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# Effectiveness of clear-cuttings in non-fragmented pine forests in relation with EU regulations for the eradication of the pine wood nematode

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## Abstract

1. The invasive pine wood nematode (PWN), *Bursaphelenchus xylophilus*, is one of the most serious threats to pine forests across the world. Detected in Europe in 1999, it has largely spread despite containment measures.
2. Following the European Union regulations, the requested eradication measure is to fell, remove and dispose of all susceptible plants within a clear-cut zone (CCZ) of a radius of 500 m around any infected tree. This measure is controversial since its effectiveness is questioned.
3. An individual-based model, describing the dispersal of the nematode vector and the nematode transmission, was used to estimate the relationship between the radius and the effectiveness of the CCZ at eradicating the PWN.
4. Clear-cutting of a 500 m-radius is poorly effective in non-fragmented pine forests since it reduces the number of PWN transmissions by only 0.6 % - 11.5 %. To significantly reduce the number of transmissions, the radius should be between 14 and 38 km, which is obviously not technically nor ethically feasible.
5. *Policy implications*. Our results, based on model simulations at a fine spatial scale, prove that clear-cutting susceptible trees 500 m around any infested tree – as requested by EU regulation to eradicate the pine wood nematode – is not effective in large and continuous pine forests. Instead, strengthened surveillance and sanitation felling could be explored.



## Résumé

1. Le nématode du pin (PWN), *Bursaphelenchus xylophilus*, est l'une des plus importantes espèces invasives menaçant les forêts de pins dans le monde. Après avoir été détecté en Europe en 1999, il s'est rapidement propagé au Portugal puis en Espagne, malgré les mesures mises en place pour le contenir.
2. Selon la réglementation de l'Union Européenne, la mesure relative à l'éradication consiste à abattre, retirer et éliminer tous les végétaux sensibles dans une zone de coupe à blanc (CCZ) d'un rayon de 500 m autour de tout arbre infecté par le PWN. Cette mesure est controversée car son efficacité est incertaine.
3. Un modèle individu-centré, décrivant la dispersion de l'insecte vecteur ainsi que la transmission du PWN, a été utilisé pour estimer la relation entre le rayon de la coupe à blanc et son efficacité à éradiquer le PWN.

4. Une coupe à blanc d'un rayon de 500 m est très peu efficace dans une forêt de pins non fragmentée car elle ne peut réduire le nombre de transmissions du PWN que de 0.6% à 11.5 %. Pour réduire de manière significative ce nombre de transmissions, le rayon devrait être de 14 à 38 km, ce qui n'est de façon évidente pas envisageable d'un point de vue technique ou éthique.
5. *Implications politiques*. Nos résultats, issus de simulations conduites à une échelle spatiale fine, prouvent que la coupe des végétaux sensibles dans un rayon de 500 m autour de tout arbre infecté – comme demandée par la réglementation de l'Union Européenne pour éradiquer le nématode du pin – n'est pas efficace dans les grandes forêts de pins non fragmentées. À la place, le renforcement de la surveillance et des coupes sanitaires ciblées devraient être envisagé.

## Keywords

Biological invasion; *Bursaphelenchus xylophilus*; clear-cut; dispersal; emergency plan; eradication; Europe; *Monochamus galloprovincialis*

Journal of Applied Ecology. 2020, 57(3), https://doi.org/10.1111/1365-2664.13564



# INTRODUCTION

The pine wood nematode (PWN), *Bursaphelenchus xylophilus* (Steiner & Buhrer, 1934) Nickle 1970, is one of the most serious threats to pine forests across the world as it can kill a tree within a few weeks (Webster, & Mota, 2008). Native to North America, it has then spread to Japan, China, Korea, Portugal, and Spain (Zhao et al., 2008; Robertson et al., 2011). The PWN requires an insect vector to disperse and be transmitted from one susceptible tree to another. The vector is a cerambycid beetle from the *Monochamus* genus. In Europe, *M. galloprovincialis* is the only known species to carry the PWN (Sousa et al., 2002). Besides, the PWN can spread at long distance with the transportation of infected wood products. In Portugal, the PWN has locally spread at 5.3 km/year on average (De la Fuente et al., 2018) but it can propagate further through human-assisted dispersal (on average at 150 km; Robinet et al. 2011).

The detection and eradication of infected trees is complex because of a latency period between nematode inoculation and apparition of wilting symptoms. Consequently, infected trees could be asymptomatic during a given period (Futai, 2003). To prevent the spread of the PWN in Europe, the EU regulation (Implementing Decision 2012/535/EU) requires the Member States to implement emergency measures. They consist of annual surveys for PWN detection, an eradication measure to eliminate the nematode where it is present, and a containment measure to prevent a further spread of the nematode where it cannot be eradicated. The requested eradication measure is to fell, remove and dispose of all susceptible trees within an area, called clear-cut zone (CCZ), of a minimum radius of 500 m (that may be reduced to 100 m subject to derogations) around any PWN-infected tree. This measure is controversial because it is expensive, difficult to implement in dense forests, and its effectiveness is questioned. Indeed, removing host trees within a radius below 30 km could not stop the spread in Portugal (De la Fuente et al., 2018). Assessing the relationship between the size and the effectiveness of CCZ at the landscape scale based on the latest knowledge about the flight capability and behavior of the insect vector is therefore a crucial step to improve the PWN management.

The effectiveness of clear-cuttings depends not only on the dispersal capacities of the insect vector, but also on the purpose of their application (Jactel et al., 2015). These clear-cuttings could be done:

- to prevent the dispersal of infected vectors the following year in case that some of them remain after the removal of the infected pines (scenario 1, "preventive action"; Fig. 1a), or

Journal of Applied Ecology. 2020, 57(3), https://doi.org/10.1111/1365-2664.13564


- to eliminate host trees potentially infected in the same year (scenario 2, "curative action"; Fig. 1b).

In both cases, we assume that the detection is done at the end or after the vector flight season, and clear-cuttings are done before the flight of the following generation (before the following spring) as imposed by the EU.

In scenario 1, we distinguish two sub-cases: the clear-cut zone has no effect on the dispersal behavior (scenario 1-1, "strategy of non-avoidance of the CCZ"; Fig. 2a) or the beetle tends to exit the CCZ and not enter it again (scenario 1-2, "strategy of avoidance of the CCZ"; Fig. 2b) because *Monochamus* beetles are known to be attracted by visual and chemical cues emitted by host pines (Giffard et al., 2017). In scenario 2, because the clear-cutting occurs after the beetles have dispersed, CCZ cannot affect the past dispersal behavior of the insect vector. In all the cases, we assume that all the products resulting from the clear-cuttings (e.g., stems and branches) are removed or chipped.

In this study, we tested the effect of CCZ radius on the effectiveness of eradication under the three above-mentioned scenarios. For this purpose, we modified a process-based model that describes the dispersal of *M. galloprovincialis* at a fine scale (Robinet et al., 2019) to include the transmission of PWN to healthy trees. We simulated both dispersal and transmission processes in a non-fragmented pine forest, and applied theoretical clear-cuts of various radii to estimate the resulting proportion of PWN transmissions avoided.

## MATERIALS AND METHODS

### *Vector dispersal*

We simulated the flight dispersal of the vector along its adult life span (120 days) using the individual-based model developed by Robinet et al. (2019). The dispersal distance was randomly chosen according to a negative exponential kernel. Then, the flight direction was set up to depend on beetle's behavior and the scenario considered (Fig. 2; see Appendix S1 in Supporting Information). In scenarios 1-1 and 1-2, if the repeated flights did not allow escaping the CCZ, we counted the number of days the beetle would remain inside the CCZ. We assumed that beetles would die there after 12 days (parameter *s* in Table 1) as they cannot survive such a long starvation period (Sánchez-Husillos et al., 2013).

Journal of Applied Ecology. 2020, 57(3), https://doi.org/10.1111/1365-2664.13564


We assumed that pine forest landscape was not fragmented (e.g., pines were present everywhere, except in the CCZ).

***PWN transmission***

At each stop between two successive flights, we assumed that infected beetles could potentially transmit the PWN while feeding on fresh pine shoots of healthy trees. The insect vector tends to transmit nematodes very frequently 1-6 weeks after its emergence, transmissions then decrease rapidly, reaching nearly 0 from the $9^{th}$-$12^{th}$ week (Naves et al., 2007a). In our simulations, we considered that transmission is possible only on days 1-77 (with a gap from day 64 to 70) to cope with the experimental results of Naves et al. (2007a). PWN transmission can also be done, to a lesser extent, when females lay eggs on decaying trees (Naves et al. 2007b). The first egg can be deposited 20 days after insect emergence and oviposition can last about 30-44 days (Naves et al. 2006), with a probability of 0.37 to transmit the nematode at this occasion (Naves et al. 2007b). In the simulations, we assumed that 50% of individuals were females, which could lay eggs from day 20 to day 53 (i.e., for 34 days). For each day of egg-laying, we chose at random whether the PWN was transmitted by the female, following a binomial law Bin ($p$=0.37).

***Effectiveness of clear-cutting***

We supposed that 100 infected beetles were initially present, able to disperse and transmit PWN. We tested the effects of clear-cutting trees on the PWN transmission for a CCZ with a radius varying from 0 to 40,000 m with an increment of 500 m and we additionally tested 100 m. Since the individual-based model is stochastic, 100 replications were done for each scenario and each radius value. The number of dispersing beetles is arbitrary in this study, but in reality it depends on local vector abundance. Additional simulations have shown that considering 100 beetles provide a representative outcome (see Appendix S2). In case that the number of beetles is lower (e.g., 10), unless conducting a higher number of replicates, stochasticity will increase and results will be more variable.

To determine the effectiveness of clear-cutting, we calculated the number of PWN transmissions outside the CCZ (number of times the beetles stopped and inoculated nematodes). Then, we calculated the relative number of transmissions, which was defined as the number of transmissions obtained for a given CCZ radius divided by the number of transmissions without CCZ (radius of 0 m). We considered a CCZ successful at eradicating PWN when the relative number of transmissions was below 0.001

Journal of Applied Ecology. 2020, 57(3), https://doi.org/10.1111/1365-2664.13564


(0.1%). We estimated the size of CCZ radius allowing to reach this threshold value, and its confidence interval (at 99%) using the 100 replicates (Fig. 3). Simulations and calculations were done in R (R Core Team, 2015; Robinet & Jactel, 2019) and the list of parameters is given in Table 1.

## RESULTS

The CCZ radius (and confidence interval, CI) required to obtain a relative value of nematode transmission of 0.001 (0.1%) was of (Fig. 4; see Robinet & Jactel 2019 for videos of the simulations):

- 14 km (CI = 14 – 15.5 km) in scenario 1-1 (preventive action; no CCZ avoidance),
- 17.5 km (CI = 16.5 – 19 km) in scenario 1-2 (preventive action; CCZ avoidance),
- 38 km (CI = 36.5 – 39.5 km) in scenario 2 (curative action).

Consequently, to reduce significantly the number of PWN transmissions outside the CCZ, clear-cutting should cover from ca. 60,000 to 450,000 ha, according to the scenarios. A radius of only 500 m would reduce the number of transmissions outside the CCZ by only 0.6 % in scenario 2, 9.4% in scenario 1-2 and 11.5 % in scenario 1-1.

# DISCUSSION

### Effectiveness of clear-cuttings

This study shows that the eradication measure requesting to cut, remove and dispose of all susceptible host trees within a radius of 500 m from infected trees is not effective to eradicate a PWN infection spot in non-fragmented pine forests. Clear-cuttings over larger radii (14 – 38 km) would be necessary but obviously not practically and ethically feasible. This result is in agreement with De la Fuente et al. (2018) who estimated that a clear-cutting wider than 30 km was necessary to stop PWN spread. They fit their model on the observed spread at the scale of Portugal, but this spread was not only the result of the vector dispersal but also of possible human-assisted dispersal via wood transport, and obviously, of the effects of control measures. Our study refines the estimate as we actually describe the dispersal mechanism at a finer spatial scale, taking into account the dispersal capacity of the vector at immature and mature stages, and its ability to transmit nematodes over time. Despite differences in both methods, they provide very similar results and the conclusion is strengthened.

Journal of Applied Ecology. 2020, 57(3), https://doi.org/10.1111/1365-2664.13564


**Important factors to consider**

Our study points out that the objective of the eradication method is important. To prevent further dispersal of insect vectors (scenario 1), effectiveness of clear-cuttings is roughly the same whatever the insect behavior is (i.e., avoiding or not to fly through the CCZ). However, if some asymptomatic pines were not detected (scenario 2), the CCZ may not be correctly centered on the insect vector source. In the worst case, the detected pine could be on the periphery on the infected area, and to remove all infected pines, the radius should be twice as large as the radius of a CCZ centered on the source. It is thus consistent that the recommended radius in scenario 2 is approximately twice the radius in scenario 1 (38 km *versus* 2 x 17.5=35 km).

This modelling study also shows that two important processes should be considered: 1) PWN transmission and 2) insect flight capability and behavior.

1) Regarding the PWN transmission process, many questions remained unanswered. It is unclear which PWN-load is carried and transmitted by the insect vector along its life span, what are the effects of PWN-load on insect flight capability and behavior, and which concentration of PWN is needed for a pine to show wilt symptoms. This study provides a solid baseline to test the effectiveness of clear-cuttings in various configurations as soon as these processes are better understood.

2) Regarding insect flight activity, there are still gaps in this knowledge as well, even if the insect dispersal has been thoroughly studied in the last years (David et al., 2014; Torres-Vila et al., 2015). Etxebeste et al. (2016) performed mark-and-recapture experiments in continuous vs. fragmented pine forests and found that insects could disperse far further in fragmented landscapes (up to 5,300 m vs. 720 m). However, habitat fragmentation could instead increase the success of eradication, as has been shown with gypsy moth (Barron et al., 2019). Therefore, we need further data and model development to describe the dispersal behavior of *M. galloprovincialis* adults in heterogeneous landscapes. Since clear-cuttings are poorly effective in non-fragmented pine forests, other eradication approaches should thus be investigated. Favoring the vector mortality by bird predation (De la Fuente & Beck, 2019) or mass-trapping (Jactel et al. 2015, 2019) would have insufficient effect to successfully control the nematode. Hereafter, we discuss more promising alternative methods.

**Alternative methods**

Journal of Applied Ecology. 2020, 57(3), https://doi.org/10.1111/1365-2664.13564



Labor and financial costs saved if clear-cuttings were not implemented could be reallocated to a more intense surveillance of insect vectors and pine trees to detect the presence of PWN. Firstly, a higher number of traps could be installed in areas at risk and the insects caught in the traps could be checked for the absence of PWN with DNA methods. Secondly, host trees could be more extensively surveyed by visual detection from the ground and/or with remote sensing techniques (e.g., Unmanned Aerial Vehicles or satellite images) with a special effort in areas at risk (e.g., in decaying pine forests, logging sites, wood-processing yards…). Indeed, early detection has proved to be the best approach to increase the probability to eradicate invasive species rather than to eradicate them when already largely established (Liebhold et al., 2016).

Once the PWN is detected in a forest stand, sanitation felling of symptomatic trees (Waring and O'Hara, 2005) could be applied. With this method, contrary to the clear-cutting, only decaying trees will be removed, one by one, so as to slow the development of the epidemics. This method is currently being tested in Portugal. Field surveillance and lab work (to confirm the presence of the PWN) would be more demanding, but it is the counterpart for safeguarding uninfected trees. In Korea, small clear-cuttings (radius of 10-50 m) appeared effective when combined with preventive nematicide-injection in the surrounding pine forests (Kwon et al., 2011).

For trees with high heritage value (e.g., urban trees) or for trees located close to risk areas (e.g., ports and sawmills), the solution could be to inject nematicide into the trunk (e.g., emamectin benzoate ; Sousa et al., 2013) or to use biological control agents such as the fungus *Esteya vermicola*, a method currently being tested with some success (Chang, pers. comm.). However, their implementation requires tedious tree by tree manual operations, which have to be repeated regularly, and this may result in phytotoxicity (e.g. by emamectin benzoate, Kuroda & Kenmochi, 2016).

## CONCLUSIONS

This study clearly demonstrates that the method of clear-cutting over radii of a few hundred meters is not relevant to eradicate the invasive PWN, at least in large non-fragmented pine forests. By quantifying the relationship between radius and effectiveness of clear-cut zones, we provide support to the new recommendations of the EPPO standard (EPPO 2018), reducing the clear-cut radius to a minimum (e.g., 50 – 100 m) and re-enforcing the surveillance efforts.

## AUTHORS' CONTRIBUTIONS

Journal of Applied Ecology. 2020, 57(3), https://doi.org/10.1111/1365-2664.13564

All authors conceived the idea in a working group, corrected and approved the article. CR made the modelling part and wrote the article. CR and HJ interacted to design relevant simulations. All authors gave final approval for publication.

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## DATA Availability statement

R script available via zenodo at https://doi.org/10.5281/zenodo.3387267 (Robinet & Jactel, 2019).

Journal of Applied Ecology. 2020, 57(3), https://doi.org/10.1111/1365-2664.13564



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# TABLES

**Table 1.** Parameters used in the model to simulate dispersal (see Robinet et al. 2019 for details) and the effects of the clear-cut zone.

| Parameter | Definition | Values |
|---|---|---|
| $\alpha$ | Mean daily dispersal distance (in meters) | 2000 |
| $\delta$ | Delay response time (in days) | 0 |
| $\beta$ | Rest between two flights (in days) | 1 |
| *n* | Number of beetles released | 100 |
| *l* | Adult longevity (in days since adult emergence) | 120 |
| *m* | Maturation age (in days since adult emergence) | 20 |
| $p_{fm}$ | Daily probability of flying for mature beetles | 0.61 |
| $p_{fi}$ | Daily probability of flying for immature beetles | 0.45 |
| *s* | Number of days a beetle can stay without feeding | 12 |
| *R* | Radius of the clear-cut zone (in meters) | 0 – 40000 |

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# FIGURE LEGENDS

**Figure 1:** Illustration of the two objectives of clear-cutting for pine wood nematode eradication. (a) In scenario 1, the clear-cut is done preventively to avoid the dispersal of remaining infected insects to neighbouring host trees. (b) In scenario 2, the clear-cut is done to remove overlooked, asymptomatic trees.

**Figure 2:** Illustration of the effects of the clear-cut zone (CCZ) on the dispersal behaviour of insect vectors in scenario 1. In scenario 1-1, *Monochamus galloprovincialis* beetles do not avoid the CCZ (a), while they try to exit the CCZ and not enter it again in scenario 1-2 (b). The authorised angles when flying are represented in grey area, *R* indicates the CCZ radius (*R*) and *r* the dispersal distance.

**Figure 3:** Calculation of the confidence interval for the recommended radius. The relative number of transmissions of the PWN decreases with the clear-cut zone (CCZ) radius. C2 gives the radius to reduce the number of PWN transmission by 99.9% on average and [C1, C3] gives the confidence interval of the CCZ radius to ensure that the number of PWN number is reduced by 99.9% at the 99% confidence level.

**Figure 4:** Effectiveness of the clear-cutting according to scenario 1-1 (preventive action and avoidance strategy), scenario 1-2 (preventive action and non-avoidance strategy), and scenario 2 (curative action) with increasing radius of the clear-cut zone (CCZ). The mean and 99% confidence interval of the relative number of transmission outside the CCZ are represented for the three scenarios (note that the confidence interval is almost not visible for scenarios 1-1 and 1-2 because very narrow). The vertical dotted grey line indicates the radius of 500 m requested by the European Union regulation.

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**Figure 1.**

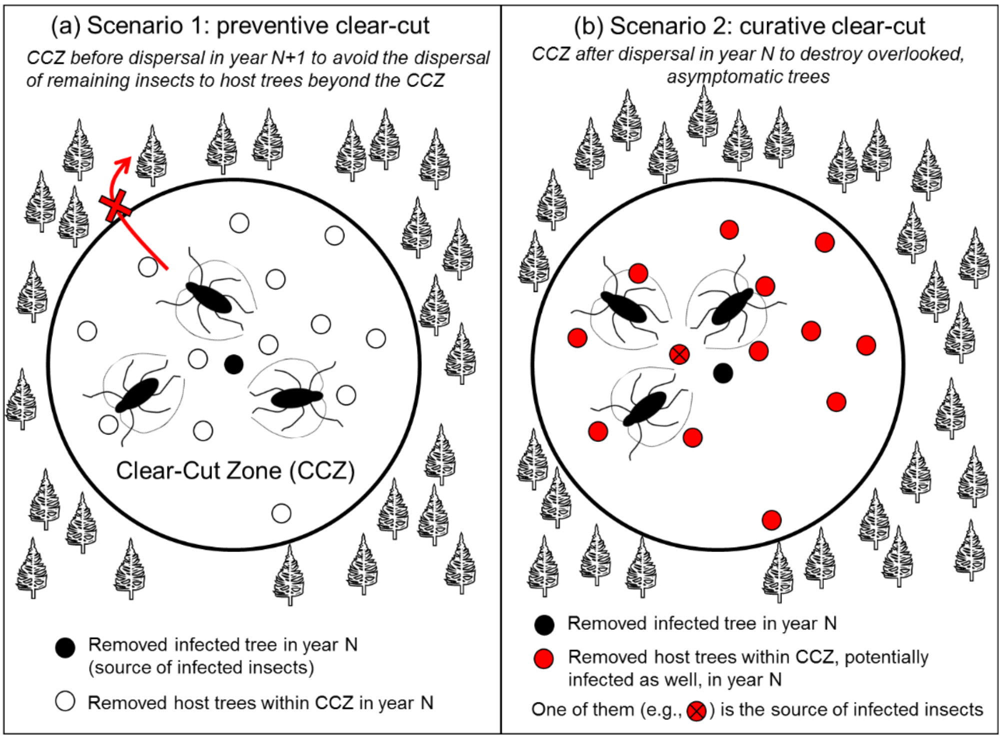


**Figure 2.**

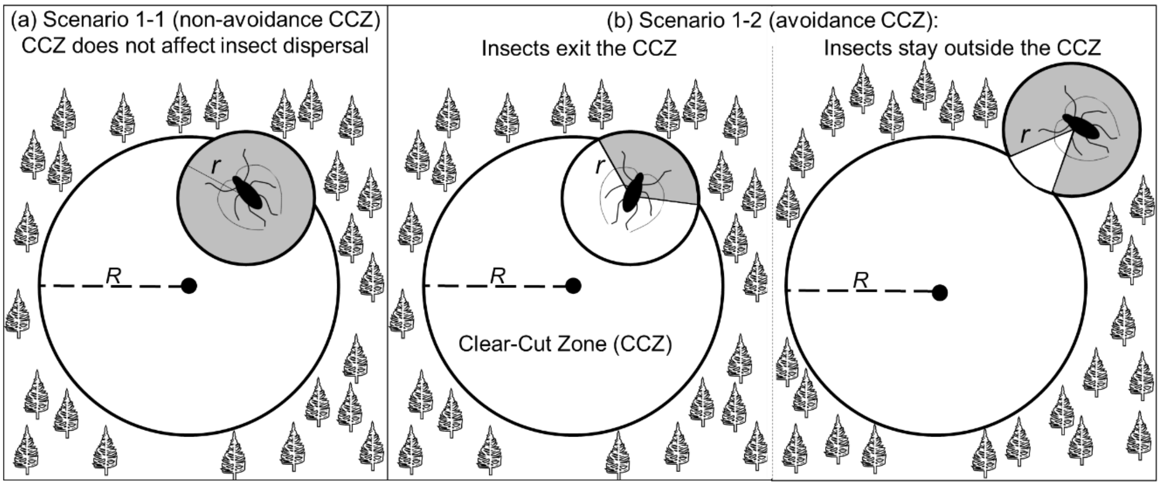

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**Figure 3.**

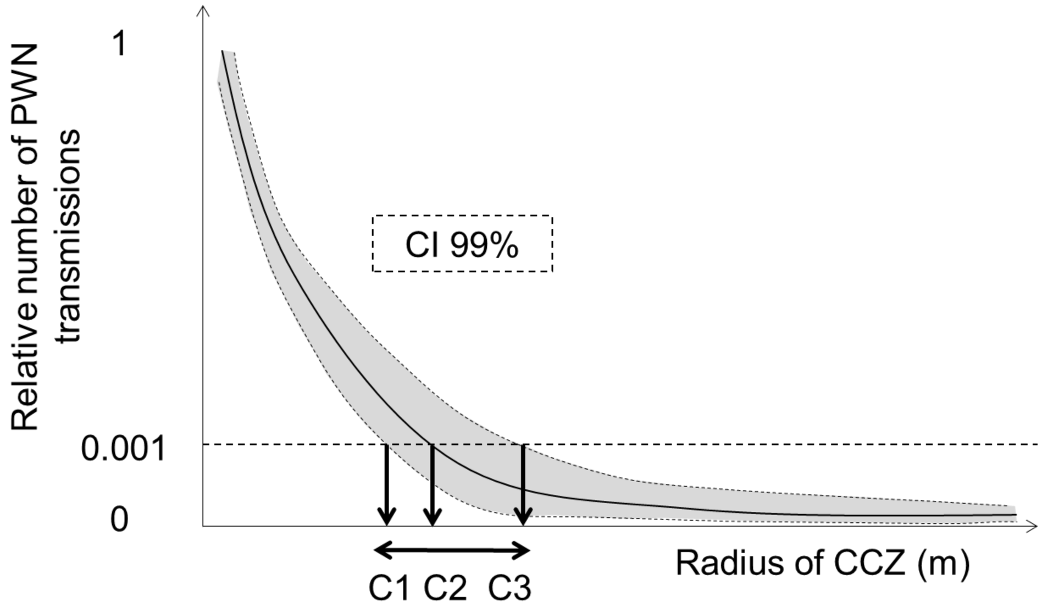


**Figure 4.**