radiation reaching the Earth's atmosphere covers most of the spectrum of electromagnetic radiation. The Sun does not radiate gamma rays, but sends X-ray radiation, ultraviolet light, visible radiation, infrared radiation, as well as radio waves. Such energy flow is described by a solar constant ( $S$ ). It is a total energy that is exported by solar radiation per time unit through unit area that is set perpendicularly to the radiation in the Earth's average distance from the Sun. It amounts to approximately  $1367 \text{ W/m}^2$  (Marshall, Plum 2008). The term constant is misleading due to the elliptical shape of Earth orbit that changes the amount of energy and the given value refers to the average distance from the sun that is about  $150 \times 10^6 \text{ km}$ . The cyclical changes of solar activity have little effect on this constant ( $\pm 0.1\%$ ) (Fu 2003).

Approximately 95% of the energy reaching the upper layers of the atmosphere is the radiation from spectrum between  $0.25$  and  $2.5 \mu\text{m}$  ( $10^{-6} \text{ m}$ ) (Marshall, Plum 2008). It mainly includes three types of radiation: about 50% is infrared radiation (near and far) ( $>0.7 \mu\text{m}$ ), about 40% is visible radiation ( $0.4\text{--}0.7 \mu\text{m}$ ) and about 10% is ultraviolet light ( $<0.4 \mu\text{m}$ ) (Fu 2003).

The spectrum of radiation reaching the Earth's surface is modified by the atmosphere, mainly through gases and aerosols. Water vapour absorbs radiation with wavelengths  $\lambda$  close to  $1100, 1400, 1600$  and  $1900 \text{ nm}$  ( $10^{-9} \text{ m}$ ). Ozone absorbs ultraviolet radiation  $\lambda < 300 \text{ nm}$ , and  $\text{CO}_2$  absorbs radiation with  $\lambda = 2750$  and  $4250 \text{ nm}$  (Bonhomme 1993). This is why models that estimate energy reaching the Earth's surface usually use the formula:

$$R_g = R_{dir} + R_{diff}$$

where:

$R_g$  – energy reaching the Earth's surface,

$R_{dir}$  – direct radiation,

$R_{diff}$  – diffuse radiation.

In models, value of direct and diffuse radiation energy is derived from value of the solar constant  $S$  ( $\text{W/m}^2$ ), so the variables  $R_{dir}$  and  $R_{diff}$  relate to the instant value of direct or diffuse radiation flux density expressed in  $\text{W/m}^2$ . Some authors (ter Steege 1997) use other units, such as  $\mu\text{mol/m}^2$ . If such need arises, models are also able to calculate the energy of a particular type of radiation in a specified period of time expressed in  $\text{J/m}^2$  or other units such as  $\text{kcal/m}^2$ .

Before direct radiation (reaching the Earth directly from the solar disc) reaches the canopy, it has to get through gases, dusts and aerosols filling the atmosphere. They can absorb (heating the atmosphere), reflect (towards the space) or diffuse (change the direction of reaching the Earth) direct radiation, which leads to a partial loss of its energy. Radiation energy measurements at the sea level, carried out on completely cloudless days, rarely exceed the value of 75% of the solar constant ( $S$ ) at the ground (Monteith, Unsworth 2008). To calculate the direct radiation energy immediately after passing through the atmosphere, Lambert-Beer law is applied. It describes absorbing electromagnetic radiation passing through partially absorbing and diffusing medium. Direct radiation energy above a tree canopy  $R_{dir}$  depends on the so-called optical depth of the atmosphere and can be described by the formula:

$$R_{dir} = S \cdot e^{-\tau \cdot m}$$

where:

- $e^{-\tau \cdot m}$  – optical depth of the atmosphere
- $m$  – physical thickness of the atmosphere
- $\tau$  – composition of the atmosphere.

The optical depth of the atmosphere ( $e^{-\tau \cdot m}$ ) is proportional to the physical thickness of the atmosphere ( $m$ ) and its optical features resulting from its composition ( $\tau$ ).

Physical thickness of the atmosphere should be understood as the length of the distance covered by radiation passing through the atmosphere before it reaches the ground. It is linked to the angular height of the Sun above the horizon and for a selected point on Earth's surface it may significantly change during the day and throughout the year, which considerably complicates the modelling.

The optical properties of the atmosphere are not the same for all types of radiation, and vary greatly depending on the content of aerosols (mainly water) and dust in the atmosphere. Attenuation coefficient (extinction)  $\tau$  can be considered as the sum of two coefficients  $\tau_m + \tau_a$  (Monteith, Unsworth 2008).

Coefficient  $\tau_m$  describes the dispersion of light by gas molecules in the atmosphere. In comparison with the amount of aerosols, the composition of the molecules can be considered constant. Blue colour of cloudless sky is a consequence of greater dispersion of blue range of spectrum of visible light by gas molecules. At sunset or sunrise, red sky coloration results from the fact that red band of visible light best overcomes the longest way through the atmosphere at this time of the day.

Coefficient  $\tau_a$  describes light dispersion by aerosol particles suspended in the atmosphere: fog (liquid particles) and dust (solid particles). The actual value of  $\tau_a$  coefficient for the same location may vary over time. On the basis of measurements performed in the UK, Monteith and Unsworth (2008) provide value  $\tau_a = 0.05$  for clean arctic air and  $\tau_a = 0.6$  for highly polluted air from middle England. Calculations indicate that for  $\tau_a = 0.6$ , reduction of energy for direct radiation was about 50%. Some studies indicate that clarity of atmosphere continuously declines, which is associated among others with burning (Stanhill, Cohen 2001). Models describing the supply of direct radiation to the canopy use some average values of the  $\tau$  extinction coefficients, and their value used in the model may have a large impact on the calculated amounts of energy.

Diffuse radiation which comes from the sky to the canopy mainly consists of energy from direct radiation diffused by the atmosphere. To a lesser extent, this radiation is reflected by the ground (Earth's albedo) which is reflected back from the atmosphere and gets back to the canopy. Energy carried by diffuse radiation reaches from each sector of the sky and its variability depends mostly on the amount of cloud cover and Sun angle above the horizon. With a clear sky, contribution of diffuse radiation in the overall balance of radiation ( $R_{diff}/R_g$ ) is about 10%–15%, while for the completely overcast sky it reaches 100%.

The given point above the canopy receives diffuse radiation from all sectors of the sky. This should be taken into account while modeling. Theoretically, in the case of perfect diffusion, all sectors of completely overcast sky should give the same portion of diffuse radiation. This assumption is called uniform overcast sky (UOS) model (Monteith, Unsworth 2008) and is used in certain models. More recent studies suggest that such a diffused intensity distribution model should be rejected (Gendron et al. 2006). Alternatively, a standard overcast sky model is used (SOC). This model assumes that the further away from the zenith, the lower the amount of diffuse light reached from a particular sector of the sky.

A crucial issue for the discussed topic is a share of photosynthetically active radiation (PAR) with the wavelength range from 0.4 to 0.7  $\mu\text{m}$  in the transmitted energy. Studies show that the share of PAR in the overall solar radiation reaching the Earth surface ( $R_g$ ) depends on location and varies from 45% to 50% (Tsubo, Walker 2005). PAR share in  $R_g$  increases as cloud cover increases (although the absolute value of  $R_g$  decreases

at that time). Since usually data on actual variability of cloud cover for the period studied are not available, in many models, for the sake of simplicity, assumptions are made as to what percentage of photosynthetically active energy in a certain location is carried by direct radiation, and what percentage of radiation is dispersed by the atmosphere. A share of direct light in overall radiation depends on the atmosphere transparency and usually ranges from 70% to 90% (Rich 1990). Different authors take different values of this ratio. Chazdon and Field (1987) on the basis of Gates' research (1980) assumed that only 15% of PAR is diffuse light, while Canham et al. (1990) on the basis of the surveys of Knapp et al. (1980) assumed that it makes up to 50%. Users of a software describing availability of various types of radiation should precisely review the assumptions made by the model authors or use the option to self-define the relevant coefficients.

As soon as the amount of solar radiation that reaches the Earth surface (over canopy) in a surveyed location has been estimated, the lines of thought presented by authors of different models used in the research and forest practice vary. There are two main directions: modeling light transmission through canopy and modeling solar radiation availability on the open surface including access restrictions related to area configuration or the presence of other obstacles such as a nearby stand edge. The first group of models pay more attention to modelling of supply of PAR, while the other emphasise direct radiation, especially infrared radiation.

### 3. Modeling under-canopy light conditions

The dominant philosophy of modelling under-canopy light conditions was an attempt to link the parameters describing the structure of canopies with a possibility of transferring light under-canopy. One of the first ideas was the use of Lambert-Beer law to describe the absorption of electromagnetic radiation passing through partially absorbing and diffusing medium, such as canopy layer. Monsi and Saeki (1953, in: Lieffers et al. 1999) suggested transformation of the equation describing the penetration of light through solutions as per the following formula:

$$R_{\text{under}} = R_{\text{dir}} \cdot e^{-k \cdot LAI}$$

where:

- $R_{\text{under}}$  – under-canopy direct radiation intensity
- $k$  – extinction coefficient, characteristic for particular tree species
- $LAI$  – leaf area index.

Whether the direct radiation or only PAR will be modeled depends on previously described model settings (on the selected value of reducing factor applied).

Most often, this relationship was used for determination of LAI index, but it can also be used for evaluation of under-canopy light conditions, provided the results of independent LAI assessment are available. Pierce and Running (1988) applied this formula and obtained high data consistency ( $R^2 \geq 0.94$ ) of measured and expected light intensity under-canopy of coniferous stands. Unfortunately, this formula has limited usefulness because it works only for the chosen angle of the Sun above the horizon and for the stands of similar extinction coefficient  $k$ . Cannell and Grace (1993) proposed that during calculations,  $LAI$  and extinction coefficient be separately determined for each species and combined by summing in the model. Further transformations of the formula allowed for the inclusion of effects of the sun angle on the change in value of the extinction coefficient (Sampson, Smith 1993, in: Lieffers et al. 1999). Value  $R_{\text{under}}$  obtained is a mean value for the stand, which for many applications is not accurate enough. The most far-reaching change of this concept comes down to modeling with the use of Lambert-Beer law – the probability of reaching a given point under-canopy by a ray of light from any sector of the sky. Such a model will then be useful for determining diffuse light transmission (Oker-Blom et al. 1986).

A weakness that is difficult to overcome in the models described is an assumption of random distribution in a space (in the canopy layer) of light-absorbing elements. This limits the predictive value of such models, because in fact the concentration of leaves around the branches and branches around the trunk means that light-absorbing elements are not distributed randomly (they are concentrated). There were attempts to solve this problem by grouping items in separate, identifiable objects such as rows of trees, canopies, canopy layers or individual shoots (Norman, Jarvis 1975). These objects are described by means of geometrical figures, such as cylinders, ellipsoids and disks, whose position in the three-dimensional space is strictly specified. In this way, the space unoccupied by canopies is also determined, which means that inclusion of gaps in stands is also possible. Among the first scientists to apply such an approach were Pukkala et al. (1993), Canham et al. (1994) and Bartelink (1998). In these models, under-canopy light transmission

depends on the total length of the segments that the ray of light passes inside the modeled canopy. The amount of direct solar radiation reaching the given point under-canopy is modeled for a particular point in time, including the position of the Sun above the horizon at that location, and then summed for the selected period (e.g. day, growing season, year). To simplify the modeling of transmission of diffuse light which comes from all directions, in such models a limited number of points (light sources) evenly distributed on the sky (e.g. 200) is analysed. For these selected points for a given moment, light transmission through canopy is modeled.

During transmission of light through canopies, some rays may be able to penetrate the leaves, and some will be reflected by the leaves and will reach under-canopy. Moreover, light diffraction on the edges of leaves and shoots is of certain importance. These phenomena make an increase of light transmission under-canopy, known as flux enrichment, which is difficult to calculate (Canham et al. 1994; Bolibok 2010). Such phenomena are usually modeled for the whole canopy layers (Norman, Jarvis 1975). Newer models often combine modeling light transmission through canopies treated as isolated objects with modeling of light flux enrichment calculated for the whole canopy layer (Grace et al. 1987; Cescatti 1997a).

Results of advanced models of determining under-canopy light conditions correspond very well with the direct measurements of solar radiation. They allow to predict the light conditions on the forest floor with complex spatial structure (Canham et al. 1999; Sprugel et al. 2009). Sometimes, the model's predictions are so accurate that they can replace direct measurements, as in the studies carried out by de Chantal et al. (2003). The authors studied the growth of spruces and pines seeded in the gaps. To describe the light conditions, for each seedling location, a model developed by Cescatti (1997a, 1997b) was applied. A determination index, which describes relation between model predictions and direct measurements for diffuse light, was very high ( $R^2=0.97$ ). However, achieving such a high consistency requires gathering a large amount of data on the surrounding stands e.g. tree height, canopy base height, height of the widest canopy section, length of canopy's radius in four directions and determining shape coefficient for each crown and exact mapping of trees position.

#### 4. Development of models of light conditions with shielding from the side and its applications

Advanced models describing under-canopy light conditions may be applied to model light conditions on the open space surrounded by a forest. In practice, the high accuracy of information they provide does not justify the costs of its gathering. Sometimes, less accurate information, but achieved at a significantly lower cost, may be of more practical relevance, as for example information on which part of a cut area or a gap is not reached by radiation due to shading by surrounding stand.

Ogijevski (1898, in: Morozov 1925) illustrated the impact of direct sunlight on the success of regenerating pines at clear-cuts by a figure showing the extent of a shadow cast by adjacent stand on a cut area of 40 m width. The quoted figure results from astronomical calculations made for the Sun positions between 4<sup>th</sup> and 16<sup>th</sup> June 1884, at a latitude of 52°30' N. Ogijevski (1898, in: Morozov 1925) on several diagrams presented the shadow coverage area at the cut areas at different times of a day from 6 a.m. to 6 p.m. with two-hour intervals. For each hour, the author presented shading at the cut area located latitudinally, longitudinally and in NE–SW and NW–SE directions. This way of presenting of sunlight impact soon became popular among foresters. Dengler (1930) in his handbook fully quoted Morozov's figure; however, he made an error in Ogijevski's name. Then, for several occasions, scientists referred back to this concept, e.g. Włoczewski (1968) published a figure of the same concept but with calculations made for 21<sup>st</sup> June for the latitude 52°02' N for a cut area of 25 m width. This idea was developed to the furthest extent by Marquis (1965). He presented a range of shadow changes for plots of different shapes (rectangular, square and circular) with the size of 1/10 and 1/2 acre (0.04 and 0.2 ha), calculated for latitude of 44° N. His figures are the most realistic because they show the impact of shading for more than one stand's edge.

Daily variability of shading of open space by surrounding stand, presented in the quoted papers, shows possible variation of this factor. Nevertheless, using this convention, it is difficult to present variability of solar exposure in a year. A better graphic solution is to show isolines denoting the number of hours when direct light reaches the given point. Of course, the number of hours is theoretical and results from the astronomical calculations. In Polish forest literature, Graniczny

(1952) was the first person to deal with this issue. He calculated isolines of solar exposure with southern shielding in gaps of various shapes (rectangular, triangular, circular) for the entire June for the latitude 52°N. The cited work shows the distribution of isolines when the opening is surrounded by a stand with height of 6, 18 and 25 m. Some of the calculations were quoted later on by Mierzejewski and Niedźwiedzki (1954). Their studies on natural regeneration on gaps confirmed purposefulness of such investigations. Graniczny (1959) pointed out that not only time of solar exposure is important for characteristic of growth conditions, but also the angle of sunlight. The higher the Sun is above the horizon, the more energy it supplies per square metre of horizontal surface (under comparable conditions of cloud cover). This significantly complicates the calculations. To expedite the calculations, the cited author used nomograms and proposed a device that allowed pointing out a line of shadow coverage at the gap or the cut area. These methods are probably the most advanced solutions proposed to foresters before computer technology became popular.

The first computer-assisted analyses of solar radiation focused on a shadow cast by a stand on adjacent clear-cut area. Halverson and Smith (1974) including trees. In timbered areas, the type of forest management practiced can help develop desired microclimates. The results depend on the size and orientation of openings created and on the shade cast by surrounding vegetation. A computerised method to calculate the extent of boundary shading for any combination of date, slope, and aspect between 23.45° N. latitude and 50° N and every day of a year. The access of direct solar radiation (especially infrared) is crucial for the length of snow cover retention. The authors presented data on snow retention during winter and spring on a rectangular cut area with the width of 42 m and E–W direction, made in a stand of 30.5 m height. These data clearly indicate that the environmental conditions gradually change along with the changes of shadow cast by the stand. In the spring, when a shadow cast by trees shrinks, thickness and coverage of snow commensurately reduces, and it is the northern part of a cut area that is uncovered first. The data collected on a similar clear-cut oriented along N–S direction show an even and slower snow melting, which is related to higher shading of this space by the surrounding stand. Owing to the results of calculations obtained with a use of this program, the authors could also determine the effect of exposure on the amount of energy received by a clear-cut area.

Halverson and Smith (1979) in another publication describe how the information obtained with the aid of this program may be useful in making economic decisions regarding protection against erosion (water run off rate control during thaws), as well as the creation of optimum conditions for natural regenerations.

Another, much more advanced model of solar radiation on the open space with shielding from the side was developed for silvicultural research purposes. Fischer and Merritt (1978) noted that although a lot of information on solar radiation above canopy or under-canopy was gathered, information on spatial variability of this factor for gaps and forest openings was lacking. As the gathering of such information for many gaps of different sizes with the use of contemporary technical means was impossible from a practical point of view, SHADOS computer model was developed with the aim of comparing its values with direct measurements. Brown and Merritt (1970, in: Fischer and Merritt 1978) developed the first version of this model. It characterised light conditions for a gap of any shape situated on flat ground and surrounded by trees of the same height. It calculated the amount of direct radiation reaching given points at the bottom of the gap in a selected period (e.g. one year) based on time when they were not shadowed by the surrounding stand. The model also estimated the availability of diffuse light at given points. The basis of this evaluation was the calculation of a sky view factor, which determines the percentage of the hemisphere of the sky visible from a given point (not shielded by the surrounding stand). The authors assumed the UOS model. Under such assumptions, the ratio of the amount of diffuse light reaching the given point at the gap's bottom to the total amount of diffuse light provided by the sky equals the sky view factor. In their model, the authors consciously did not take into account two additional beams of solar radiation to be expected at the bottom of the gap: direct and diffused solar radiation getting through canopies of surrounding stands. They considered such radiation too difficult to model, and simultaneously carrying too little energy to be included in the model.

Over time, models of solar radiation on a particular open space with side shielding have improved. Harrington (1984) built a model for a stripped cut area in which, like in the SHADOS model, stand walls were not penetrated by the sunlight. This model, however, was able to provide results even for the sloping surfaces. Chen et al. (1993) built a model that was working only for gaps of elliptical shape on any exposure. It stood

out from other models, as it included radiation getting through canopies surrounding the gap. This model was used to analyse the effect of light conditions on the growth of regeneration at the gaps (Coates, Burton 1997; Coates 1998), as well as to design studies aimed at gap size optimisation (Spittlehouse 2004).

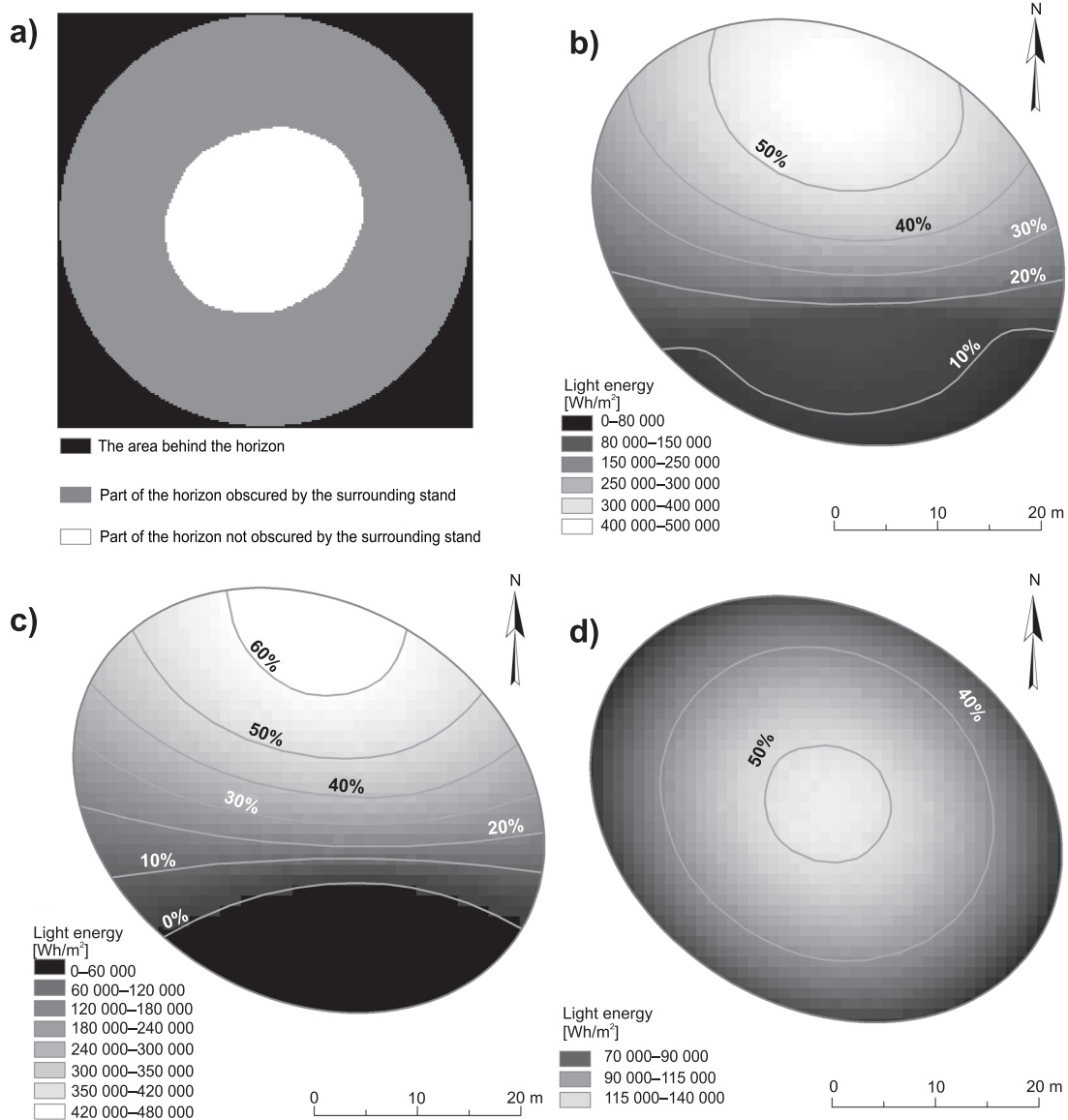
A weakness of the models discussed is the fact that they are separate software applications for which data should be specially collected and prepared. Owing to the development of Geographic Information Systems (GIS), huge databases were created with information (digital terrain model) which may be used in solar radiation models on the open space with shielding from a side. One of the first models of this kind was SOLARFLUX (Rich et al. 1994), later developed and implemented as Solar Analyst in ArcView (Fu, Rich 1999, 2002). Afterwards, other software i.e. solarradn (Kumar 1997) or POTRAD (van Dam 2000, in: Bolibok, Andrzejczyk 2008), also using the potential of this technology, were created; however, they are less popular.

The concept of SOLARFLUX derives from CANOPY developed by Rich (1989) and used to determine light conditions under-canopy based on the analysis of hemispherical images. The idea of this solution boils down to the use of hemispherical image depicting canopy stand seen from the forest floor (Bolibok 2010). After adequate processing, such an image provides information on the parts of the sky obscured by the trees, as seen from the place where the photo is taken. Afterwards, apparent motion of the Sun on the sky is modeled and the time of direct radiation getting through gaps in canopy is checked (modeled position of the Sun falls on the unobstructed part of the sky). The processed image may also be used for the sky view factor calculation, which in the context of hemispherical image analysis is called weighted openness (Bolibok 2010). This allows for relatively easy estimation of diffuse light availability on the forest floor, where a picture was taken.

The main idea of SOLARFLUX is substantially similar to that of CANOPY, but the source of information on the parts of the sky obscured in the latter program

is a digital terrain model, not a hemispherical image. One can say that an algorithm in SOLARFLUX takes at given points a series of virtual hemispherical images, where obstacles obscuring the Sun are visible (Fig. 1a). Based on the analysis of these images, the program assigns calculated level of solar radiation intensity, including an exposure and slope, to the selected points (Fig. 1b, c, d).

Modeling the variability of solar radiation intensity at the landscape scale is important for understanding ecological processes observed at large spatial scales. SOLARFLUX model (Rich et al. 1995) was intended to be highly flexible and allows for modeling the impact of topography on direct and diffuse solar radiation at different spatial scales: landscape, stand or small gap in a stand. The presented model and its recent implementations turned out to be useful in large-scale studies. It was used to create a model of air temperature variability on the surface of the Yellowstone National Park, which helped to identify the area of winter concentration of wild game (Huang et al. 2008; Huang, Fu 2009). In Alaska, it helped to analyse and model changes of top forest border (Stueve et al. 2011). Information on the impact of topography on the intensity of solar radiation also proved to be useful to explain trends in the changes of the forest species composition on dry mountain habitats (Harrod et al. 1998). Analyses were also carried out on a smaller spatial scale. On the basis of the numerical model describing the surface of canopies of loose juniper-pine stands, thermal conditions on the ground between the trees were modeled (Rich et al. 1993; Dubayah, Rich 1996). Rich et al. (1995) published figures showing the distribution of solar radiation within small circular gaps of a diameter of 20 m. This proves that this model is highly useful for the breeding studies. In the Polish forests, gap cuts are very popular; however, the knowledge of the variable light conditions within the gaps is not equally common. Easy to use models of light conditions on the open space, including side shielding, may be a tool for interpretation of the growth of regenerations in the gaps, and also a tool for designing an optimal shape of gaps for the selected species in a given location.



**Figure 1.** Results of modeling of light conditions on the opening in a stand made in the ARC GIS 10.1 environment: a) modeled viewshed in the middle of the gap, it is the virtual equivalent of hemispherical photography of the sky made in the middle of the gap; b) the spatial variability of global light availability within the gap; c) spatial variability of direct light availability; d) spatial variability of the diffuse light availability. Isolines at b), c), d) describe what percentage of the type of light that reaches the surface gets the certain gap area.

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