

The role of host patch characteristics and dispersal capability in distribution and abundance of *Arhopalus rusticus* in central Argentina

Mariano P. Grilli*  & Romina Fachinetti

CONICET, Centro de Relevamiento y Evaluación de Recursos Agrícolas y Naturales (IMBIV), Facultad de Ciencias Agropecuarias, Universidad Nacional de Córdoba, Av. Valparaíso s/n, CC 509-5000, Córdoba, Argentina

Accepted: 25 October 2017

Key words: *Arhopalus rusticus*, invasive pest, pine forest, landscape configuration, flight mill, Coleoptera, Cerambycidae, longhorn beetle

Abstract

Host patch characteristics may influence the abundance of a species, but this will depend on the species' dispersal ability and the distance between suitable patches. In central Argentina, an area of introduced pine forest was planted for wood production in the 1940s. In 2006, an invading longhorn beetle, *Arhopalus rusticus* (L.) (Coleoptera: Cerambycidae), was detected in the area. Since then, the species has expanded its range until it occupies the whole area. We analyze how the configuration of host patches and flight performance of *A. rusticus* affect its distribution. The study was performed in the center-west of Córdoba Province, Argentina, with 24 000 ha of introduced pine forests the main pine production zone of the province. Land cover was estimated using Landsat 8 scenes. Landscape was quantified by estimating the focal patch's area, fractal dimension index (FRAC), and Euclidean nearest neighbor distance (ENN). Focal patch area showed a positive relationship with *A. rusticus* abundance, whereas ENN and FRAC had a negative relationship. The dispersal ability of *A. rusticus* was determined by putting recently emerged individuals to fly in flight mills. The flight performance results indicated that the species was probably introduced in the area by human activity, then rapidly established and expanded to the whole area. This indicates the importance of preventing its arrival in other pine production areas of Argentina, as it has proved to be an extremely successful invader.

Introduction

In the central region of Argentina, there is an area of 24 000 ha of introduced pine forests (CNA INDEC, 2002). Most of the mainly *Pinus elliotii* Engelm. and *Pinus taeda* L. (Pinaceae) were planted during the 1940s (Izurieta et al., 1993). The cultivated woodlands form discrete patches, interspersed in a matrix dominated by natural pastures and shrublands. In 2006, an invading longhorn beetle species, *Arhopalus rusticus* (L.) (Coleoptera: Cerambycidae: Aseminae), was detected for the first time in these forests (López et al., 2007). This species was first recorded in Argentina 6 years earlier in Buenos Aires Province, 900 km away (Di Iorio, 2004). *Arhopalus* is a Northern

Hemisphere genus with about 25 species and subspecies whose larvae develop in coniferous trees (Villiers, 1978). The genus is present in all major biogeographic regions of the world through the spread of trade (Özdikmen, 2014). *Arhopalus rusticus* is found mainly in conifers of the genus *Pinus*. Its larvae infest the roots and the base of the stems of stressed or dead trees, occasionally damage structural timber, and potentially cause tree decline and loss of timber value (Kolk & Starzyk, 1996). It is well established that the occurrence of a species and its population density within a habitat may depend on processes on a larger spatial scale, among which we can mention size, shape, spatial arrangement and isolation of host patches (Tscharrntke & Brandl, 2004). However, host patch isolation will depend not only on the distance between patches but also on the organism's gap-crossing ability (Maes et al., 2014). In the case of insects like *A. rusticus* that disperse by flying, this

*Correspondence: E-mail: mariano.grilli@unc.edu.ar

ability will be directly related to the flight performance of the species.

In the first record of *A. rusticus* in Córdoba Province, Argentina (López et al., 2007), the species was observed in only one sampling site whereas our recent observations indicate the species is now present in the whole pine production area of the province. Therefore, it is evident that, at least in this area, the species has found favorable conditions to spread fast. In order to improve our understanding of its invasion process, we analyze how pine patch characteristics and the flight performance of adult individuals may have an effect on the distribution of *A. rusticus* in the pine production area of Córdoba.

Material and methods

Study area

The study was performed in the center-west of Córdoba Province (Argentina), in an area ranging from 31°33'30"S in the north to 32°33'00"S in the south. This is the main pine production region in the center of the country. The study area is mainly mountainous, dominated by shrublands and high-altitude grasses with exotic pine forests of *P. taeda* and *P. elliottii* (Figure 1).

Insect sampling

The cross-vane trap design was chosen because it is more effective than other traps for capturing borers (de Groot & Nott, 2001). The traps were baited with turpentine, composed mainly of α -pinene, β -pinene, and other terpenes (100 ml) and 70% ethanol (100 ml), in two plastic containers. The combination of ethanol, α -pinene, and β -pinene is an effective bait for *A. rusticus* (Wang et al., 2014). Collection cups contained a solution of water with sodium chloride as a preservation agent.

In order to analyze the abundance of *A. rusticus* inside host patches, samplings were carried out during the spring and summer seasons of 2013, 2014, and 2015. Over the study period, 20 sampling sites were randomly selected and sampled during the whole period. At each site, five traps were randomly placed close to each other inside the pine forest patch. Each trap was hung from the branch of a pine tree with a separation of 50 m between them. This distance was chosen arbitrarily, as there are no reports about the radius of influence of the trap on these cerambycids. Traps were deployed 50 m into the pine forest and were checked and lures replaced every 30 days, when the turpentine and alcohol containers still had half of their contents. The samples collected from the traps were processed in the laboratory under a stereomicroscope. Insect

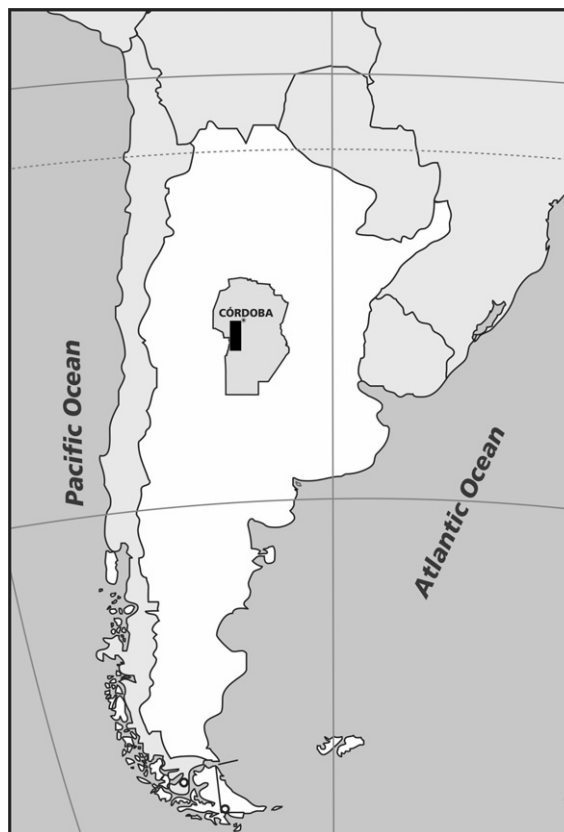


Figure 1 Study area (central rectangle) within Córdoba Province, Argentina.

abundance was recorded and expressed as number of individuals collected in each trap.

Flight potential of *Arhopalus rusticus*

To analyze the potential dispersal ability of *A. rusticus*, 45 recently emerged individuals were put to fly in flight mills. Insects were obtained from logs collected in the study area field during the study period. Each individual was put to fly for 8 h. A couple of flight mills were employed, based on the model described by Bruzzone et al. (2009), consisting of a wooden box with a holder placed in its center for a vertical needle. The needle was supported by the magnetic field generated by two neodymium magnets. A light horizontal wooden rod was attached to the needle (off-centered) and adult cerambycids were glued by the thorax, using cyanoacrylate glue, to one end of the balanced wooden rod with an entomological pin of 4 cm. *Arhopalus rusticus* individuals were placed at 6 cm from the axis, resulting in a rotational length of 37.7 cm. As mentioned, the mills were placed inside wooden boxes within a closed room with controlled temperature (25 °C). Individuals were put to fly in the evening and the mills inside the boxes

were kept in the dark, based on the crepuscular habits of other species of the same genus (Suckling et al., 2001). The rotation of the mills was recorded using an infrared optical sensor connected to a computer. Data were recorded using specially developed software. One rotation was recorded each time a beam of a light-emitting diode (LED) was interrupted by the tip of the wooden rod opposite to the one where the cerambycid was held. The software recorded every rotation and automatically calculated total flight distance (m).

To represent the dispersal distance probability of *A. rusticus* individuals, an inverse cumulative relative frequency distribution of the distance flown by the tested individuals was generated. A distance dispersal kernel was generated, adjusting a quadratic function to obtain a dispersal probability function (Nathan et al., 2012). A χ^2 test was employed to test for goodness of fit of this quadratic function. Later, a flight potential map was generated using TerrSet software (Eastman, 2015), showing the probability of dispersal from pine patches based on the probability distribution (Grilli & Fachinetti, 2017).

Land-cover estimation

Two Landsat 8 scenes – frames 229/82 and 229/83 – were used to estimate the distribution of host pine patches in the study area using TerrSet software (Eastman, 2015). A supervised classification was employed to perform the estimate of land use. Although five classes were considered for practical purposes – pine forest, shrublands, grasslands, exposed rock, or naked soil and water – only pine patches were kept for further analysis. To test the accuracy of the classification, ground truth was obtained during each sampling period by recording the land cover in the field in order to generate an error matrix (Congalton & Green, 2009). The images were classified using the algorithms of Fisher's linear discriminant classifier. An accuracy assessment was made using land-cover records not employed as training sites. An error matrix was applied to compare the classes obtained with the real ground classes found in the field and to tabulate the overall proportional error. Finally, only the pine patches were employed to obtain the landscape metrics.

Landscape quantification

Each of the pine patches where traps were placed was identified in the field using the global positioning system (GPS) and these were defined as focal patches. For landscape analysis, patch metrics of the pine patches were computed. Patch metrics are values computed for every patch in the landscape – in our case, for the focal patch where traps were placed – and are based on the relationship of the focal patch with all the other pine patches in the area.

All the metrics were estimated based on a 9-km radius circle area centered in the focal patch. This radius was established on the basis of the maximum dispersal range of *A. rusticus* observed in the flight mill. All the metrics were estimated using FRAGSTATS v.3.3 (McGarigal & Marks, 1995). We employed only patch metrics that were not correlated and that, by definition, were not redundant. We selected three metrics that measured various aspects of the landscape pattern: an area metric (focal patch area), an isolation metric (Euclidean nearest neighbor distance), and a shape metric (fractal dimension index).

Focal patch area (AREA). This metric is defined as the area (ha) of the focal patch, in our case, the patch where the traps were placed.

Focal patch Euclidean nearest neighbor distance (ENN). ENN is the distance (m) to the nearest neighboring patch of the same class (in our case pine patches). It is the simplest measure of patch isolation.

Focal patch fractal dimension index (FRAC). FRAC is a metric that quantifies the relationship between the area and the perimeter of the focal patch. This metric approaches '1' if the patch has a simple perimeter, such as a square, and approaches '2' for shapes with highly convoluted perimeters. This overcomes the major limitation of the simpler perimeter area ratio of varying with the variation in the size of the focal patch.

Data analysis

To analyze the effects of host patch characteristics on *A. rusticus* abundance, a generalized linear mixed model with a Poisson error distribution was applied. Landscape metrics were set as explanatory variables and insect abundance as the response variable. Model selection was performed using Akaike's information criterion (AIC) to compare candidate models, including the biologically meaningful non-redundant explanatory variables in a progressive way, from a single variable to the whole set of proposed variables. Coefficients and confidence intervals were estimated for each variable in each model. All analyses were conducted using the 'glmer' module in R v.3.4.0 for Windows (R Development Core Team, 2017).

Results

Land use and land cover

Land use and land cover in this area are mainly determined by climate, topography, and human activity. Estimations from Landsat images indicated that there is very little local

variability in land cover. Natural vegetation is limited to grasslands and shrublands, and the only anthropogenic disturbance in the area is the pine forest cultivated for wood.

Classification of land use

Classification of land cover by Fisher's linear discriminant classifier proved to be very precise. When considering the area classified as pine forest, we found that it represented only 2.95% of the area. The error matrix indicated that the classification of this class was extremely accurate, with less than 4% classification error.

Relationship between landscape metrics and the abundance of *Arhopalus rusticus*

Patch-level metrics for pine patches were generated for each of the 20 sampling sites in the study area (Figure 2). AIC was employed to find the model including those metrics that best explained the abundance of *A. rusticus* in the field. The model included the patch metrics as covariables and patch, site, trap, and date as random effect factors. We found that the most parsimonious model (with the lowest AIC) was the one that included the three patch metrics: a density metric (AREA), an isolation metric (ENN), and a shape metric

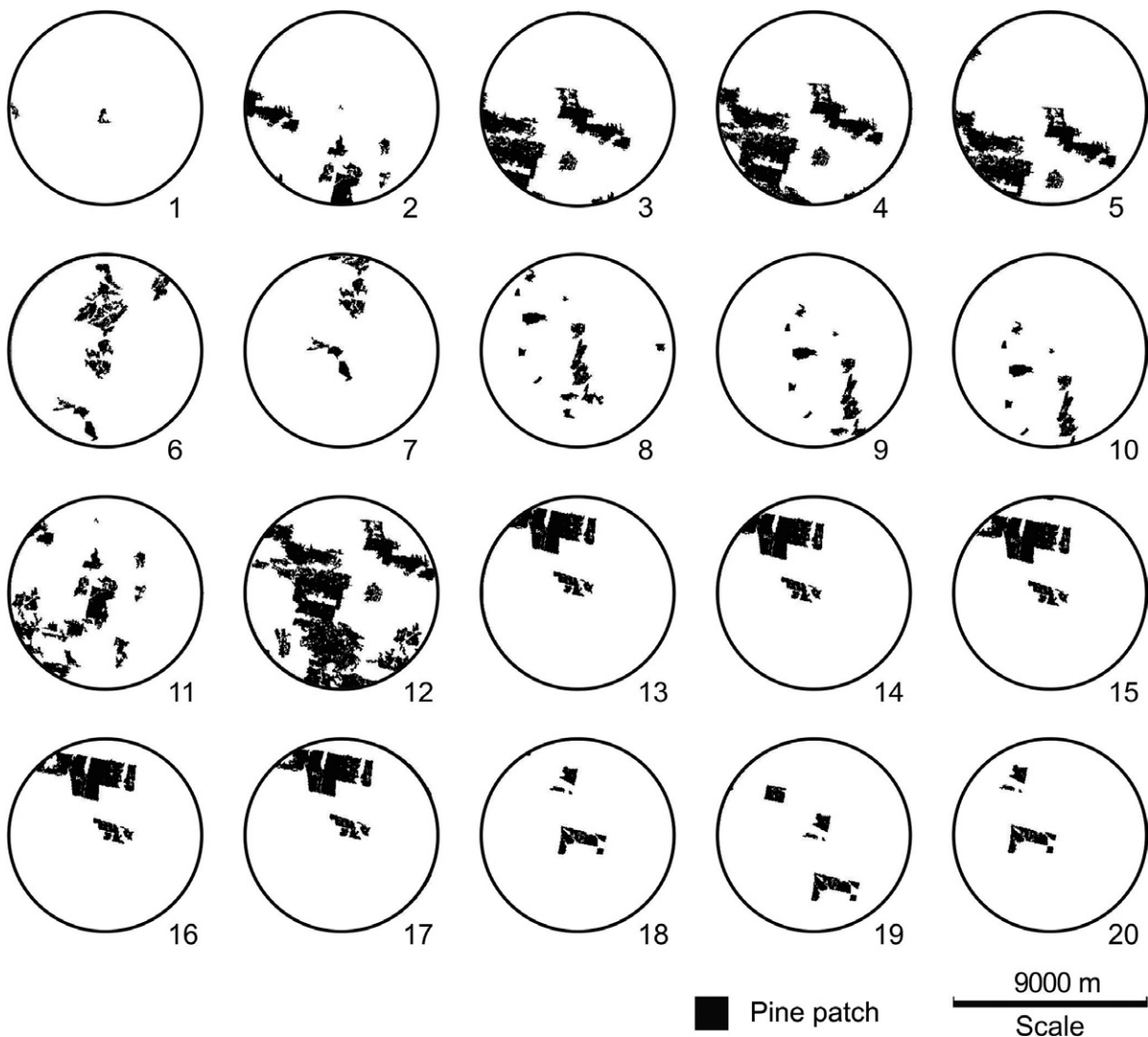


Figure 2 9-km area around each of the 20 sampling sites in the study area with host patches extracted from Landsat 8 classified images. Only pine patches were preserved.

Table 1 Generalized linear mixed models explaining the abundance of *Arhopalus rusticus* in the focal patches

Model	AIC	Selected variables	Coefficient	95% confidence interval
M ₀	5040	Null model	–	–
M ₁	2285	AREA	0.00095	0.00045 to 0.00144
M ₂	2271.8	AREA	0.00061	0.00015 to 0.00109
		ENN	–0.00050	–0.00075 to –0.00025
M ₃	2269.8	AREA	0.00106	0.00041 to 0.00171
		ENN	–0.00048	–0.00073 to –0.00023
		FRAC	–3.64243	–7.182177 to –0.102688

AIC, Akaike's information criterion.

(FRAC). All variables included were significant (Wald χ^2 test). The full model indicated that *A. rusticus* abundance has a positive relationship with AREA and a negative relationship with ENN and FRAC (Table 1).

Flight potential

A total of 45 cerambycids (23 females, 22 males) were flown successfully in the mills. Individuals were kept in the flight mill for 8 h. Flight time was variable with a mean of 3 h 23 min, a maximum flight time of 7 h 48 min (one beetle), and a minimum flight time of 5 min (one beetle). Individuals were still alive when recovered from the mill.

The distance flown by *A. rusticus* was very variable between individuals, but the data demonstrated that some individuals were able to fly long distances. The mean (\pm SD) distance flown was 7 625 \pm 5 481 m, with a minimum of 77 m and a maximum of 18 570 m. The dispersal kernel obtained from the distances flown by the individuals in the flight mills fitted a quadratic model (see caption Figure 3A). A potential probability dispersal map was generated, using the probability density function. This map showed that most of the pine patches were easily reachable from any nearby pine patch by *A. rusticus* dispersal (Figure 3B).

Discussion

Patch characteristics play a major role in insect populations. Patch size and isolation have a central role within patch population dynamics (Tscharntke & Brandl, 2004). Many studies showed an increase in herbivorous insect density with patch size (Hambäck & Englund, 2005). Our results showed that *A. rusticus* populations in the pine patches that we studied follow this pattern. There is a positive relationship between patch area and *A. rusticus* abundance, that is, the larger the focal patch, the more abundant is *A. rusticus*. According to metapopulation theory, patch size and isolation will affect local populations, with small patches expected to have smaller populations, whereas isolated patches will have a lower probability of receiving

immigrants (Hanski, 1999). Similarly, we observed a negative ratio between the Euclidean distance to the nearest-neighbor pine patch and the abundance of *A. rusticus* in the focal patch. In other words, the more isolated the focal pine patch, the lower the abundance of the insect pest in this patch. Various studies show that interpatch distance can affect population dynamics within the patch, mainly because of its effect on immigration and emigration. Isolated patches have lower densities (Hanski, 1999) and lower growth rates (Fahrig & Merriam, 1985) because landscape connectivity affects the movement of organisms between patches (Haddad, 1999). In this situation, dispersal is particularly important in the local dynamics of small populations in which stochastic demographic processes increase the risk of extinction (Gonzalez et al., 1998). However, the effect of habitat isolation will depend on the dispersal ability of the species (Tscharntke & Brandl, 2004). Population abundance and distance to other host patches in the landscape will have a direct effect on net movement rates between host patches, but distance inevitably increases the cost of dispersal, meaning that fewer dispersers can successfully reach other host patches (Haddad, 1999).

Although the results indicate that *A. rusticus* has a potential mean flight distance of 7 625 m, when analyzing the distribution of the distances flown by all the individuals, it was found that some of them managed to fly more than 15 or even 18 km. We can conclude that, although with a low probability, some individuals potentially reach any pine patch in the whole region based on the dispersal probability map.

The dispersal range of *A. rusticus* estimated using the flight mill also places this species within the range of other forest pests (Dearborn et al., 2016).

Specialist herbivores are more likely to find and remain in large patches of their host plant (Connor et al., 2000) and here the underlying idea is that the higher densities of insects in large patches are caused mainly by movement behavior between patches. In our case, an increase in the size and proximity of pine patches will cause an increase in the abundance of *A. rusticus* in the focal patch as, based on

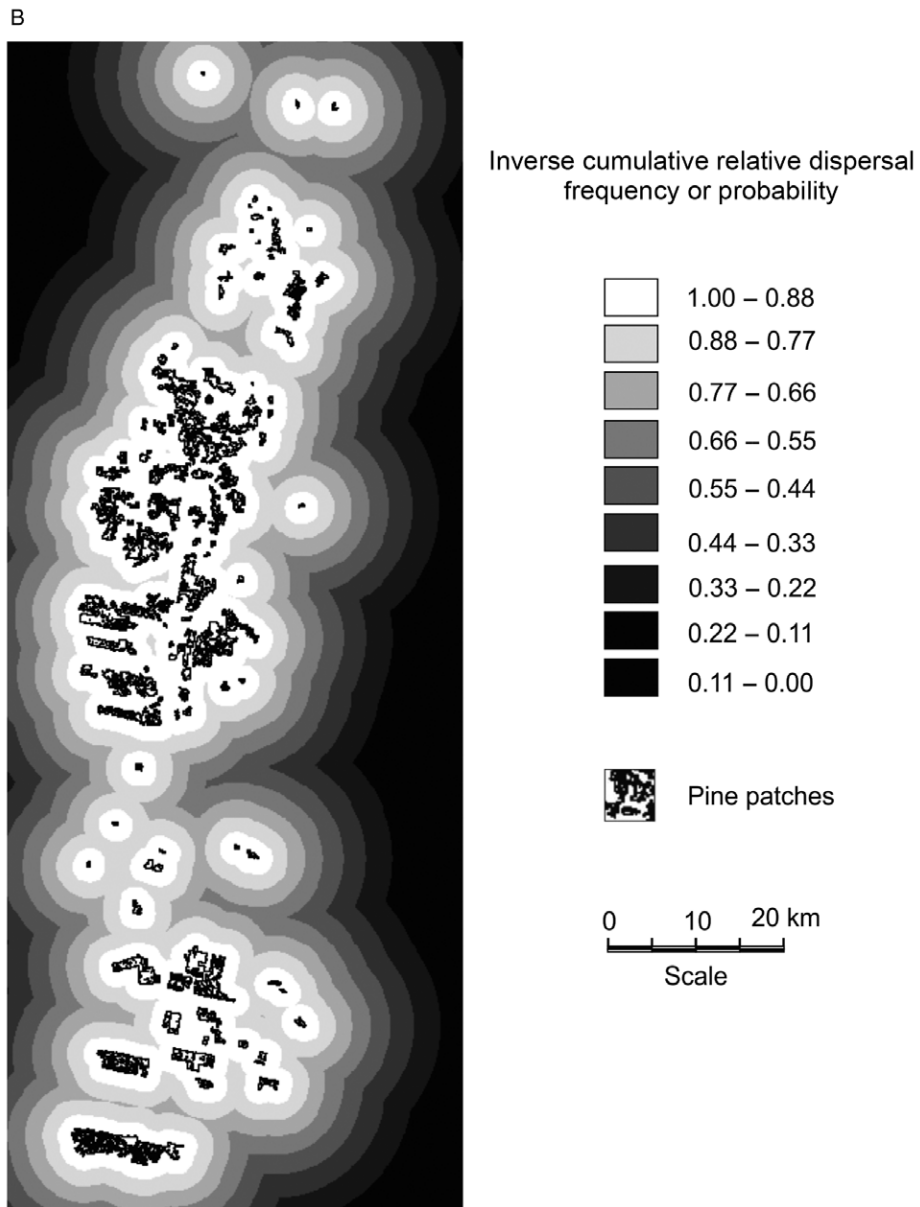
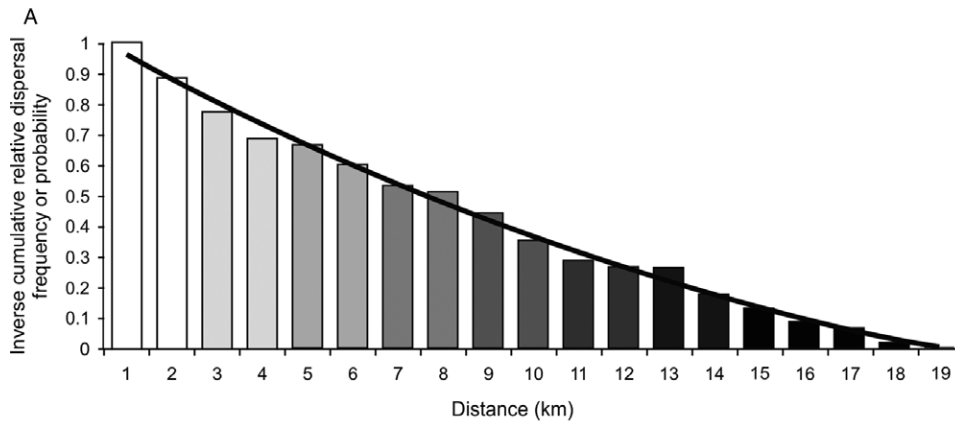


Figure 3 (A) Histogram of the cumulative frequency distribution of 18 dispersal distances of *Arhopalus rusticus* individuals and the fitted dispersal distance kernel, that is, the probability density function of the distribution of the dispersal distance travelled by the individuals in the flight mill (solid line: dispersal probability = $1.1473 \times 10^{-9} \times \text{flown distance}^2 - 8.13 \times 10^{-5} \times \text{flown distance} + 1.0392$). (B) Dispersal probability map of *A. rusticus* from each source patch generated using the probability density function of the dispersal kernel. Color scale of the map matches both panels.

their dispersal capacity, they can freely move between nearby patches. In a similar invasion scenario, Rhainds et al. (2010, 2011) demonstrated that the invading cerambycid *Tetropium fuscum* (Fabricius) was limited to a maximum dispersal threshold of ca. 80 km from its point of introduction, probably because of a limited dispersal capacity of the adults or because of a failure of low-density populations to become established (Rhainds et al., 2011).

Finally, we found a negative relationship between patch border complexity (represented as a fractal dimension) and *A. rusticus* abundance; that is, the patches with more complex borders tend to have lower *A. rusticus* abundance. According to the principle of shape and function, those patches with more complex shapes should promote exchange between the inner patch and the outer environment (Su et al., 2015). In our case, less complex borders probably tend to lose fewer or receive more individuals than those patches with more complex borders. There are two aspects of landscape boundaries that affect the movement of individuals: shape and contrast (Collinge & Palmer, 2002). Of the different shape descriptors of the landscape, perimeter–patch ratios, such as the fractal dimension index we estimated, have received the most attention in the literature due to their effect on animal movement into and out of the host patches. The general theory indicates that, as perimeter-to-area ratio increases, emigration from the focal patch also increases (Turchin, 1998).

In every invasion, the spread of the invading species is critically limited by its dispersal potential (Lander et al., 2014). This is where the spatial structure of landscapes and patch characteristics can influence the abundance and distribution of a species in a region (Wiens, 1997). Pine patches represent only a minuscule area of the landscape studied, increasing the importance of dispersal potential in the dynamics of *A. rusticus*. We found that *A. rusticus* is more abundant in large patches closer to other host patches, and these results match what we observed in the flight mill; based on the dispersal capability of the insect, closer patches will have a higher probability of receiving dispersing individuals, which will increase the population within the patch.

The pine production region of Córdoba presents an ideal situation for the spread of *A. rusticus*. The design of pine plantations could be the key to preventing the successful colonization and establishment of this species in new areas and minimizing the impact of this pest. The

smaller the patches, the more complex the borders, and a greater separation between them may reduce *A. rusticus* populations within the patch, reducing the probability of colonizing of new patches.

Considering that the main pine production area of Argentina is in the northwest of the country, 1 000 km away from our study area, and that, to date, there are no reports of the presence of the insect in this area, it would be very important to prevent the arrival of the pest by anthropogenic means, probably by increasing measures controlling the movement of pine wood products from other regions of the country. However, if the insect arrives in the area, local measures will need to be taken to minimize the spread of this pest, probably implementing procedures similar to those proposed by Herms & McCullough (2014) for the invasive Emerald ash borer (*Agrilus planipennis* Fairmaire), that is, monitoring the distribution, abundance, and condition of ash trees, the insect pest population density, and local factors, like timber harvest. The search for natural enemies and the potential use of the trunk-injected insecticide emamectin benzoate can also be recommended. In the case of *A. rusticus*, limiting the movement of logs and monitoring the movement of the insect using kairomone traps similar to the ones employed in this study could reduce the risk of spread of this pest.

Acknowledgements

This work was carried out in part with a grant provided by the Agricultural Ministry of Argentina (SAFO 111, Unidad Para el Cambio Rural, Ministerio de Agricultura, Ganadería y Pesca, Proyecto BIRF 7520), the University of Córdoba—Secyt 162/2012, and CONICET PID 114—201001 00209 KA1. The authors sincerely thank Mr. A. Barbeito for the editing of Figures 1 and 3, Mr. Joss Heywood of English Language Services for checking our English, and to four anonymous reviewers for their suggestions that substantially improved the manuscript.

References

- Bruzzone OA, Villacide JM, Bernstein C & Corley JC (2009) Flight variability in the woodwasp *Sirex noctilio* (Hymenoptera: Siricidae): an analysis of flight data using wavelets. *Journal of Experimental Biology* 212: 731–737.

- CNA INDEC (2002) Censo Nacional Agropecuario – Instituto Nacional de Estadísticas y Censos de la República Argentina. Available at: https://www.indec.gov.ar/index_agropecuario.asp (accessed on 3/9/2017).
- Collinge SK & Palmer TM (2002) The influences of patch shape and boundary contrast on insect response to fragmentation in California grasslands. *Landscape Ecology* 17: 647–656.
- Congalton RG & Green K (2009) Assessing the Accuracy of Remotely Sensed Data: Principles and Practices. CRC Press, Boca Raton, FL, USA.
- Connor EF, Courtney AC & Yoder JM (2000) Individuals area relationships: the relationship between animal population density and area. *Ecology* 81: 734–748.
- Dearborn KW, Heard SB, Sweeney J, Deepa S & Pureswaran DS (2016) Displacement of *Tetropium cinnamopterum* (Coleoptera: Cerambycidae) by its invasive congener *Tetropium fuscum*. *Environmental Entomology* 45: 848–854.
- Di Iorio OR (2004) Especies exóticas de Cerambycidae (Coleoptera) introducidas en Argentina. Parte 2. Nuevos registros, plantas huéspedes, periodos de emergencia, y estado actual. *Agrociencia* 38: 663–678.
- Eastman JR (2015) TerrSet Manual. Clark University, Worcester, MA, USA.
- Fahrig L & Merriam G (1985) Habitat patch connectivity and population survival. *Ecology* 66: 1762–1768.
- Gonzalez A, Lawton JH, Gilbert FS, Blackburn TM & Evans-Freke I (1998) Metapopulation dynamics, abundance, and distribution in a microecosystem. *Science* 281: 2045–2047.
- Grilli MP & Fachinetti R (2017) The role of sex and mating status in the expansion process of *Arhopalus rusticus* (Coleoptera: Cerambycidae) – an exotic cerambycid in Argentina. *Environmental Entomology* 46: 714–721.
- de Groot P & Nott R (2001) Evaluation of traps of six different designs to capture pine sawyer beetles (Coleoptera: Cerambycidae). *Agricultural and Forest Entomology* 3: 107–111.
- Haddad NM (1999) Corridor and distance effects on interpatch movements: a landscape experiment with butterflies. *Ecological Applications* 9: 612–622.
- Hambäck PA & Englund G (2005) Patch area, population density and the scaling of migration rates: the resource concentration hypothesis revisited. *Ecology Letters* 8: 1057–1065.
- Hanski I (1999) *Metapopulation Ecology*. Oxford University Press, Oxford, UK.
- Hermes DA & McCullough DG (2014) Emerald ash borer invasion of North America: history, biology, ecology, impacts, and management. *Annual Review of Entomology* 59: 13–30.
- Izurieta G, Abud D & Izaurralde J (1993) Plantaciones de Pinos de la Provincia de Córdoba. *Actas del Congreso Forestal Argentino y Latinoamericano*. AFOA, Paraná, Entre Ríos, Argentina.
- Kolk A & Starzyk JR (1996) Longhorn beetle *Arhopalus rusticus* (L.). *The Atlas of Forest Insect Pests*. The Polish Forest Research Institute, Multico Warszawa, Poland. Available at: https://wiki.bugwood.org/Archive:Atlas/Arhopalus_rusticus (accessed on 3/9/2017).
- Lander TA, Klein EK, Oddou-Muratorio S, Candau JN, Gidoïn C et al. (2014) Reconstruction of a windborne insect invasion using a particle dispersal model, historical wind data, and Bayesian analysis of genetic data. *Ecology and Evolution* 4: 4609–4625.
- López A, García J, Demaestri M, Di IO & Magris R (2007) *Arhopalus syriacus* y *A. rusticus*, cerambycidos relacionados a *Sirex noctilio*, sobre *Pinus elliotii* en Córdoba – Argentina. *Actas de la Primera Reunión Sobre Forestación en la Patagonia*. Eco For-estar (ed. by H Gonda, M Davel, G Loguercio & O Picco), pp. 336–337. Ciefap, Esquel, Argentina.
- Maes S, Massart X, Grégoire JC & De Clercq P (2014) Dispersal potential of native and exotic predatory ladybirds as measured by a computer-monitored flight mill. *BioControl* 59: 415–425.
- McGarigal K & Marks BJ (1995) FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure. General Technical Report PNW-GTR-351, USDA Forest Service, Pacific Northwest Research Station, Portland, OR, USA.
- Nathan R, Lein E, Robledo-Arnuncio JJ & Revilla E (2012) Dispersal kernels: review. *Dispersal Ecology and Evolution* (ed. by J Clobert, M Baguette, TG Benton & JM Bullock), pp. 187–210. Oxford University Press, Oxford, UK.
- Özdikmen H (2014) Turkish Red List Categories of Longicorn Beetles (Coleoptera: Cerambycidae) Part IV – Subfamilies Necydalinae, Aseminae, Saphaninae, Spondylidinae and Apatophyseinae. *Munis Entomology & Zoology* 9: 440–450.
- R Development Core Team. (2017) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
- Rhainds M, Heard SB, Sweeney JD, Silk PJ & Flaherty L (2010) Phenology and spatial distribution of native and exotic *Tetropium* longhorned beetles (Coleoptera: Cerambycidae). *Environmental Entomology* 39: 1794–1800.
- Rhainds M, Mackinnon WE, Porter KE, Sweeney JD & Silk PJ (2011) Evidence for limited spatial spread in an exotic long-horn beetle, *Tetropium fuscum* (Coleoptera: Cerambycidae). *Journal of Economic Entomology* 104: 1928–1933.
- Su Z, Li X, Zhou W & Ouyang Z (2015) Effect of landscape pattern on insect species density within urban green spaces in Beijing, China. *PLoS ONE* 10(3): e0119276.
- Suckling DM, Gibb AR, Daly JM, Chen X & Brockerhoff EG (2001) Behavioral and electrophysiological responses of *Arhopalus tristis* (Coleoptera: Cerambycidae) to burnt pine and other stimuli. *Journal of Chemical Ecology* 27: 1091–1103.
- Tscharntke T & Brandl R (2004) Plant-insect interactions in fragmented landscapes. *Annual Review of Entomology* 49: 405–430.
- Turchin P (1998) *Quantitative Analysis of Movement*. Sinauer Associates, Sunderland, MA, USA.
- Villiers A (1978) *Faune des Coléoptères de France*. 1. Cerambycidae. Lechevalier, Paris, France.
- Wang Y, Wang Z, Xue J, Kim H & Sung C (2014) An effective attractant for the pinewood nematode vector *Arhopalus rusticus* in South Korea. *Journal of Entomology and Zoology Studies* 2: 76–80.
- Wiens JA (1997) Metapopulation dynamics and landscape ecology. *Metapopulation Biology: Ecology, Genetics, and Evolution* (ed. by IA Hanski & ME Gilpin), pp. 43–68. Academic Press, San Diego, CA, USA.