Applying cost-distance analysis for forest disease risk mapping: Phytophthora austrocedrae *as an example*

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Applying cost-distance analysis for forest disease risk mapping: *Phytophthora austrocedrae* as an example

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Abstract Cost-distance model analyzes the relative difficulty in reaching each spot of the landscape for the object or species under study. It calculates the effective distance, which is the Euclidian distance modified by the friction to movement through different landscape elements. This work deals with the application of cost-distance analysis in forest pathology, considering *Austrocedrus chilensis* root rot caused by *Phytophthora austrocedrae* as an example. In this case, cost-distance analysis was used to determine the relative difficulty for the pathogen to reach healthy forest patches from the patches that are presently diseased. Friction values were assigned on the basis of abiotic conditions, biological characteristics of the pathogen and host presence. Since cattle may be a vehicle for *Phytophthora* dispersion, three hypothetical situations of ranching were considered. Cost-distance application resulted useful to define minimum risk areas for conservation purposes. In the study case, minimum risk area strongly varied in response to cattle presence. This study provided valuable information for *A. chilensis* disease management and showed one of the broad applications of cost-distance analysis in forestry.

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Introduction

The habitat suitability modeling can be used to generate risk maps of forest diseases, an important tool for developing forest management criteria (Meentemeyer et al. 2004; Van Staden et al. 2004; Venette and Cohen 2006). Environmental heterogeneity can influence various stages of pathogen invasion process: dispersal, colonization, and population growth (Hastings et al. 2005). Several studies on the pathogen's spread combined information of environment and pathogen biology (Jules et al. 2002; Meentemeyer et al. 2008a; Ferrari and Lookingbill 2009; Smolik et al. 2010).

Cost surface maps may be useful tools for identifying disease risk caused by an invasive pathogen. Even though this tool has been scarcely used to predict disease spread, its importance lies in the consideration of connectivity. Landscape connectivity, defined as "the degree to which the landscape facilitates or impedes movement of organisms among source patches" (Taylor et al. 1993), was shown to be a key factor in determining the spatial pattern of forest disease (Ellis et al. 2010; Jules et al. 2002).

Cost-distance analysis is an approach with a broad potential application in forestry. This analysis has been widely applied in economic studies, transport planning and urban planning, and even in logging planning and wood chip transportation (Moller and Nielsen 2007). Models based on least cost analysis have also been applied in biodiversity conservation, as a tool for sustainable ecosystem management (Adriaensen et al. 2003; Poulsom et al. 2005; Walker et al. 2007; González López 2008).

Cost-distance analysis calculates effective distance which is Euclidian distance modified by the resistance (i.e., friction) to movement through different landscape elements. Thus, effective cost has two components, landscape structure and biological behavior of the organism under study. Friction values are assigned according to the surface facilitating or hindering effect on the movement process, and its meaning varies depending on each case: It may be measured in terms of travel time or fuel expended, and it represents the cost in money; or it may be measured in ecological terms with habitat suitability values for movement across an heterogeneous land mosaic. The cost-distance surface shows the relative difficulty/ease in reaching each spot of the territory for the object or species under study. In the case of a forest disease caused by a pathogen, the cost-distance surface shows the relative difficulty for the pathogen in reaching healthy patches from the patches that are presently diseased, and where the inoculum is present. The friction values are assigned on the basis of abiotic factors that facilitate/hinders the pathogen movement. This work deals with the use of cost-distance analysis as a tool for developing a risk model for *Phytophthora austrocedrae*, a pathogen that attacks *Austrocedrus chilensis* forests in Patagonia.

Phytophthora austrocedrae is a soil pathogen that causes mortality of *Austrocedrus chilensis* (D. Don) Pic. Ser. & Bizzarri (cypress), which is its unique known host. *A. chilensis* is a native species endemic to the Patagonian Andes forests of southern Argentina and Chile that grows in pure forest or mixed with *Nothofagus* spp. or *Araucaria araucana (Molina) K. Koch*. *A. chilensis* is an important economic and ecological resource for the cordillera region. Besides, it is a foundation species (Ellison et al. 2005) because, being dominant or co-dominant, it defines forest structure, microclimate, and dynamics. As in the case of other foundation species, cypress mortality may have great ecological effects, altering forest structure and functionality, microclimate, and ecosystem processes (Ellison et al. 2005; Loo 2009).

Phytophthora austrocedrae kills the roots and grows upwards along the bole, killing cambium, phloem, and, partially, the xylem. It causes necrotic red-brown lesions in the phloem that can extend more than 1 m above ground. This species is the etiological agent of *A. chilensis* root rot, which has been also called "Mal del ciprés", a disease that was first reported in Patagonia in 1948, and is now widespread in the *A. chilensis* forests of Argentina. Its present wide distribution is not surprising since, assuming the first report of the disease coincides with the introduction of the pathogen, it has been spreading for more than 70 years without any control. Similar fast and wide spreading has been observed in other non-indigenous *Phytophthora* species in forest ecosystems (Hansen 1999; Rizzo et al. 2002; Weste and Marks 1987; Meentemeyer et al. 2008b; Hansen et al. 2000).

Austrocedrus chilensis root rot is clearly associated with site conditions, particularly high soil moisture and poor drainage (Baccalá et al. 1998; La Manna and Rajchenberg 2004a, b) at both microsite and landscape scales (La Manna et al. 2008). Recent studies suggest a relationship between disease spatial pattern and land use (La Manna et al. 2012). One of the most important impacts on *A. chilensis* forests is cattle (Veblen et al. 1995), and it is known that soilborne *Phytophthora* species can be spread by soil clinging to the cattle feet (Hansen et al. 2000).

Other *Phytophthora* caused forest diseases show that it is very difficult to control efficiently the pathogen dispersion. Implementing control measures in large areas has economic and practical restrictions. This evidences the importance of concentrating efforts in those areas where possibilities of success are the greatest. Risk models and cost-distance analysis are very useful tools regarding this aim.

The objective of this work was to identify *A. chilensis* forest patches (stands) having minimum risk of infection by *P. austrocedrae*, in response to the abiotic conditions, pathogen biological behavior, and present distribution of the affected forests, under hypothetical scenarios of ranching. This purpose was achieved by applying cost-distance analysis.

Materials and methods

Study area

The study was carried out in "16 de Octubre" Valley, in Chubut Province, Argentina, where the disease is widely distributed (Fig. 1). This valley includes protected areas (Los Alerces National Park) as well as farms and lands under forestry and ranching. There are no reliable data about when and where the disease started. However, personal communications with local inhabitants suggest that it might have begun in the 1960s. Cypress distribution was mapped in this Valley (Carabelli 2004), as well as the distribution of symptomatic forests, showing that 24 % of the area is affected (La Manna et al. 2008). This map, which is based in SPOT PAN and XS images with a resolution of 10 m, covers an area of 30 × 30 km. The present study was focused in 3,185 ha of cypress forests which were intensely checked. The map includes affected patches equal or larger than 400 m^2.

Stands included were visited in order to diagnose the cause of mortality. In all the visited stands, the symptomatology corresponding to the affection by *P. austrocedrae* (Greslebin and Hansen 2010) was observed, and its

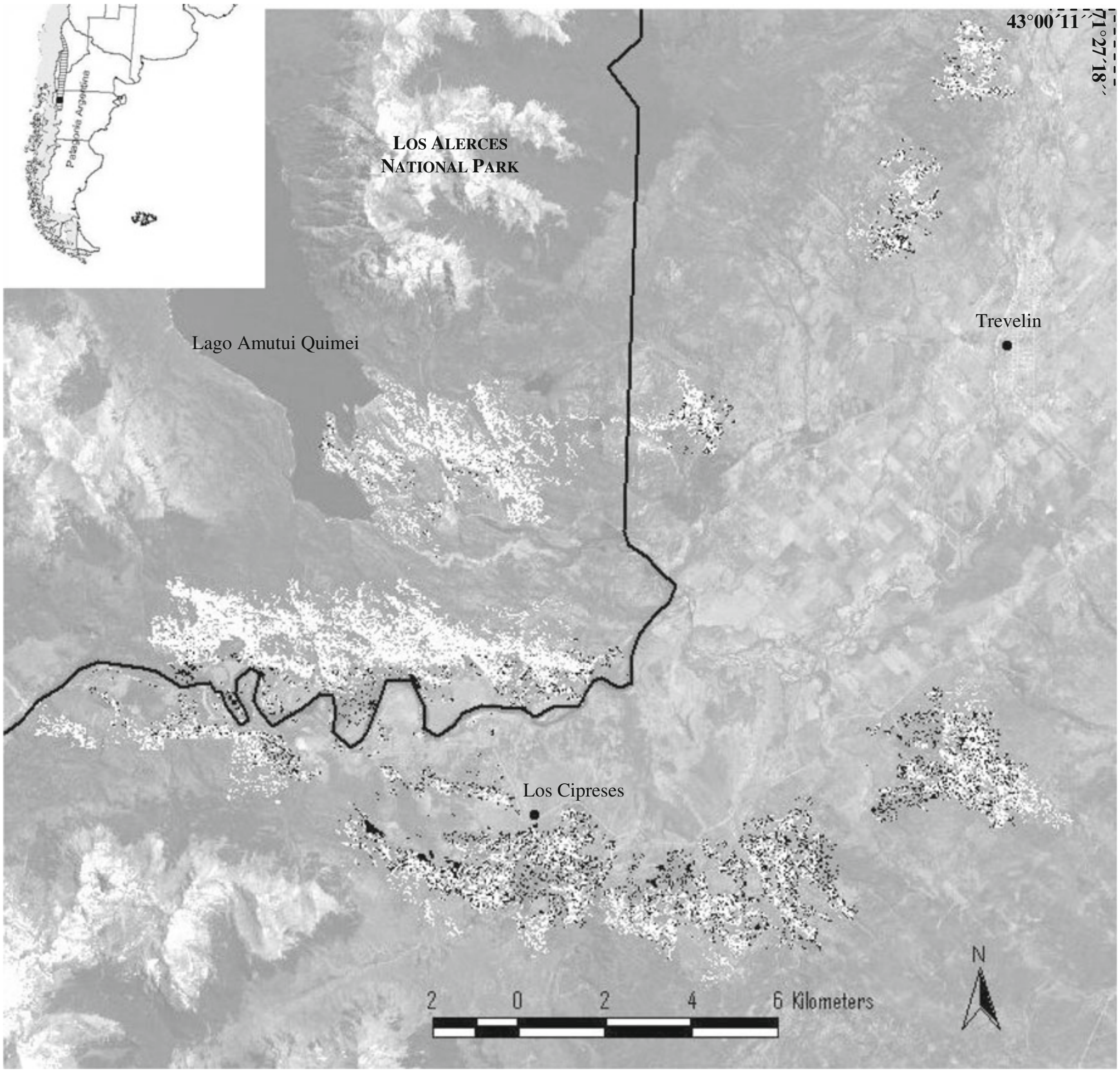

Fig. 1 Distribution of symptomatic (in *black*) and asymptomatic (in *white*) *A. chilensis* forests in 16 de Octubre Valley. The *black line* indicates the limit of Los Alerces National Park. *Upper left* range of *A. chilensis* in Argentina (*striped square*) and study area (*black square*)

occurrence was confirmed by isolation of the pathogen from necrotic lesions of affected trees and/or through ELISA immunoassays in affected tissues. Isolation was attempted in the field by direct plating necrotic phloem tissue on selective media CMA-PAR (Corn meal agar (17 g l^{-1}, Sigma) amended with Pimaricin 10 mg l^{-1}, Ampicillin 200 mg l^{-1}, and Rifampicin 10 mg l^{-1}. A portion of each lesion and a portion of healthy tissue from at least one tree of each visited stand were taken to the laboratory and kept at -20 °C to perform ELISA immunoassays (DAS ELISA reagent set for *Phytophthora*, ADGIA Inc., Elkhart, IN, USA). Assays were performed according to the manufacturer's instruction. Since *P. austrocedrae* is the only *Phytophthora* species that has been isolated from necrotic lesions of cypress (Greslebin and Hansen 2010), positive ELISA tests on *A. chilensis* necrotic phloem were assumed as positive detections of *P. austrocedrae.*

Cost-distance analysis

Cost-distance analysis calculates the effective distance which is Euclidian distance (from diseased forests) modified by the resistance (i.e., friction) to movement through different landscape elements.

This analysis was performed in a GIS environment from two raster layers: a friction or resistance layer that indicates the relative cost of moving through each cell, and a feature image with the location of the spreading source (i.e., symptomatic patches which are source of the inoculum). In the present study, the raster map has a 10-m resolution (each cell unit has 10 × 10 m).

Quantifying friction: A. chilensis disease as an example

Friction surface defines the cost of moving through different land cover types. In this case, friction refers to the cost for the pathogen movement through the landscape, and it is obtained from previous knowledge on the disease and the pathogen biology. The term "friction" seems a bit difficult to understand, since its quantification involves some subjectivity. For appropriately defining friction in a forest disease study, a thorough knowledge about the disease and conditioning external factors is needed.

In our study case, a strong relationship between the disease and site conditions was proved (Baccalá et al. 1998; La Manna and Rajchenberg 2004a, b; La Manna et al. 2008) and a risk model based on abiotic factors has been developed (La Manna et al. 2012). Then, friction values were obtained from the logistic model, which evidenced a high performance in the assessment of disease occurrence.

The logistic model considers the following variables: distance to water courses, elevation, slope, relative orientation, and pH in sodium fluoride (NaF) of superficial soil. pH NaF is an indicator of the presence of allophane, which is an aluminosilicate derived from volcanic ash alteration (Fieldes and Perrot 1966). The parameters of the logistic models are shown in Table 1, and the characteristics of the thematic layers used to generate the model were detailed in La Manna et al. (2012). According to this model, risk of disease increases with nearness to water courses, low altitudes and slopes, and poor drained soils.

The logistic regression presents the following formula:

$$\text{Logit}(P) = \beta_0 + \beta_1 \times V_1 + \beta_2 \times V_2 + \ldots + \beta_n \times V_n$$

where P is the probability of *A. chilensis* disease occurrence; β_0 is the Y-intercept; and $\beta_1 \ldots \beta_n$ are the coefficients assigned to each of the independent variables ($V_1 \ldots V_n$). Probability values are calculated based on the equation below, where e is the natural exponent:

$$P = e^{\text{logit}(P)}/1 + e^{\text{logit}(P)}$$

Table 1 Parameters of the logistic regression model (La Manna et al. 2012) used to calculate the friction of each cell

Environmental variable	β error standard	Wald's statistic	*p value*
Intercept	19.335 ± 4.634	17.4	<0.001
Distance to streams	−4.446 ± 1.234	13.0	<0.001
pH NaF	−0.454 ± 0.399	1.3	0.256
Elevation	−0.019 ± 0.004	18.7	<0.001
Relative east aspect	−0.014 ± 0.005	7.6	0.006
Relative south aspect	−0.024 ± 0.006	16.3	<0.001
Slope	−0.134 ± 0.046	8.5	0.004

Since P is a probability value, it varies between 0 and 1.

Friction values for applying cost-distance analysis should start at 1, which indicates no resistance, increasing as resistance increases (Adriaensen et al. 2003). Then, in order to convert P values to friction values, the following equation was performed:

$$\text{Friction} = -[(P - 1) \times 9] + 1$$

Friction varies between 1 (minimum friction; when $P = 1$ and abiotic factors favor the pathogen movement) and 10 (maximum friction; when $P = 0$ and abiotic factors hinder the pathogen movement).

Roads are important vehicles of *Phytophthora* dispersion (Colquhoun et al. 2000; Hansen et al. 2000; Jules et al. 2002; McDougall et al. 2002); thus, a friction value of 1 was assigned to a 10-m buffer along each side of roads. Assuming the inoculum is washed out from car wheels after a distance, roads were taken into account only up to a distance of 400 m from cypress. Although this distance was arbitrarily assumed, it was based on the general knowledge about soils and kind of roads, and vehicles transiting the area. A conservative value was chosen between the minimum and the maximum estimated dispersion distance in order to avoid an overestimation of dispersion capacity.

Water courses are also vehicles of *Phytophthora* dispersion (Hansen et al. 2000; Gibbs et al. 1999; Davidson et al. 2005), and they were included in the friction (see Table 1).

Cost-distance models also consider the existence of habitats that act as barriers, avoiding pathogen dispersion, which correspond with areas of maximum resistance to movement. An arbitrary value of 100 was given to barriers, following González López (2008). Barriers were defined according to three hypothetical situations of ranching.

Scenario 1 Cattle in the whole area. Since the pathogen can be transported throughout the study area by cattle, even the sectors with no cypress forests, i.e., with no host, may contain the pathogen in the soil. Assuming the inoculum is washed out from the cow's hoofs at a minimum distance, of 400 m, areas located at distance greater than 400 m from cypress were considered as barriers if the host is absent. Although, this distance was arbitrarily assumed, it was based on the general knowledge about soils and dispersion agents (Zobel et al. 1985).

Scenario 2 Cattle on 45 % slope or less. Since livestock rarely wander on slopes higher than 45 %, they are considered as barriers, excluding sectors that have affected forest patches upslope, since the spores could be dispersed downslope by runoff. Areas without host located at distance greater than 400 m from cypress were also considered barriers.

Scenario 3 No cattle. It was assumed that all the area with no host behaves as barrier (friction = 100), except at road sides.

Table 2 summarizes the factors considered for assigning friction values for each scenario.

The friction surfaces were constructed by applying the *map calculator* and Find distance tools of ArcView 3.1 software.

Quantifying cost-distance: A. chilensis disease as an example

A cover map with the distribution of symptomatic and asymptomatic forests (Fig. 1) and the friction surfaces constructed for each scenario (Fig. 2) were used to perform the cost-distance analysis.

For each scenario, the dispersion cost was calculated through applying cost-distance tool of ArcView software, which calculates cost as a product of friction multiplied by distance. This function calculates the accumulated cost to reach each cell from the sites where the inoculum is present (i.e., patches of diseased forest), according to friction values. The raster map was clipped with a cover map of asymptomatic cypress, to obtain the cost values for the area of interest (i.e., forests which are not yet affected by the disease). The result, for each scenario, is a cover map of asymptomatic forests rated by its cost value.

Table 2 Criteria for calculating friction for cost-distance analysis

	Modifiers of friction
Basic friction = $-[(P^* - 1) \times 9] + 1$	
Scenario I: cattle in the whole area	Friction = 1 for all cells located at 10 m around roads[a]
	Friction = 100 (barrier) for areas without host located at distance greater than 400 m from cypress
Scenario 2: cattle on ≤45 % slope	Friction = 1 for all cells located at 10 m around roads[a]
	Friction = 100 (barrier) for areas without host located at distance greater than 400 m from cypress
	Friction = 100 (barrier) for areas with slopes higher than 45 % without affected forest upslope
Scenario 3: no cattle	Friction = 1 for all cells located at 10 m around roads[a]
	Friction = 100 (barrier) for areas without host

* *P* is the probability of disease occurrence according to the logistic model (Table 1)

[a] Roads were taken into account only up to a distance of 400 m from cypress

The cost surface for each scenario was reclassified into classes for better interpreting the results (Table 3). Even though the thresholds for grouping are arbitrary, they consider the meaning of cost-distance unit of measurement, which is the grid cell equivalent, i.e., the cost of moving through cells of friction = 1. In our example, a cost value of 100 or less indicates that the pathogen has to move at the most a distance of 10 cells (= 100 m) with friction = 1 or one cell of friction = 10 (Table 3). The area of asymptomatic forest corresponding to each class was calculated using the "Tabulate area" tool.

Results

The dispersion and total area of disease risk classes depends on presence of cattle, showing the importance of ranching in cypress infection. The higher restrictions to cattle, the greater area acting as barrier, as it is shown in the friction surfaces (Fig. 2) and the higher total area with minimum risk (Figs. 3, 4).

In scenario 1, the cost-distance analysis evidenced that asymptomatic forests at minimum risk occupied only 62 ha of the 3185 ha analyzed (1.9 %) (Fig. 4a). Almost the entire minimum risk area was within the limits of the National Park (61.7 ha) (Fig. 3a). This area represents forests located far away from diseased patches and with unfavorable abiotic conditions for the pathogen, which would constitute protection areas (Table 3). On the other hand, the low risk area, with cost-distance values between 1,000 and 10,000 (Table 3), occupied 1,020 ha (Fig. 4a).

In scenario 2, the cost-distance analysis showed that the area of asymptomatic forests at minimum risk was larger than in scenario 1, covering 189 ha (Fig. 4b), of which 170 ha are within the limits of the National Park (Fig. 3b). The asymptomatic forests having low risk covered 930 ha (Fig. 4b).

In scenario 3, the cost-distance analysis evidenced that the area having minimum risk increased dramatically, up to 846 ha, of which 772 ha are within the National Park (Figs. 3c, 4c). A great portion of the area, classified as low risk in the previous scenarios, are classified as minimum risk areas.

Discussion

This study shows the application of cost-distance analysis in forest pathology. This technique allowed improving a risk model based on abiotic factors, by the inclusion of different ranching scenarios. The cost-distance approach is rarely used in forestry, even though this technique has broader potential application (Moller and Nielsen 2007;

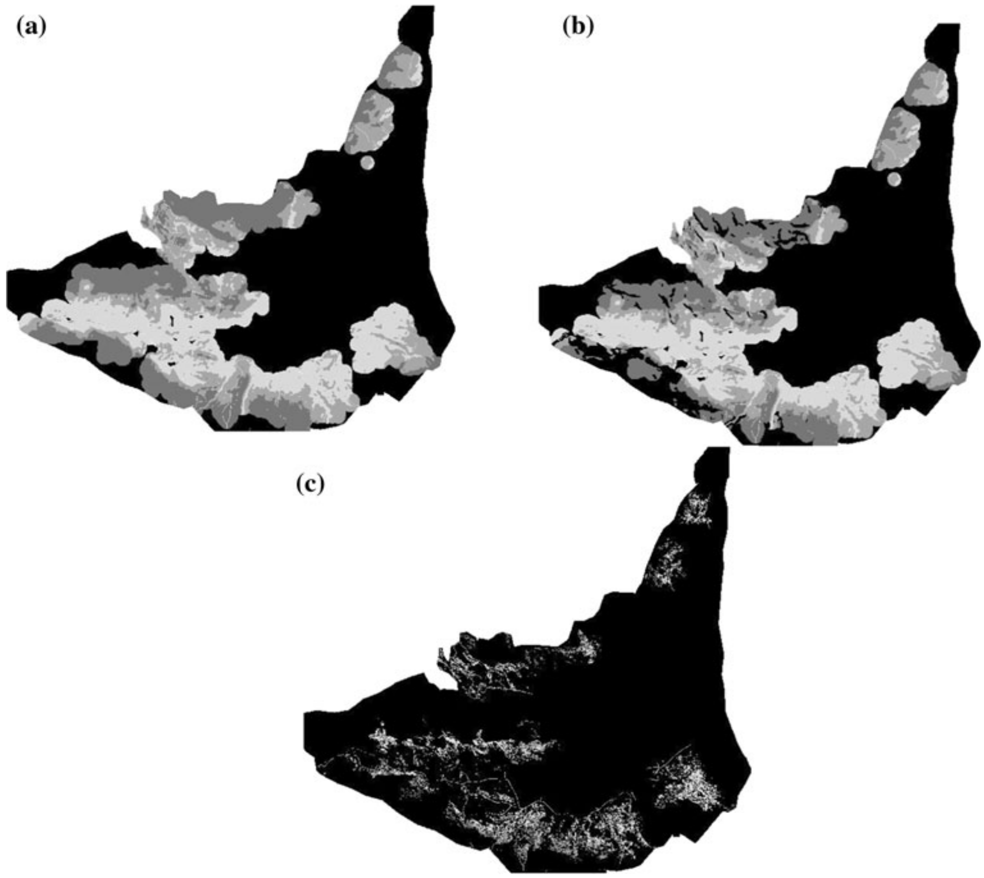

Fig. 2 Friction surfaces under different hypothetical scenarios of land use: **a** scenario 1: cattle use in the whole area; **b** scenario 2: cattle use restricted in slopes higher than 45 %; **c** scenario 3: no cattle use. The criteria used for calculating frictions are shown in Table 2. Friction values were classified in the figure just for improving the display: *light gray* friction = [1–3]; *medium gray* friction = [3–9]; *dark gray* friction = [9–10]; *black* friction = 100 (barrier)

Table 3 Thresholds used to define risk levels for *P. austrocedrae* according to cost-distance models

Cost-distance value	Meaning	Interpretation
<100	To reach this cell, the pathogen must "go through", at the most, 100 m of minimum friction (1), or 10 m of high friction (friction = 10)	High risk
100–1,000	To reach this cell, the pathogen must "go through" between 10 and 100 m of high friction or up to 10 m of barrier	Moderate risk
1,000–10,000	To reach this cell, the pathogen must "go through" more than 100 m of high friction cells, or between 10 to 100 m of barrier	Low risk
>10,000	To reach this cell, the pathogen must "go through" more than 1,000 m of high friction cells, or more than 100 m of barrier	Minimum risk (protection areas)

Ellis et al. 2010). Mapping risk and the definition of minimum risk areas for protection in diseased forests is just an example.

In this study, the asymptomatic forest area with minimum risk strongly varied according to cattle presence. Assuming that cattle roams freely and carries the pathogen at distances up to 400 m, the soil might be infected at this distance, even in absence of asymptomatic cypress trees. In this situation, the minimum risk area varies from 62 ha (scenario 1) to 189 ha (scenario 2), most within Los Alerces National Park. The difference between both scenarios is the hindering effect of slope on cattle movement in scenario 2, which is valid only for livestock. These results suggest that a large portion of the minimum risk area corresponds to sectors having steep slopes. However, it should be noted that wildlife (wild boars, foxes, hares, etc.) inhabit the area and can spread the inoculum even through steep slopes. The results are conditioned by the arbitrary definition of dispersion distance (400 m) for both roads and cattle. The minimum risk area would vary if there was a great difference between the estimated distance and the real one.

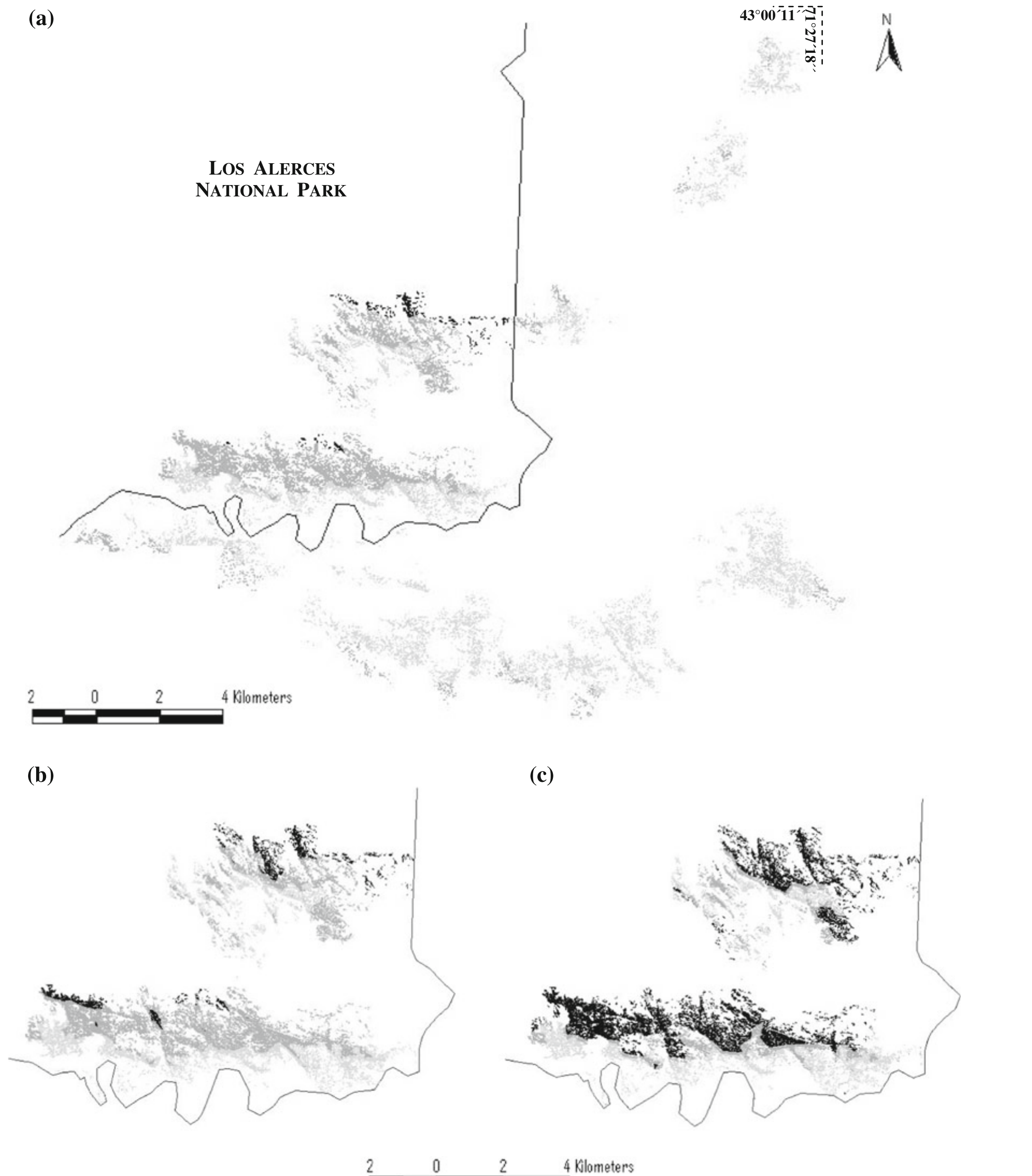

Fig. 3 Asymptomatic *A. chilensis* forests according to risk of affectation by *P. austrocedrae* assessed according to cost-distance functions under different hypothetical scenarios of land use: **a** scenario 1: cattle use in the whole area; **b** scenario 2: cattle use restricted in slopes higher than 45 %; **c** scenario 3: no cattle use. **b** and **c** Only the area included in Los Alerces National Park. *Light gray* high and moderate risk; *medium gray* low risk; *black* minimum risk

In scenario 3 (no cattle), the areas having vegetation other than cypress are considered a barrier for the pathogen, except where roads connect the areas. On this scenario, the area of minimum risk increased dramatically, covering 846 ha, 772 ha out of which are within the limits of Los Alerces National Park. These areas correspond to asymptomatic forests located in unfavorable sites for *Phytophthora* and distance from the spreading focuses. These results show that if ranching is restricted, the area of forest with minimum risk is 4.5 times larger. On the

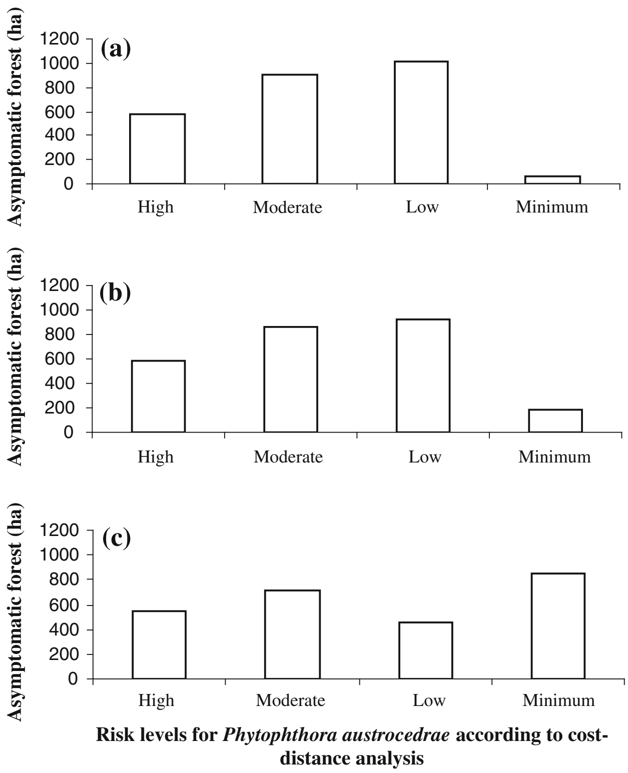

Fig. 4 Area of asymptomatic *A. chilensis* forests with different risk levels of affectation by *P. austrocedrae* according to cost-distance value under different hypothetical situations of cattle use: **a** scenario 1: cattle use in the whole area; **b** scenario 2: cattle use restricted in slopes higher than 45 %; **c** scenario 3: no cattle use

contrary, the different scenarios have little effect on the high and moderate risk area, because the risk, in these cases, is mostly explained by the nearness to the spreading focuses.

Under the three hypothetical scenarios, the largest area of forest with minimum risk of disease is located within the limits of Los Alerces National Park. This could be due to the combination of different factors. In the first place, the disease distribution map in 16 de Octubre Valley evidences that, within the National Park, the proportion of affected forests is much lower and clustered than outside it. Thus, there exists a lower and less dispersed number of spreading focuses, in addition to a lower density of roads, resulting in a lower risk of *Phytophthora* spreading. On the other hand, in the National Park, the proportion of forest located in sites with unfavorable conditions for *Phytophthora* is higher than outside (La Manna et al. 2012). On the contrary, the distribution of diseased forests outside the park is dispersed probably by human activities (agriculture, cattle-raising, forestry, tourism, etc.), which implies more roads and movement which favors pathogen dispersion.

Management rules for forests affected by *Phytophthora* are based on protecting healthy sites by avoiding the pathogen to reach them (Roth et al. 1987; Colquhoun et al. 2000; Hansen et al. 2000). Since these management actions imply economic and politic efforts, the focus should concentrate especially in the sites presenting optimum conditions for their conservation. Cost-distance analysis applied in this study allows the identification of minimum risk sites, providing information to make critical decisions on the best allocation of often-scarce resources. The fact that a large portion of the area of cypress having a minimum risk is located within the jurisdiction of the National Parks Administration facilitates disease monitoring and control. Actions to avoid *Phytophthora* spread in the minimum risk areas within Los Alerces National Park should be proposed and encouraged.

It is important to remark that this study focused on giving an example of application of cost-distance analysis in forest pathology. The model was applied to a complex disease in a complex ecosystem considering only known variables, and other relevant variables may have been omitted. This should be taken into account when transferring the results to management actions.

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