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Research article

Forest landscape shield models for assessing audio-visual disturbances of wind turbines

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ABSTRACT

Wind power is one of the fastest growing renewable energy sectors and plays a focal role in the transition to a fossil fuel free society in Europe. Technological developments have enabled the construction of turbines within forested areas, which has raised concerns regarding the audio-visual impact on these landscapes. However, there is a paucity of research with regard to the role that forests may play in mitigating the negative impacts of wind farms. In this study, we created a simplified model for noise attenuation based on the ISO 9613-2 and Nord2000 noise models and a visibility model which both relates the audio-visual effect to forest stand structure and applied them in the GIS environment. Our findings suggest that forests can act as effective noise barriers, with the sound attenuation level dependent on the distance that sound travels through the forest, as well as the size and density of the trees. However, in the case of a high elevation sound source (such as wind turbines), the forest begins to act as a noise shield from a distance of between 500 and 1500 m, depending on the height of the forest and the land topography. While current noise models do not consider the impact of tree species, our visibility model accounts for tree size, density and species, as well as understorey and thinning. Our results indicate that spruce trees provide a better visual constraint whereas visibility distances within mature *Calluna*-type pine forests tend to be more extensive. Both models include variables that can be adjusted by forest management, thereby allowing integration with forest planning software. Overall, this study presents indicative methods for the evaluation of potential forest landscape shields, a concept that could have broad applications, including Landscape Value Trading.

1. Introduction

Wind energy has emerged as one of the fastest growing green energy production sectors given its potential to combat climate change through the reduction in consumption of fossil fuels and the corresponding decrease in greenhouse gas emissions. The European Union (EU) has set ambitious targets for the expansion of renewable energy sources, with the Green Deal (Fetting, 2020) and the Renewable Energy Directive 2018/2001/EU (RED II, 2018) highlighting the importance of wind energy in achieving these goals. Finland has made a significant leap in the wind energy sector, with a notable increase in the number and size of installed wind turbines in recent years. In 2022, wind energy from 1400 turbines accounted for 14% of total energy production, whereas in 2014 the proportion was only 1% from 230 turbines (Finnish Wind Power Association, 2022). In addition to the increase in the number of installed turbines, the size of the turbines has grown; currently, the average hub height exceeds 140 m but was 80 m in 2010 (STT info, 2022). Technical advances in the construction of taller wind turbines have enabled their placement in forested areas. Forests reduce the wind speed and increase the turbulence in the air directly above the canopies, which had previously been an obstacle to profitable energy production (Sogachev et al., 2020). Mostly located in rural, sparsely populated regions, wind farms alter the landscape and require considerable infrastructure development, such as roads and cable connections, but generally impose few

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restrictions on forest management (Holttinen, 2021).

The main disturbances caused by wind turbines during operation are visual and audible, and affect both humans and wildlife (e.g., Knopper et al., 2014; Skarin et al., 2018; Teff-Seker et al., 2022), particularly the 200–300 m tall (hub + blade) wind turbines that are visible from long distances. Visibility also depends on the weather conditions and whether the turbine blades are in motion or not, with the effect beyond 30 km considered negligible (Bishop, 2002). Wind turbines produce both audible and infrasounds, which emanate from aerodynamic noise and noises from the electrical engines, gears, generator, and cooling system (Motiva, 2020). While studies have demonstrated no health-related effects from turbine noise (e.g., Knopper and Ollson, 2011; Radun et al., 2022), residents living nearby often report disturbances from noise, visual impacts, and flickering shadows (Havas and Colling, 2011). In recent years, technological advances in wind turbine design have reduced noise levels (Oerlemans, 2009; Bertagnolio et al., 2023), while noise immissions could be reduced by the establishment of extended distances between the turbines and residential buildings. The presence of a forest, which acts as noise attenuation barrier and as a landscape shield, can also lead to a reduction in the visual effects. Studies have shown that natural sounds, such as the sound of the wind in the tree canopy, can mask the noise from the wind turbines, lower detectability, and therefore reduce the annoyance level (Bolin et al., 2010, Etha Wind, 2020).

Environmental noise guidelines for the European Region (WHO, 2018) recommend an average exposure level for wind turbine noise of <45 dB L_{den} (dB = decibel, L_{den} = Day-evening-night energy equivalent level). In Finland, noise levels are regulated by State sound guideline values, with limits of 40 dB(A) at night and 45 dB(A) during the day for residential buildings (Finlex 3§ 1107/2015). The regulated minimum distance between wind turbines and residential buildings varies considerably between countries; from a few hundred meters to 3000 m (Dalla Longa et al., 2018). In Finland, however, the exact distance is not regulated but is based on noise modelling and estimated noise level limits. Typical sound pressure levels near turbine generators are comparable to live rock music (108–114 dB), while levels directly underneath a wind turbine are similar to a conversation in a restaurant (60 dB). For human ears, 20 dB is considered as silence and corresponds to a whisper or rustling of leaves (Etha Wind, 2020; IAC Acoustics, 2023). The evaluation of the noise level of a wind farm is carried out in the planning phase based on an upper noise limit that uses warranted level values provided by the turbine producers. In Finland, two noise calculation methods, ISO 9613-2 and Nord2000, are mainly used in noise level modelling with standard values employed for land absorption by hard or soft surfaces (Ympäristöhallinnon ohjeita, 2014). However, these noise modelling estimations do not take into account the attenuation effect of the forest, probably since the forest is dynamic and the structural changes that occur over time make noise attenuation difficult to implement in modelling programs.

The main factors that affect sound propagation outdoors are ground attenuation, atmospheric absorption, turbulence, and refraction, caused by wind and temperature gradients, aside from the Law of Spherical Spreading in which noise is reduced by 6 dB when the distance between the noise source and receiver is doubled (ISO 9613-2, 1996). Calculation of each of the factors differs slightly between the various noise models, as does the attenuation effect of the vegetation. Vegetation can reduce environmental noise levels although its impact varies between noise models (e.g., Fang and Ling, 2003; Tekeyhah et al., 2019; Zhao et al., 2021; de Oliveira et al., 2022). The ISO 9613-2 standard is a commonly used prediction method for outdoor noise levels (ISO 9613-2, 1996), but it has limitations with regard to wind turbine noise modelling, especially for high above ground (>30 m) noise sources and distances over 1 km (e.g., Evans and Cooper, 2012; Keith et al., 2016; Echeverri-Lodoño and González-Frenández, 2018). Nevertheless, the model is widely used by wind power developers as it provides a rapid estimate of noise levels, although attenuation by vegetation is not incorporated (Etha Wind, 2020; Nyborg et al., 2022). The ISO 9613-2 model can account for the noise attenuation provided by dense foliage, although it lacks specific parameters related to forest structure, which are difficult to incorporate into the noise model.

The Nordic noise prediction model, Nord2000, was developed by the Danish Environmental Protection Agency to model traffic noise levels and has been also used for wind turbines (Nord2000 model, 2000). The model also accounts for forest structure, such as tree density and stem diameter (Environmental Protection Agency, 2022) and offers good accuracy up to 1000 m and acceptable accuracy up to 3000 m (Kragh, 2000). The model includes a scattering part for noise attenuation by vegetation, which can reflect, refract and absorb sound energy. However, this part is typically not used in wind turbine noise modelling (Søndergaard et al., 2009; Nyborg et al., 2022). Coniferous tree species, especially spruce, are effective at noise attenuation (Dobson and Ryan, 2000) and Tarrero et al. (2008) found that the Nord2000 model was able to predict sound attenuation reasonably well at distances over 40 m in several forest types (the study was carried out at distances between 10 and 80 m).

In Finland, most wind farms are located in forested areas and require forest logging prior to construction. Each turbine requires around 4000 m^2 for installation, which must be completely cleared of trees, in addition to the area needed for road construction and electric grid connection (Holttinen, 2021). However, forest management activities around the wind turbines remain largely unrestricted. The visual impact of the wind turbines could be reduced by strategic location planning and by the preservation of forest stands near residences. Mäntymaa et al. (2021) noted that over 70% of the respondents in their study were interested in Landscape Value Trading for wind turbines, using forest stands as a landscape shield. A landscape shield could be located between wind turbines and residences and would block view of the turbines. Therefore, assessment of landscape shields is essential to define the type of forest structure that would best serve in terms of visibility and noise attenuation. This requires models that include forest stand structural variables that can be integrated into forest planning systems. By using a forest simulation optimization program, the effect of different forest management alternatives can be evaluated, and the management objectives can include noise reduction and/or visibility.

In a GIS environment, viewshed analysis is conducted using a digital elevation model (DEM) to determine areas or objects that remain unobstructed by topographical features. The analysis primarily focuses on the identification of unobstructed areas or objects, with no consideration given to distinguishing or recognizing specific features. Viewshed analysis also has a long heritage in landscape architecture (Tandy, 1967; Amidon and Elsner, 1968; Lynch, 1976) and has applications in psychological, cognitive, and perceptual studies. The effect of forest operations on viewsheds and visibility could be integrated into GIS-based forest planning. Visual accessibility, as defined by Ode (2003), incorporates open areas, topography, and the extent of visibility. Fang and Ling (2003) also employed visibility as an independent variable in their noise reduction model, although visibility in their case was measured as the distance at which an object became completely non-visible, and thus lacked gradient information.

Our study aims to develop a simplified model to incorporate the impact of forest stand structure on visibility along with noise attenuation modelling as current noise models are too complex and require several physical-related parameters. The main objective here is to create a simplified model that can be easily integrated into forest planning systems. Evaluation of the potential of a forest stand to act as a landscape shield is based on visibility model assessment. The development of models to evaluate the auditory and visual disturbances associated with wind turbines could help reduce the disturbance effects in forest-dominated landscapes. The integration of these models into forest management and planning system offers the possibility to evaluate different management alternatives and the possible costs related to the preservation of a forest stand as a landscape shield. The development of these models, which could be integrated into the forest planning system to evaluate auditory and visual disturbances, could help to reduce the negative effect of the wind turbines. The specific objectives are as follows:

1) Create a simplified model to evaluate the noise level generated by wind turbines located in a forested landscape.
2) Create a visibility model to assess the potentiality of a forest stand to act as a landscape shield.
3) Estimate the impact of forest stand structure on both noise attenuation and visibility.

2. Material and methods

2.1. Study area

The study area was located at Honkajoki (22.296220°E, 61.963800°N) in the Satakunta region of southern Finland. The topography of the region is characterized by relatively low elevations, which range from 95 to 122 m a.s.l. At present, two wind farms are operational in the area and a third farm is currently at the planning stage (Finnish Wind Power Association, 2021). The land use in the vicinity of the wind farm consists of forest lands, peat extraction areas, natural peatlands, and industrial sites for biogas production, as well as areas dedicated to garden and greenhouse cultivation. The focal area of the study includes one of the present wind farms, which consists of nine turbines, each with a total height of 200 m above ground.

2.2. Data

Data on existing and planned wind farms were retrieved from the Finnish Wind Power Association (2021). The location of individual wind turbines was collected from the National Land Survey database of Maastotietokanta 1:5000 (NLS, 2021) and the total height of each turbine (tower plus blade) was collected from the online map of the Finnish Wind Power Association (2021). A digital elevation model (DEM) with a 2 × 2 m resolution was obtained from the Finnish National Land Survey (DEM, 2021). Forest stand data (private forest owners) were retrieved from Metsäkeskus (2021).

2.3. Noise calculation

The noise attenuation effect of the forest stands was calculated based on two methods, i.e., the ISO 9613-2 and Nord2000 models. We only considered the present forest attenuation effect. Atmospheric conditions were considered as constant in both methods, and sound spreading was assumed to be spherical, which means that the sound waves uniformly propagate away from a point source (wind turbine) in all directions. The spatial calculation was performed using ArcGis 10.5 program. The input level of the noise calculations was 104.5 dB L_{WA}, which is the A-weighted sound power level produced by a single wind turbine in the wind farm (YVA, 2014). The input sound power levels per octave band frequencies in Hertz are shown in Table 1. The input levels were used as raster values, separately for each frequency, which resulted in six raster layers per wind turbine. This was used as the base level from which the attenuation factors were reduced to achieve the final sound pressure levels.

Table 1
Input values for the sound pressure level calculation as a function of nominal octave band center frequency level (Hz) (ISO 9613-2).

Nominal octave band center frequency	63	125	250	500	1000	2000
Input sound power level (dB)	83	90	94.8	96.4	99.3	98.2
Propagation through dense canopy						
Propagation distance df (m)	Attenuation (dB/m)					
10 ≤ df ≤ 20	0	0	1	1	1	1
20 ≤ df ≤ 200	0.02	0.03	0.04	0.05	0.06	0.08
Attenuation due to atmospheric absorption						
Attenuation (dB/km)	0.11	0.38	1.12	2.36	4.08	8.80
Ground reflection effect						
Attenuation (dB)	−3	2.5	0.7	−1.4	−1.4	−1.4

2.3.1. ISO 9613-2 – stand height-based estimation

For the calculation of the attenuation effect with the ISO 9613-2 model, we first identified the forest canopies where noise was attenuated. This was achieved by adding the mean height of the forest stands to the DEM to produce a digital surface model (DSM) with a 2 × 2 m resolution. Using the visibility tool, wind turbines were considered visible with a total turbine height of 200 m above ground and a calculated distance of 3 km around the turbines. Once the forest canopy areas of noise attenuation were defined (i.e., the propagation distance), raster cells were assigned a value for each frequency level according to Table 1. Noise attenuation is defined as the reduction in dB level per meter when sound passes through the tree canopy. Cumulative attenuation by propagation distance was estimated using the cost distance tool, which covers a 360° radius around each turbine. Attenuation due to atmospheric absorption was calculated at an air moisture content of 70% and air temperature of 15 °C as per the recommendations of the Finnish Environmental Agency (Ympäristöhallinnon ohjeita, 2014). Noise attenuation was calculated per frequency band using ISO 9613-2 standard values for atmospheric absorption (dB/km) and ground reflection as a constant value (values shown in Table 1).

Physical noise effects were calculated for each of the six frequency levels as a reduction from the input sound power level. The final noise level per cell was then determined using Equation (1). In the GIS environment, the raster calculator was employed to compute the final sound pressure level by summing up the frequencies according to:

$$L_{pA,tot} = 10\lg\left(\sum 10^{\frac{L_i}{10}}\right) \tag{Eq. 1}$$

where $L_{pA,tot}$ is the total sound pressure level in decibels (dB), and L_i are the calculated frequency band levels for 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1 kHz and 2000 kHz.

Geometrical divergence refers to the spherical spreading in the free field from a point source, whereby noise attenuation can be calculated following the ISO 9613-2 standard according to:

$$Adiv = \left[20\lg\left(\frac{d}{d_0}\right) + 11\right] \tag{Eq. 2}$$

where $Adiv$ is the attenuation due to geometrical divergence (dB), d is the distance (m) from the source to receiver, and d_0 is the reference distance (1 m). In the GIS environment, the geometrical divergence calculation was performed by applying the Euclidian distance function to the wind turbines, the creation of a continuous 2 × 2 m cell size raster layer, and the implementation of Equation (2) in the raster calculator to determine the sound pressure level for each raster cell. Geometrical divergence was then reduced from the $L_{pA,tot}$ level of the wind turbine. The calculation steps were repeated separately for each of the nine wind turbines. Finally, the sound pressure level for the whole wind farm area was calculated by merging the nine raster layers into a single layer and summing the decibel level from several sound sources as described in Equation (1), where L_i is now the sound pressure level of a single turbine.

2.3.2. Nord2000 – tree size and stand density-based estimations

The role of the forest in noise attenuation was assessed theoretically using the Nord2000 model, which considers tree density and mean tree diameter (see Supplementary material for detailed formulas and calculation methods). The effect of forest structure was calculated at distances of 60, 100, 300, 500, 1000, 1500 and 2000 m, for tree diameters of 10, 15, 20, 25 and 30 cm, and for tree densities of 50, 100, 200, 300, 400, 600, 800 and 1000 trees/ha. The starting input noise level was the same (104.5 dB) as in the ISO 9613-2 model and the sound pressure frequency starting levels were identical (Table 1). The absorption coefficient α (set at 0.2) for forests was obtained from the Scattering Zone Attenuation Table $\Delta L(h', \alpha, r')$ (Supplementary material), and the final sound pressure levels were calculated using Equation (1).

In the Nord2000 model calculation, tree stem diameter and density in the theoretical study forest were converted to a variable commonly used in forest planning, namely the basal area (m^2/ha). Once the noise levels were calculated for the theoretical forest, a regression model was developed using basal area and distance. Analyses were carried out with R (version 4.1.3. R Core Team, 2022). Sound pressure level calculation, without the forest attenuation effect, were performed following ISO 9613-2 guidelines and by incorporation of the values shown in Table 1, alongside the geometrical divergence (Equation (2)) for 2 × 2 m rasters. This process was done separately for each of the turbines and the final sound pressure level was calculated according to Equation (1). The effect of the forest on sound attenuation was calculated using the forest stand data (Metsäkeskus, 2021). The attenuation effect was calculated for each stand using the constructed model, where the width of the forest stand was used as a distance variable.

2.4. Forest stand visibility

Forest stand visibility was assessed using the SmartForest-software (Orlando, 1994) and a regression model (Fig. 1). SmartForest can visualize forest stands based on following data; stand density, mean diameter, mean height and tree species. For the visualization model forests were created for coniferous forests >8 m in height. The model forest used theoretically simulated pine, spruce, and mixed forest stands with young to old forest structures (Koivisto, 1959). Based on data presented in Koivisto (1959), 110 stands were generated, which included 50 pine stands, 36 spruce, and 24 mixed pine/spruce; 18 stands contained understorey vegetation. A Weibull function determined tree diameter (0–50 cm) distribution for both pine (*Pinus sylvestris*) (parameters from Mykkänen, 1986) and spruce (*Picea abies*) forests (parameters from Kilkki et al., 1989) and six size strata of basal area were used. The number of stems were further calculated using mean diameter and the basal area proportion of the stratum. Mean height by species were calculated using the Näslund height curve with the estimation method described in Siipilehto (1999). Modelled forests included natural forests with no harvesting, harvested stands, and some stands with natural regeneration. The mixed stands were generated as two forms: (i) 2/3 pine and 1/3 spruce proportional to basal area, and (ii) 2/3 pine and 1/3 spruce, respectively. Stand characteristics were defined according to the main species (Koivisto, 1959). The different stages of visibility model development in a forest stand are presented in more detail in Riippi (2005).

The SmartForest program was used to generate simulated views for 110 model forests, each encompassing ten views at 20 m horizontal intervals ranging from 20 m up to 200 m. These simulated views were estimated at 3 m height above ground, with 31° vertical and 90° horizontal view angles, which were deemed to represent human vision (Fig. 2). Thereafter, view pictures were interpreted using the Jasc PaintShopPro program. Visibility in this study refers to the degree of tree cover that obstructs the view compared to no obstruction. The toggle histogram tool was utilized to estimate the proportion of trees covering the background. Finally, based on the data obtained from model forests the least squares linear regression models was fitted to predict the proportion of trees that covers the background thus defining the visibility range.

Visibility in relation to the distance from the stand edge was calculated for a theoretical forest based on Equation (3). The forest stand visibility model included seven variables obtained from the Metsäkeskus (2021) stand database. The visibility model is as follows:

$$Visibility = 100\left(sin\left(\left(\sum_{i=1}^{n}(k_iM_i)+c\right)*\frac{\pi}{180}\right)\right)^2 \quad \text{(Eq. 3)}$$

where *Visibility* is the percentage of tree cover in the background, *n* is the number of parameters, k_i is a parameter, M_i are the explanatory variables and *c* is a constant (Table 2). The goodness of fit value (R^2) for the model was 0.8779. Distance (m) refers to distance from the edge of the forest stand to the inner parts of the stand from which the natural logarithm was taken for the model input. The proportion of spruce trees was calculated from the basal area (m^2/ha), understorey denotes the number of small trees, thinning is the binary variable in the model (0 = no thinning, 1 = thinning) and the presence of Calluna forest type (Ct) is a binary variable (0 = other forest type, 1 = Ct). The visibility model was validated with testing data consisting of photos taken within actual forest stands. The methods described were followed though the results from real forest photos showed some bias in relation to small tree cover values but were a better predicter when tree cover values were >60%.

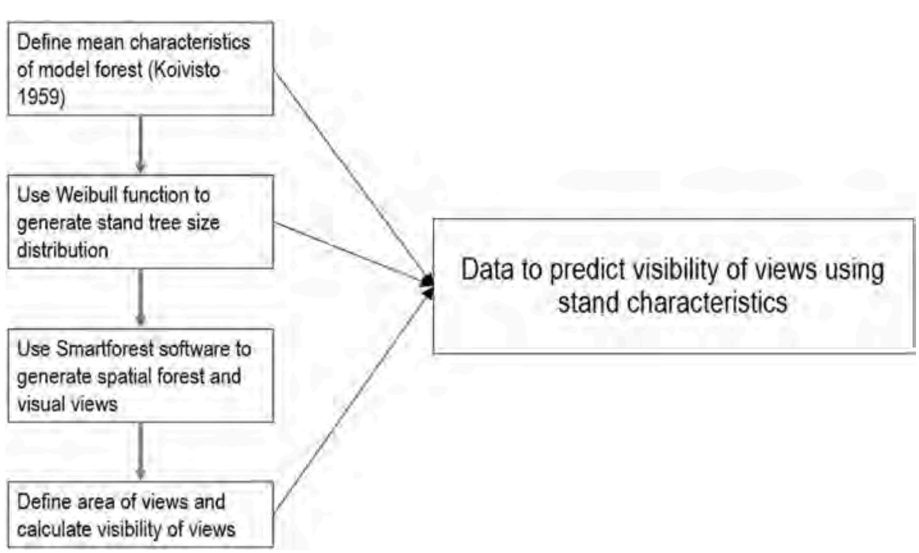

Fig. 1. Concept for generating data for modelling forest stand visibility.

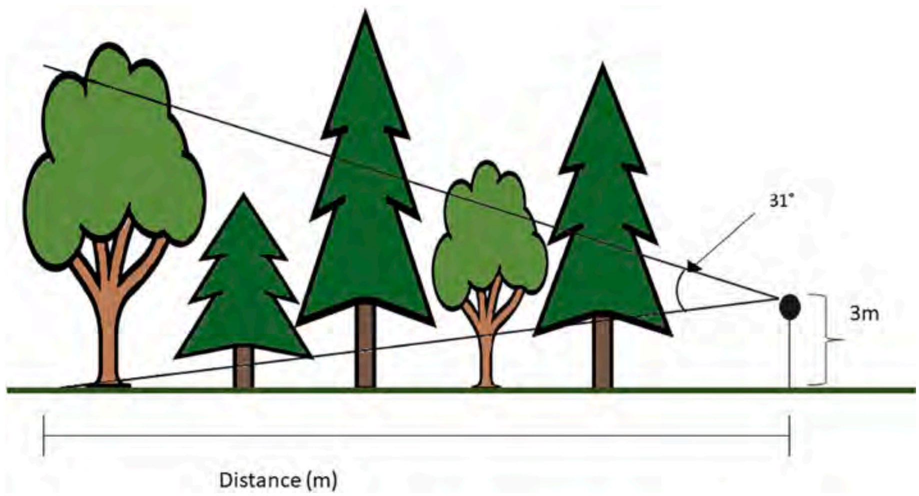

Fig. 2. Scheme of the view limit. Horizontal distance ranged between 20 and 200 m.

Table 2
Parameter estimates for the forest stand visibility model (Equation (3)).

Variable	Estimate	SE	*p* - value
constant	5.33	2.5	0.034
lnDistance (m)	18.16	0.52	<0.0001
basal area (m^2/ha)	1.15	0.046	<0.0001
dbh (cm)	−2.12	0.045	<0.0001
share of spruce (%)	0.05	0.007	<0.0001
understory	0.007	0.002	<0.0001
thinning[a]	5.36	1	<0.0001
Ct (Calluna forest type)	−6.54	1.27	<0.0001

[a] Management with repeated thinning.

3. Results

3.1. Spatial modelling of the forest for noise attenuation

Noise reduction was found to be dependent on basal area, with up to 11 dB reduction observed in some cases (Fig. 3). The level of reduction was greater when the distance for the sound to travel through was longer. A forest with a basal area of 40 m^2/ha reduced noise levels by < 2 dB at a distance of 60 m, and by > 9 dB at 300 m. Maximum reduction levels could be reached in stands with >15 m^2/ha basal area at distances between 1500 and 2000 m. However, at shorter distances (e.g., 500 m), the stand structure needed to be more dense, at around a basal area of

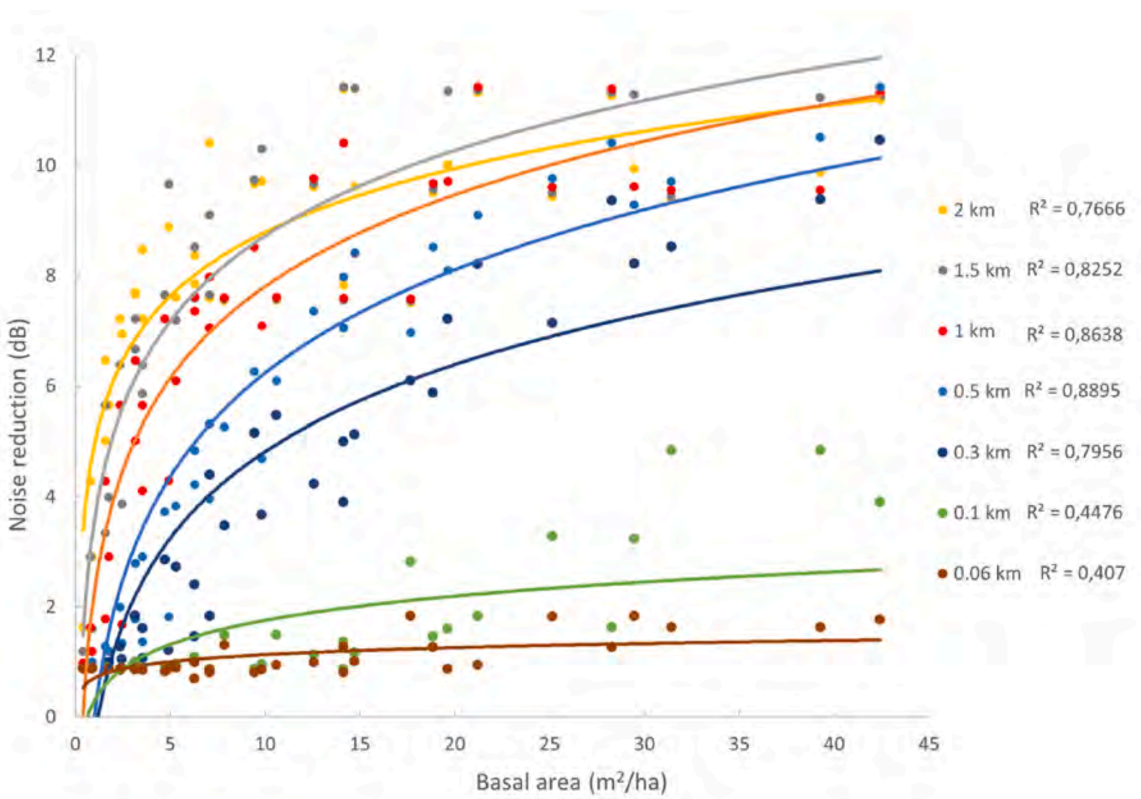

Fig. 3. Noise attenuation effect as a function of basal area and distance (points), according to the Nord2000 model (calculated using Eq. (4)). Logarithm trendlines and goodness of fit (R^2) values are shown.

40 m^2/ha. We used a linear regression model (Eq. (4)) to estimate noise attenuation based on basal area, and the results were mapped using ISO 9613-2 principles, accounting for stand effects (Fig. 4).

The model was as follows:

$$\ln(noise) = 4.8202389 - 0.0256747 * \ln(ba) - 0.0277844 * \ln(distance) + \varepsilon \quad \text{(Eq. 4)}$$

where *noise* (dB) is the noise attenuation effect, *ba* (m^2/ha) is the basal area and *distance* (m) is the horizontal path of the sound through the forest. The model had a bias of 1.28×10^{-14}, a root mean square error (RMSE) value of 1.07 and a R^2 value of 0.87.

Both ISO 9613-2 and Nord2000 noise attenuation models predicted greater noise levels further from the turbines in the north-eastern and south-eastern sectors where there were fewer forests and where the area was mainly composed of treeless peat extraction sites. Noise levels reduced more rapidly in the more forested southern and north-western directions (Fig. 4). In both models, the presence of a forest had an

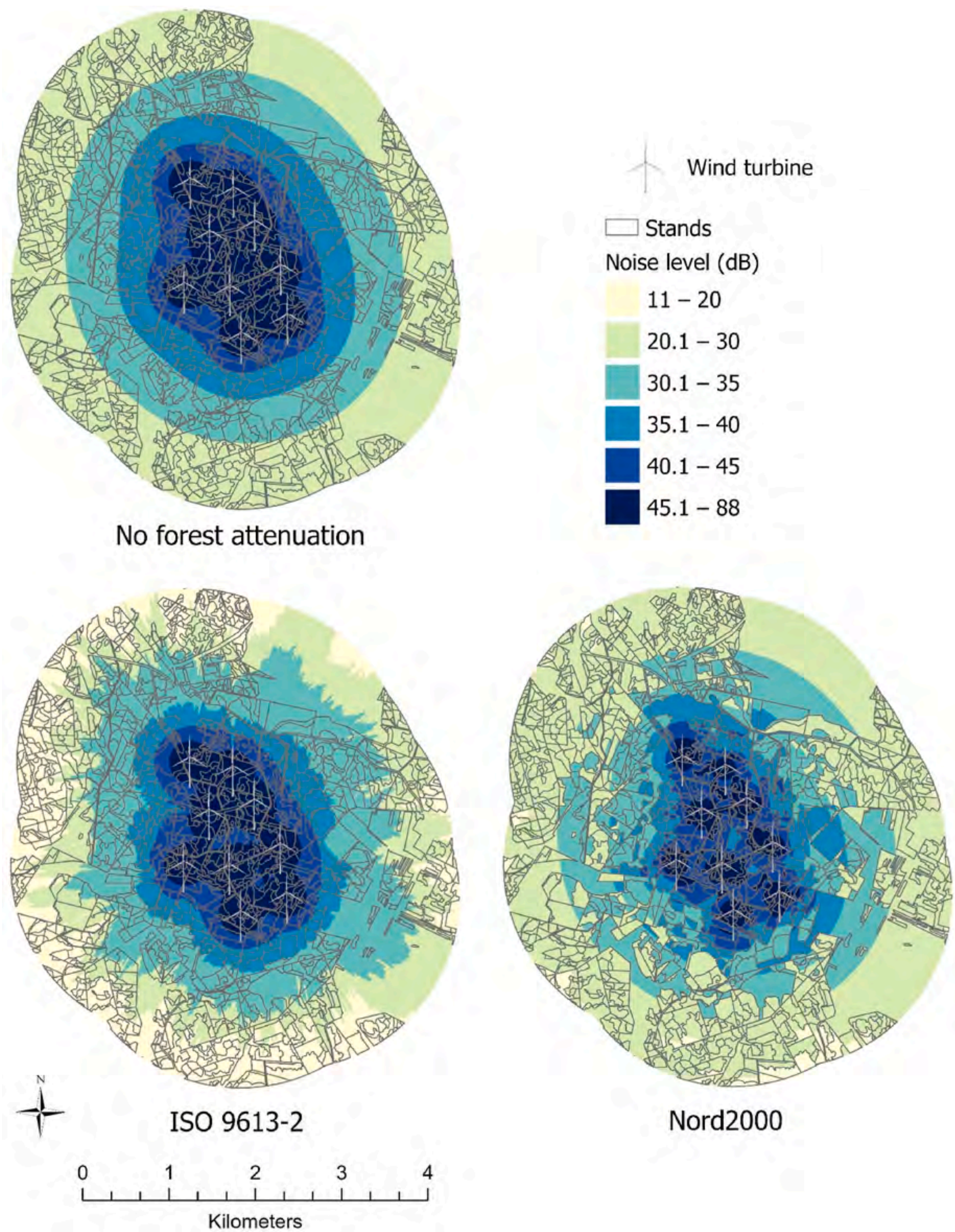

Fig. 4. Example of noise levels without forest attenuation and the forest effect on noise attenuation using the ISO 9613-2 and Nord2000 models.

effect on noise reduction, although there were differences between the models. In ISO 9613-2, the sound travelled through the canopy regardless of the effect of the stand structure but was affected by the height of the canopy, thereby implying that more mature forests are likely to have larger canopy areas for noise attenuation. In contrast, Nord2000 accounted for forest structure, which also suggests that a mature forest can reduce noise levels more effectively. For Nord2000 (Fig. 4), the attenuation effect was calculated for each stand as it is a management unit in forestry and the results showed a slightly greater attenuation effect closer to the wind turbines compared to ISO 9613-2 model.

3.2. Effect of stand structure on visibility

The effect of stand structure on visibility is presented as the distance from the stand edge (m) for four different stand basal areas (G = m^2/ha) and tree diameters (cm) in a forest stand without spruce trees, and understory or thinning (Fig. 5, result from Eq. (3) and parameters from Table 2). Visibility does not grow linearly, as the presence of more trees is likely to result in the obscuration of other trees. Our model was used to calculate the visibility within three forest stands in the study area. An example of stand visibility was calculated for forest stands that were located between a house and a wind turbine (Fig. 6). These stands acted as a landscape shield by blocking the view to the wind turbine. The visibility value in the map indicated the proportion of trees (%) that blocked the view. In practice, values > 91% essentially indicate that the background of the trees is non-visible.

The impact of forest structure on visibility was influenced by tree size and density. In particular, smaller trees, with a diameter at breast height (dbh) of 10 cm, were found to be more effective at reducing visibility at a height of 3 m due to their lower canopies. However, as trees grow and canopies rise, visibility range might increase depending on the species composition of the forest stand. The presence of an understorey layer also contributed to reduced visibility.

4. Discussion

Forest management planning software can generate alternative management schemes by modelling the various decision-making factors. However, noise and visibility within a forest are rarely integrated into planning systems. Such information can be of benefit during the application process for forestry and environmental permits. The incorporation of this information into the models would enable the planning of a "virtual forest" shield, which would ensure that a sufficient number of large trees are retained between the wind farm and inhabited areas to reduce audio-visual disturbances. These models can be utilized to estimate the extent to which forest structure impacts noise reduction and visibility, as well as how the different forest management alternatives influence these factors.

In general, wind energy is perceived as a green solution and an environment-friendly alternative to fossil fuel energy production. However, the negative impacts of wind farms related to noise and visual aspects have not received much attention. On the other hand, there are several studies related to the displacement, avoidance or collision of birds and other wildlife (Tolvanen et al., 2023). In many European countries, wind turbines are mainly located offshore or near agricultural areas, and less often in forested areas (Bunzel et al., 2019; Nitsch et al., 2019). In Finland, the majority of new wind turbines will be located in forested areas. However, studies related to the role of the forest in noise attenuation (e.g., Kellomäki et al., 1976; Tarrero et al., 2008) and as a visual barrier (Haapakangas et al., 2020) are scarce, with even less related to wind turbines (Wondollek, 2009). The primary challenge is the elevated location of the sound source, which makes it difficult to define the sound path from source to receiver. Moreover, the forest

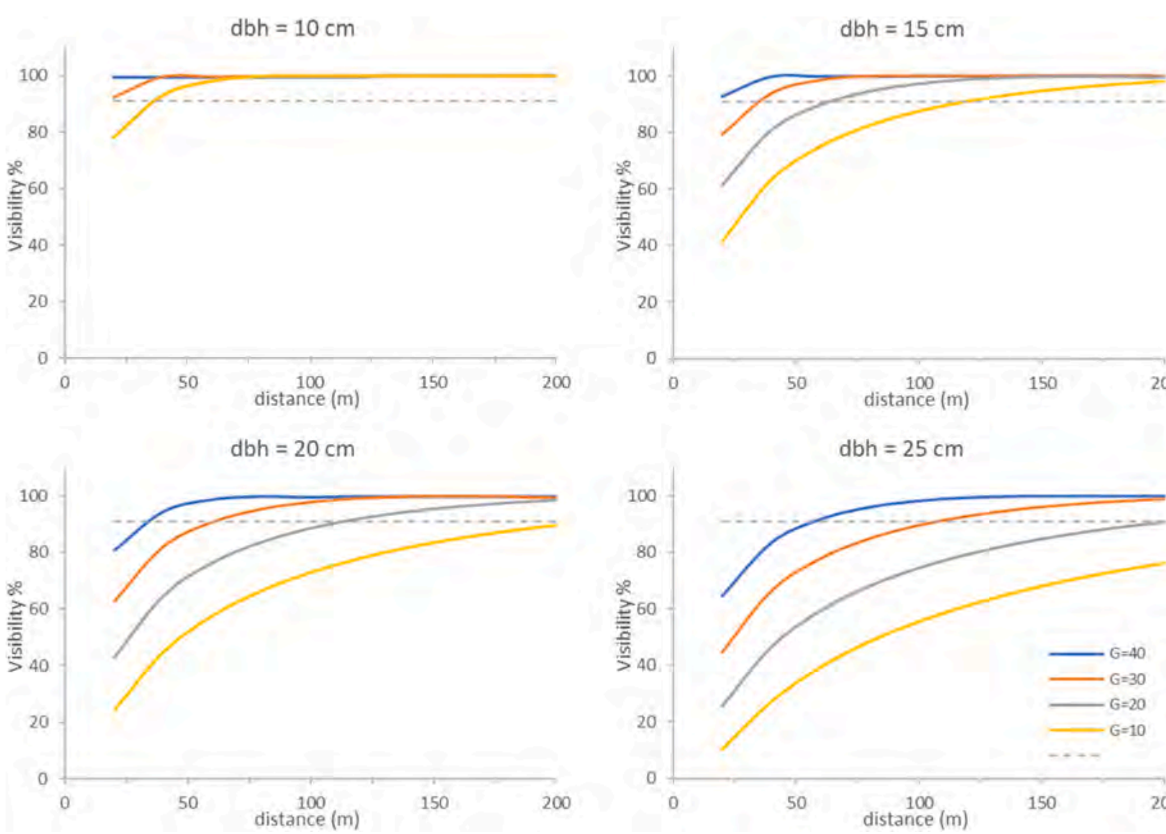

Fig. 5. Effect of stand structure on visibility distance as a function of stand basal area (G = m^2/ha) and mean tree diameter at breast height (dbh) (grey dashed line represents the 91% visibility limit).

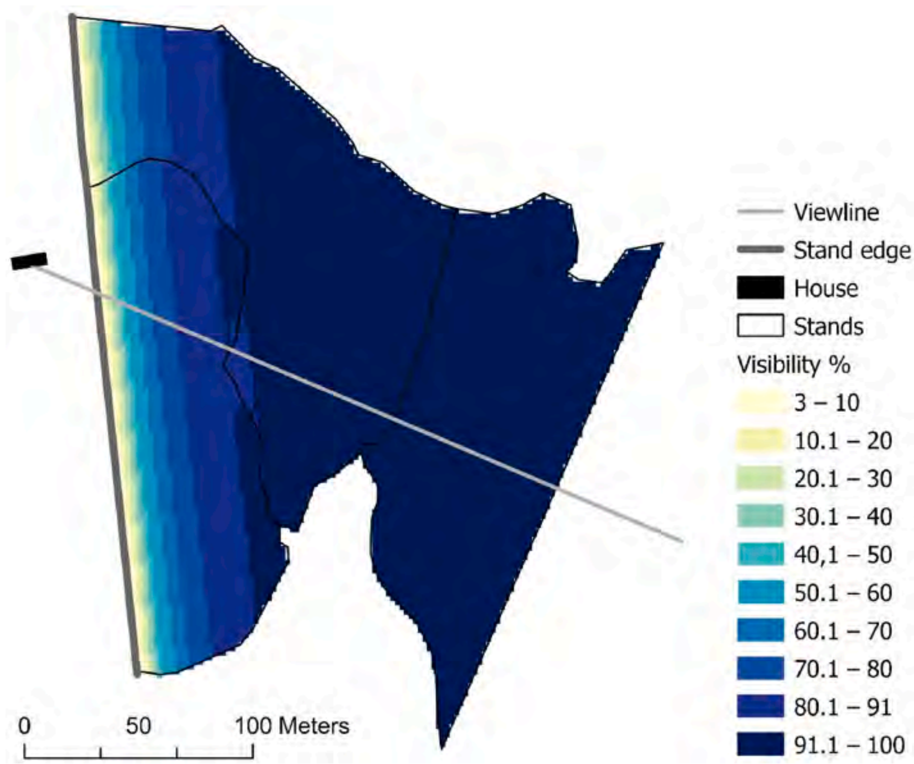

Fig. 6. Example of forest stand visibility view. Values between 91 and 100% indicate that the forest stand acts as a full visual obstruction.

structure is dynamic and changes considerably over time due to natural growth and forest management and is, therefore, complicated to integrate into noise modelling software. It is worth noting that the noise calculations currently conducted during the planning stage of wind farms do not account for the attenuation effect of the forest. In addition, the validation status of the forest-related effect of the Nord2000 model remains unclear (Wondollek, 2009). Although Tarrero et al. (2008) used the model with different forest types, the measurement distances were only recorded for distances <80 m. Likewise, ISO 9613-2 has not been validated for a source height >30 m or at distances >1000 m (Wondollek, 2009). This would indicate that more detailed research is required on this topic.

Noise calculation models are typically complex and require specialized programs. Therefore, we developed a simplified model in this study for integration into forest simulation programs. However, the model is based on certain turbine sound level (104.5 dB L_{WA}) which would require recalculation according to the formulas presented if the sound level differs. Factors, such as atmospheric conditions and wind direction, were held constant in this study, and adhered to the guidelines of the Finnish Environmental Agency (Ympäristöhallinnon ohjeita, 2014). Both noise attenuation models (ISO 9613-2 and Nord2000) are commonly used in wind turbine noise modelling. According to our results, the sound pressure level around the wind turbines decreases rapidly and reaches 45 dB level, on average, at a distance of 300 m, and 40 dB at around 500 m, without considering the attenuation effect of forests. The spatial arrangement of turbines within the wind farm also affects the attenuation distance as several turbines located near each other can increase the sound pressure level. Our results demonstrate that forests can provide up to 10 dB of additional attenuation, consistent with previous research (White and Swearingen, 2004). However, it is essential to consider the extent of forests along the path of the sound waves, especially when the point source is high above the ground. In the case of wind turbines, the greater the hub height, the less effective the forests are as a feasible noise buffer. For a 200 m high turbine, a forest located at a distance of between 1 and 1.5 km could serve as a noise buffer, and forest attenuation could be up to 8 dB. It is worth noting that a forest adjacent to the turbine can also provide some level of attenuation through its effect on ground impedance (Attenborough, et al., 2011).

Forests can contribute to further noise level reductions through multiple mechanisms. Firstly, as sound passes through the forest, it is attenuated due to the acoustic properties of trees (Swearing and White, 2007). Secondly, the forest ground acts as an impedance, causing the sound waves that pass over it to lose energy (White and Swearingen, 2004). Thirdly, forests can indirectly reduce noise annoyance by providing other "natural" sounds, such as rustling leaves and singing birds, which can mask or distract from the noise of a wind turbine. Indeed, a study conducted by Bolin et al. (2010) demonstrated that ambient sounds can decrease the perceived noise of wind turbines by up to 5 dB. Fourthly, any additional attenuation effect of the forests may vary considerably depending on the season — greater in summer than winter due to leaves on the trees (Van Renterghem et al., 2021).

According to our results noise attenuation and visibility are controlled by stand density (basal area) and mean diameter, which enables analysis of forest structure effects. Spruce stands are optimal for noise attenuation, as well as visibility, due to their evergreen structure and canopy shape. However, a limitation exists in both the Nord2000 and ISO 9613-2 models, as neither consider tree species. The ISO 9613-2 model only considers the distance that the noise travels thought the canopy, while the Nord2000 model incorporates tree density and tree diameter, which enables integration into forest planning. Nonetheless, these noise models still do not consider tree species or composition effects, such as the wider canopy and increased branches of spruce trees, which can reduce both noise and visibility. Several studies have demonstrated that vegetation can reduce noise levels and that certain species are better noise barriers than others (Kellomäki et al., 1976; Tekeyhah et al., 2019; Yang et al., 2010; Van Renterghem et al., 2021). Moreover, the density and structural arrangement of forests have been shown to be effective in reducing noise levels (Swearing and White, 2007). Young forests dominated by pine and spruce species perform better in noise reduction compared to mature forests (Kellomäki et al., 1976). In young forests, the canopy is more dense, lower and covers the tree stems, whereas in mature forests, the proportion of bare stems is greater, which can actually increase noise levels as sound waves reflect from hard surfaces (Kellomäki et al., 1976). Mixed stands that contain coniferous and deciduous trees with a scrub understory layer have been found to be most effective for noise attenuation (e.g., Fang and Ling, 2003; Samara and Tsitsoni, 2007).

Visibility is affected by the lower limit of the tree canopy and the crown ratio. In a spruce stand, the crown ratio is affected by thinning intensity, where more intense thinning increases the proportion of the crown (Äijälä et al., 2019). Visibility estimations, suitable for assessing landscape shield efficacy, are conducted for short distances, while in practice, the management target would be one or a few stands in a defined location. This requires an initial assessment of the viewer and the object, as well as the view lines between them, to locate appropriate stands. The visibility model can be used to assess the effectiveness of the forest landscape shield for determining how it could be managed, how wide the shield should be in order to works, as well as to estimate the cost of preserving the structure which maximizes the benefit.

Environmental noises can cause disturbance, especially when they originate from technical sources (WHO, 2018), and annoyance is often emphasised together with visual contact (Yu et al., 2017; Schäffer et al., 2019). However, the perception of noise can be reduced by vegetation (Van Renterghem, 2019). Improvements to the noise model could involve incorporation of a wind directivity factor, as sound has been shown to travel for longer distances downwind (Hannah, 2006). Furthermore, the development of more accurate noise models, which take into account tree species, would be beneficial. Defining forest stands that can be utilized as landscape shields and evaluating the management alternatives that consider the visibility and noise reduction of these stands could help mitigate the detrimental effects of wind turbines. This would involve planning where to harvest the trees and determining the appropriate quantity of trees retained to maintain the shield. In addition, noise and visibility models have potential application beyond this study. They can be employed in the planning of forest management operations near recreational trails or industrial sites to minimize the negative impact of noise and/or visibility. These models could be used to assess the feasibility of voluntary landscape value trading as proposed by Mäntymaa et al. (2021), wherein the forest stand acts as a shield or "fence" between the viewer and the wind turbine or any other disturbing views.

This study presents indicative methods for the evaluation of a forest landscape shield to assess audio-visual disturbances, which could have several potential applications. There is a need for research on sound propagation in forested areas and the development of enhanced models, as suggested by Wondellek (2009), although only a limited number of studies have been conducted to date. We aim to fill this knowledge gap by investigating noise and visibility models which considers forest structural variables making it possible to integrate them into forest planning and environmental impacts assessments.

CRediT authorship contribution statement

Mari Selkimäki: Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Juha Riippi:** Formal analysis, Methodology, Writing – review & editing. **Parvez Rana:** Conceptualization, Funding acquisition, Writing – review & editing. **Lasse Lamula:** Formal analysis, Methodology, Writing – review & editing. **Marko Antila:** Formal analysis, Methodology, Writing – review & editing. **Tero Heinonen:** Formal analysis, Writing – review & editing. **Timo Tokola:** Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data used is from open source databases, sources are referenced.

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Appendix A. Supplementary data

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