



Drivers and spread of non-native pests in forests: The case of *Gonipterus platensis* in Spanish *Eucalyptus* plantations

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ABSTRACT

Plantations of *Eucalyptus* species have been widely used in Spain to meet the high demand for wood given their rapid growth and high wood production capacity. Defoliation induced by the invasive eucalypt weevil (*Gonipterus platensis* (Marelli)), however, has been causing significant economic damage to Spanish *Eucalyptus* spp. plantations since the 1990s. *G. platensis* is native to Tasmania, Australia, where populations are controlled by natural enemies including the egg parasitoid *Anaphes nitens* Girault. In this study, spatio-temporal Universal Kriging was applied to examine the dynamics of defoliation damage caused by *G. platensis* in Spanish *Eucalyptus* spp. plantations and to identify the main factors associated with the presence and spread of the pest. The data set combines the Spanish national plots belonging to the network of the European transnational survey of forest condition in Europe (ICP Forest Level I, 16 × 16 km grid) along with regional plots, measured using similar field protocols, in which *Eucalyptus* spp. are present. A total of 264 *Eucalyptus* plots were included in the study, *G. platensis* being present in 167 of these plots at some time during the observed period (2005–2020). Our results show that defoliation damage > 0% and defoliation damage > 5% caused by *G. platensis* increased over the period 2005–2010 and then decreased between 2010 and 2020. Defoliation damage > 15% incidence steadily decreased from 2005 to 2015, but showed an upturn in 2020. Stands belonging to the Atlantic region are more affected by this pest (76% of the Atlantic sampling plots affected versus just 4% of the Mediterranean plots). The species *Eucalyptus globulus* Labill. and monospecific stands, as well as spring precipitation of the current year were found to be positively associated with the incidence of *G. platensis* whereas the relationship with summer temperature of the previous year was negative. Finally, maps showing the degree of incidence over time have been produced to support decision-making for pest prevention and control. This study puts forward a methodology which allows the spread of this pest to be better understood and simulated, thus facilitating risk prevention.

1. Introduction

Eucalyptus spp. have been extensively planted outside their native Australian range, their distribution having expanded dramatically over the last three decades (Bennett, 2011; Wingfield et al., 2015), also in the Mediterranean area (López-Sánchez et al., 2021; Queirós et al., 2020). *Eucalyptus* spp. are used in commercial plantations because of their rapid

growth, adaptation to different environments (different altitudes, climates and soil types) and their multiple end uses (pulp paper, timber, medicinal, perfumery, oil, firewood) (Da Silva et al., 2011; Sunder, 1995). One of the key drivers contributing to the global expansion of intensively managed *Eucalyptus* spp. stands was the initial lack of natural enemies beyond their native range and the concomitant favorable conditions for growth (Colautti et al., 2004).

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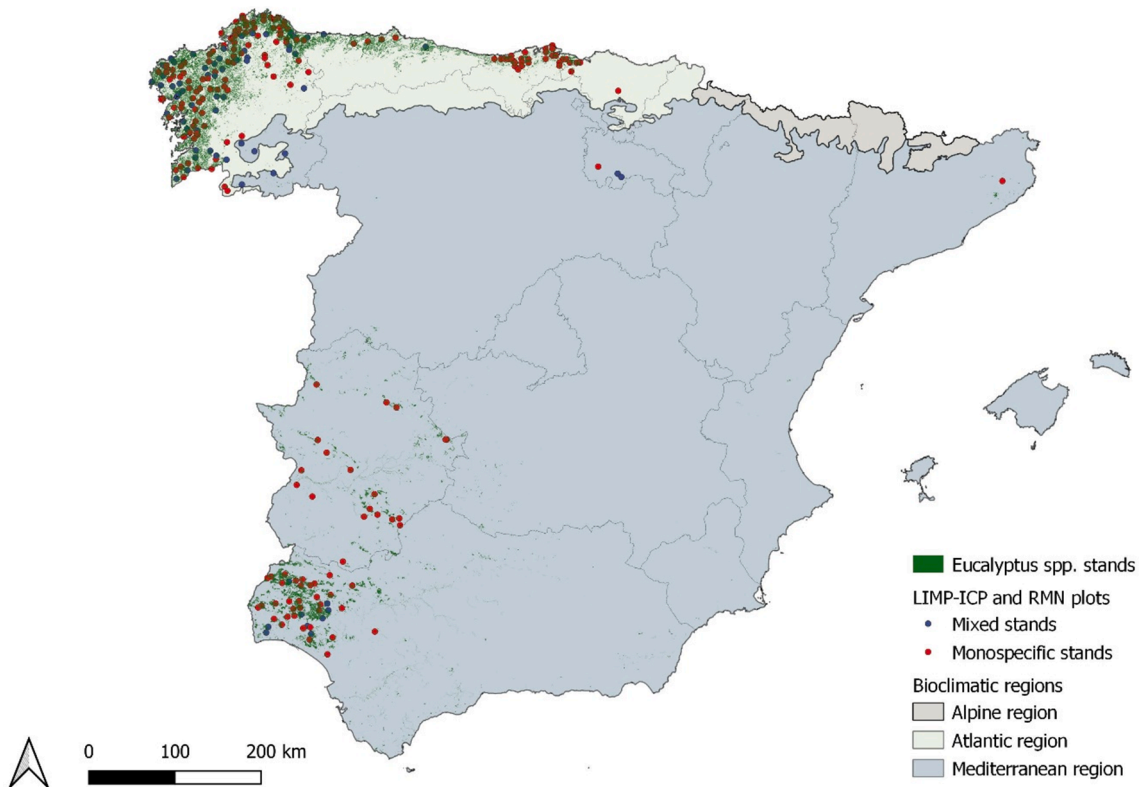


Fig. 1. Bioclimatic regions (Rivas-Martínez et al., 2004), distribution of *Eucalyptus* spp stands according to Spanish Forest Map (SFM) and plots belonging to ICP-Forests (LIMP-ICP) and Regional Monitoring Networks (RMN).

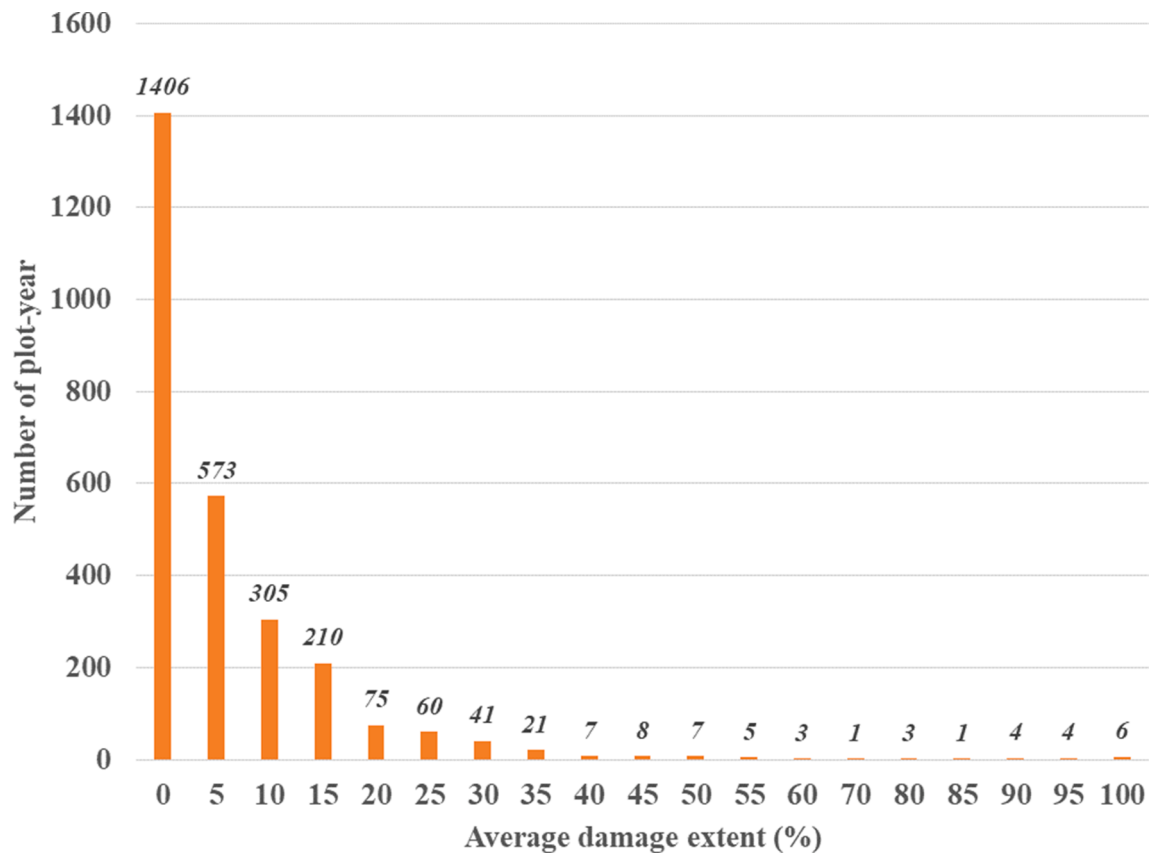


Fig. 2. Average damage extent (%) caused by *G. platensis* in *Eucalyptus* spp. plot-year for the reference period 2005–2020 in Spain.

Table 1
Average defoliation damage caused by *G. platensis* in *Eucalyptus* spp. plots belonging to LIMP-ICP and RMN between 2005 and 2020.

YEAR	TOTAL																				
	BIOClimATIC AREAS						FOREST STRUCTURE														
	ATLANTIC AREA			MEDITERRANEAN AREA			<i>Eucalyptus</i> spp.			OTHER <i>Eucalyptus</i> spp. STANDS			MONOSPECIFIC STANDS			MIXED STANDS					
	Plots	Aff	Dmg	Plots	Aff	Dmg	Plots	Aff	Dmg	Plots	Aff	Dmg	Plots	Aff	Dmg	Plots	Aff	Dmg	Plots	Aff	Dmg
2005	60	23	5.79	27	22	12.87	33	1	0.01	54	23	6.44	6	0	0.00	48	20	6.24	12	3	4.00
2006	103	48	7.84	74	48	10.91	29	0	0.00	96	47	8.26	7	1	2.08	83	39	7.36	20	9	9.83
2007	195	96	5.48	144	95	7.42	51	1	0.01	161	93	6.36	34	3	1.31	142	86	7.16	53	10	0.99
2008	197	133	7.00	151	133	9.14	46	0	0.00	171	128	7.78	26	5	1.89	171	116	7.04	26	17	6.75
2009	200	136	8.09	149	136	10.86	51	0	0.00	174	132	9.00	26	4	2.01	174	117	8.26	26	19	6.95
2010	198	131	7.16	146	130	9.71	52	1	0.00	173	127	7.92	25	4	1.93	172	112	7.33	26	19	6.04
2011	191	111	5.01	138	111	6.94	53	0	0.00	166	107	5.57	25	4	1.28	164	96	5.23	27	15	3.69
2012	161	113	6.84	129	112	8.53	32	1	0.03	152	109	7.02	9	4	3.77	134	98	7.39	27	15	4.10
2013	155	111	7.54	124	109	9.42	31	2	0.01	146	107	7.60	9	4	6.60	130	96	8.15	25	15	4.33
2014	163	121	6.76	130	119	8.34	33	2	0.56	154	116	6.83	9	5	5.53	137	104	7.20	26	17	4.45
2015	138	99	6.31	117	97	7.40	21	2	0.21	131	95	6.36	7	4	5.36	116	86	6.73	22	13	4.11
2016	178	93	7.72	144	90	9.36	34	3	0.79	169	90	7.93	9	3	3.77	149	77	8.24	29	16	5.08
2017	183	84	7.60	148	81	9.35	35	3	0.22	173	79	7.81	10	5	4.04	155	70	7.79	28	14	6.58
2018	181	97	3.11	148	94	3.72	33	3	0.37	171	92	3.20	10	5	1.49	154	82	3.51	27	15	0.82
2019	200	101	2.87	150	97	3.72	50	4	0.31	173	96	3.22	27	5	0.61	168	83	3.27	32	18	0.79
2020	132	74	12.35	116	74	14.05	16	0	0.00	110	70	14.79	22	4	0.14	115	61	14.07	17	13	0.70

Plots: Number of *Eucalyptus* spp. plots.

Aff: Number of *Eucalyptus* spp. plots affected by *G. platensis*.

Dmg: Average defoliation damage caused by *G. platensis* (%).

Following their introduction into Europe in the late 18th century (Badalamenti et al., 2018), plantations of *Eucalyptus* spp. expanded rapidly from the middle of the 20th century in some of the most productive areas of the Iberian Peninsula (López-Sánchez et al., 2021; Rodríguez-Soalleiro et al., 2018; Tomé et al., 2021). In Spain, *E. globulus* Labill. is the preferred species because of its rapid growth and wood properties, hence it is by far the predominant species, followed by *E. nitens* H. Deane & Maiden and *E. obliqua* L'Hér. in the north, and *E. camaldulensis* Dehnh. in the south (López-Sánchez et al., 2021; Queirós et al., 2020; Tomé et al., 2021). In 2018, Spanish *Eucalyptus* spp. plantations covered a total area of almost 620,000 ha. It is estimated that this represents 80 M m³ of standing wood, producing more than 7.8 M m³ of merchantable wood each year, which can reach a value of more than €200 M. Furthermore, *Eucalyptus* spp account for 39% of total fellings in Spain, more than any other species (MITECO, 2018).

The eucalypt weevil *Gonipterus scutellatus* Gyllenhal (Coleoptera: Curculionidae), presently recognized as representing a complex of at least ten cryptic species (e.g., *G. platensis* (Marelli) and *G. pulverulentus* Wakef) (Mapondera et al., 2012; Schröder et al., 2020), was one of the first invasive insect pests of *Eucalyptus* spp. to be recorded outside its native range (Clark, 1937; Tooke, 1955; Withers, 2001). *Gonipterus* spp. have become a global pest of *Eucalyptus* and have spread to numerous countries over the five continents (Hurley et al., 2016; Schröder et al., 2020). Italy was the first country in Europe to detect the insect in 1975, while in Spain, it was detected in 1991 (Mansilla Vazquez, 1992). Mapondera et al. (2012) identified the species *G. platensis* as the *Gonipterus* sp. presents in Spain, therefore this reference will be used henceforth in this article.

Significant losses in growth and wood production have been attributed to *G. platensis* feeding damage in *Eucalyptus* spp. plantations. The feeding damage includes defoliation of the crown, epicormic and stunted growth caused by the larvae and adults (Tooke, 1955). While the larval stages prefer young leaves, which mainly occur in the upper third of the crown, the adults feed on the edges of the mature leaves. Consequently, the larval stage is the most damaging feeding stage (Rua et al., 2020; Schröder et al., 2020). Infected trees show a 'stag-horned' or 'witches broom' appearance with clusters of dead shoots, resulting in significant growth loss (Lanfranco and Dungey, 2001; Tooke, 1955). Crown-loss defoliation of 25–50% can result in over 20–85% loss in wood production, respectively, over a 10-year growth period (Reis et al., 2012). In continental Portugal, wood loss in *Eucalyptus* spp. associated with damage caused by *G. platensis* amounted to €648 M in the last 20 years (Valente et al., 2018). The larval parasitoid *Anaphens nitens* Girault (Hymenoptera: Mymaridae) has been used to control *G. platensis* across most of its distribution area (Valente et al., 2017b), but it has failed to provide satisfactory results in several regions (Cordero Rivera et al., 1999; Gumovsky et al., 2015; Loch, 2008; Reis et al., 2012; Tooke, 1955; Tribe, 2005; Valente et al., 2004). However, despite the severe consequences of *Gonipterus* spp. in *Eucalyptus* plantations, few studies have addressed (e.g. Alvarez Taboada et al., 2004; Lottering et al., 2019) the biotic or abiotic drivers of the pest and its rate of spread beyond its native range.

The impact of a given pest or disease not only depends on the host but also on the climate, stand features and the complex interaction between biotic and abiotic variables (Toigo et al., 2020). For instance, changes in the climate regime can enhance the populations of a pathogen and reduce the vitality of the host and its resistance to the pathogen. Although most of the effects of climatic change are likely to result in increased forest damage, several climate-driven processes can have negative effects on herbivorous insects in forests, such as heat waves or droughts (Huffaker et al., 1976; Jactel et al., 2019). This scenario becomes more complex for non-native forest plantations. Non-native forest species released from their coevolved pests and pathogens will initially benefit, although the natural enemies will eventually reach the new regions in which their host plant has become established and will compromise plantation health and productivity. Abiotic and biotic

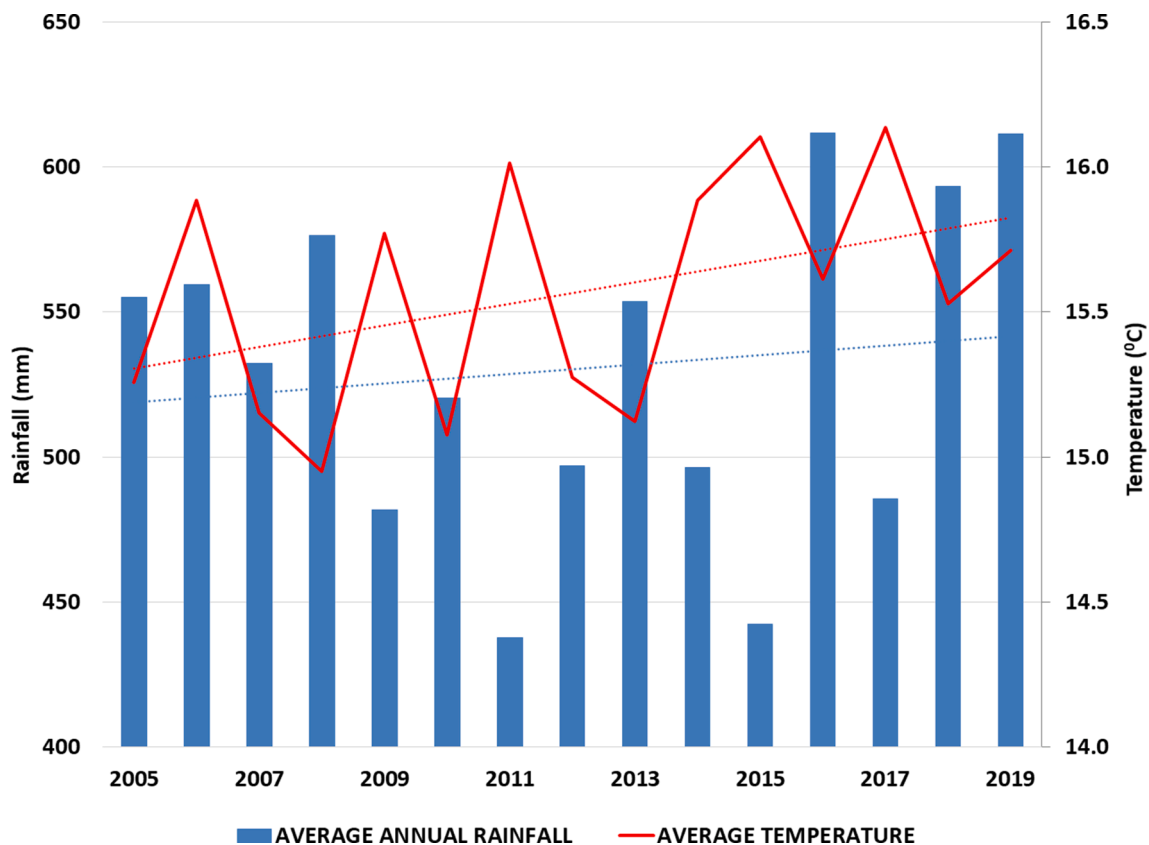


Fig. 3. Average annual temperature and annual rainfall in *Eucalyptus* spp. distribution areas between 2005 and 2019 in Spain. Dotted lines show trends of average annual rainfall (blue) and temperature (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

factors associated with global change, such as climate warming, wildfires and biological invasions, are increasing the vulnerability of *Eucalyptus* spp. to pests and diseases even outside their native range (Machado et al., 2019; Tomé et al., 2021). Over the past century, in terms of pest insects originating in Australia and introduced to other parts of the world, 42 specialist insects from 16 families have been documented feeding on *Eucalyptus* species outside their native range (Hurley et al., 2016).

The International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests, <http://www.icp-forests.net>) has been in operation for over three decades in Europe and is the only existing pan-European network that monitors the status of forests using common standards and harmonized methods for data collection (Puletti et al., 2019). Long-term forest health monitoring networks such as ICP-Forests provide powerful tools for studying spatial and temporal distributions and relationships between forest health and the abiotic and biotic factors involved in forest development under both the current climate and future climate change scenarios. Several recent studies have used ICP-Forests to analyse forest health in Europe (Bussotti et al., 2018; Ciriani and Dalstein, 2018; Duque-Lazo and Navarro-Cerrillo, 2017; Janik et al., 2020; Toigo et al., 2020; Wulff et al., 2012).

A Species Distribution Model (SDM) is a statistical and/or analytical algorithm that predicts the distribution of a species (either actual or potential), based on field observations and auxiliary maps (Hengl et al., 2009). They allow model-based predictions of species occurrence to be made, thus contributing to the fields of biogeography, evolutionary ecology, invasive species ecology, conservation biology and natural resource management (Duarte et al., 2018). There are several statistical techniques suited to species distribution modeling such as geostatistics, autoregressive models, geographically weighted regression, generalized additive/linear models or machine learning techniques (Miller et al.,

2007; Norberg et al., 2019). Geostatistical methods are based on statistical models that include spatio-temporal autocorrelation, defined as the statistical relationships among the measured points. These techniques not only allow a prediction surface to be created but also provide a measure of the accuracy of the predictions. Kriging techniques, e.g., Ordinary Kriging (OK) or Universal Kriging (UK), are some of the most common geostatistical approaches used to model shifts in species distribution (Hernández et al., 2014; Moreno-Fernández et al., 2016).

In this study, a geostatistical SDM based on UK models (Lappi, 2001) is used to assess and project the spatio-temporal patterns and spread of *G. platensis* in *Eucalyptus* spp. plantations in Spain based on data recorded between 2005 and 2020. Specifically, we aim to identify the climatic variables, *Eucalyptus* species and forest structure based on *Eucalyptus* spp. plot dominance (monospecific or mixed stands) that favor the eucalypt weevil, as well as the spatio-temporal dynamics of pest outbreaks. This study proposes a new approach based on a harmonized forest monitoring network, which is easily replicable across Europe and enables us to understand and to simulate the spread of pests, thus facilitating risk prevention.

2. Materials and methods

2.1. Selection of data

The spatio-temporal analyses of *G. platensis* incidence in *Eucalyptus* spp. plantations in Spain were based on single-tree data collected as part of the European Level I Monitoring Programme (LIMP) of ICP Forests (ICP Forests, <http://www.icp-forests.net>). The LIMP is a 16 × 16 km network established over three decades ago covering the whole of Europe (around 7,500 points or plots) for the purpose of monitoring the health status, vitality, and biodiversity of European forests (Ferretti,

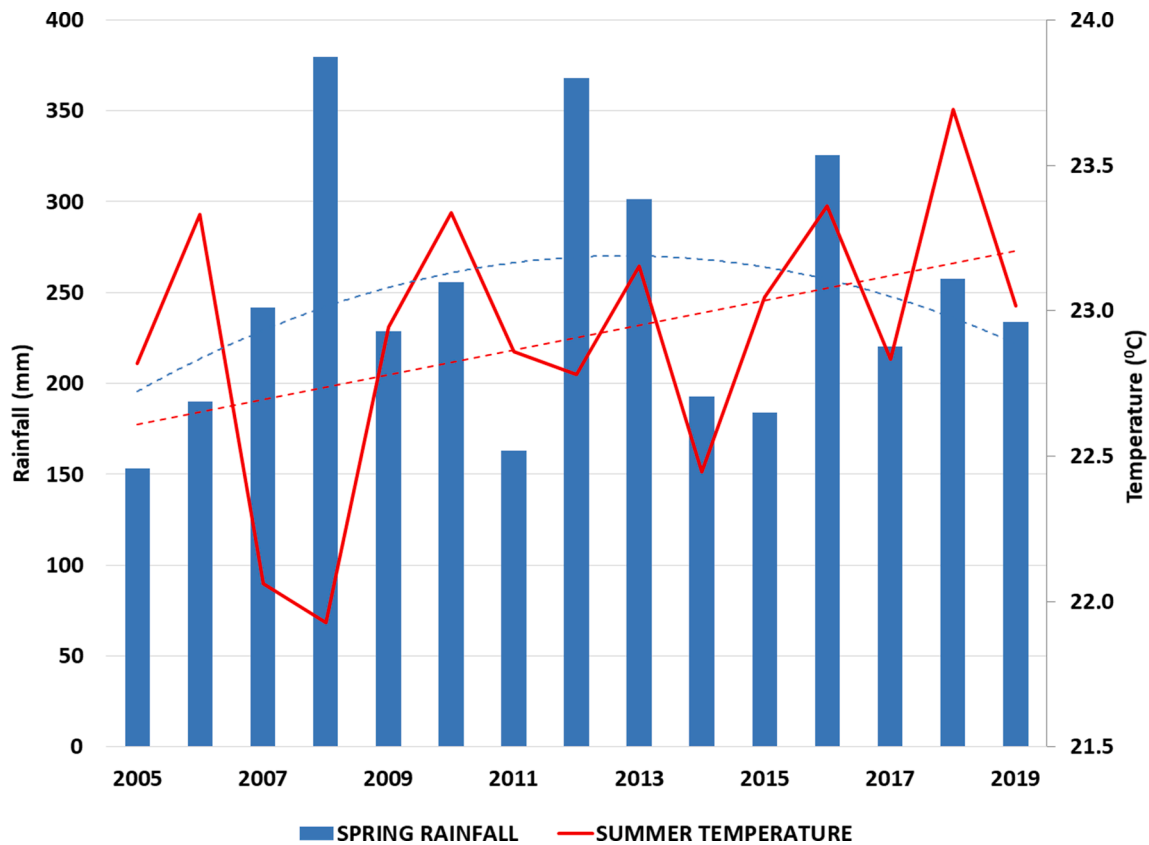


Fig. 4. Summer temperature and spring rainfall in *Eucalyptus* spp. distribution areas between 2005 and 2019 in Spain. Dotted lines show trends of spring rainfall (blue) and summer temperature (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

Parameters of the models to estimate probability of occurrence of defoliation damage caused by *G. platensis* in *Eucalyptus* spp. plantations in Spain.

MODEL	Int.	Stand 1	Stand 2	Stand 3	Last Summer Temp	Spring Rainfall	Nugget	Spatial sill (km)	Spatial range (km)	Temporal sill (years)	Temporal range (years)
Damage > 0%	0.4464	-0.0897	0.1218***	0.1334**	-0.0111	0.00048***	0.0881	0.3042	1003.8	0.0142	5.85
Damage > 5%	0.6096	-0.1058	0.2025***	0.1969***	-0.0265**	0.0003***	0.2033	0.0332	581.1	0.0009	0.1
Damage > 15%	0.2465	0.0089	0.096***	0.112*	-0.0135*	0.0001*	0.0358	0.0504	29.4	0.0216	0.5

Stand 1: Mixed *Eucalyptus* spp.stands.

Stand 2: Monospecific *Eucalyptus globulus* stands.

Stand 3: Monospecific *Eucalyptus* spp. stands.

***p < 0.001.

**p < 0.01.

*p < 0.1.

2013).

The Spanish LIMP network is composed of 620 plots, which include 24 dominant or co-dominant trees at each plot. Sample trees are chosen according to strict criteria: six trees per quadrant (NE, SE, SW and NW) are selected, taking into consideration their proximity to the centre of the plot (Ferretti, 2013). Tree crown condition (defoliation, crown transparency and discoloration) and tree damage assessments (agent, affected areas, intensity) were evaluated once annually from 1986 to 2020. *G. platensis* was included in the agent group 200 (insects) present on broadleaves in 2003 (Eichhorn et al., 2020).

We used average extent of the defoliation damage caused by *G. platensis* in all *Eucalyptus* spp. trees in each plot as an explanatory variable in the analysis. The extent of the damage indicates the portion of affected leaves (%) due to the action of *G. platensis* and was related to the whole crown of the tree (ICP Forests, <http://www.icp-forests.net>).

To enhance the available information on the health of forests, the Spanish National Parks Network and Spanish regional government administrations have used regional monitoring networks (RMN) in their corresponding areas since 1986 and 2000, respectively. These networks comprise plots at which measurements are taken using similar field protocols as those used in the LIMP network. In these networks, *G. platensis* has been included as an agent since 2000. This additional regional network provides a more intensive sampling density, contributing an additional maximum of 2,211 plots to the existing national LIMP network by 2010. In 2020, 1,636 regional plots continue to be measured along with the 620 plots belonging to the national LIMP network.

Information on *Eucalyptus* spp. assigned to the LIMP and RMN network plots was taken from closest polygon of the Spanish Forest Map (SFM), classifying the plots as a factor with two levels: *E. globulus* and

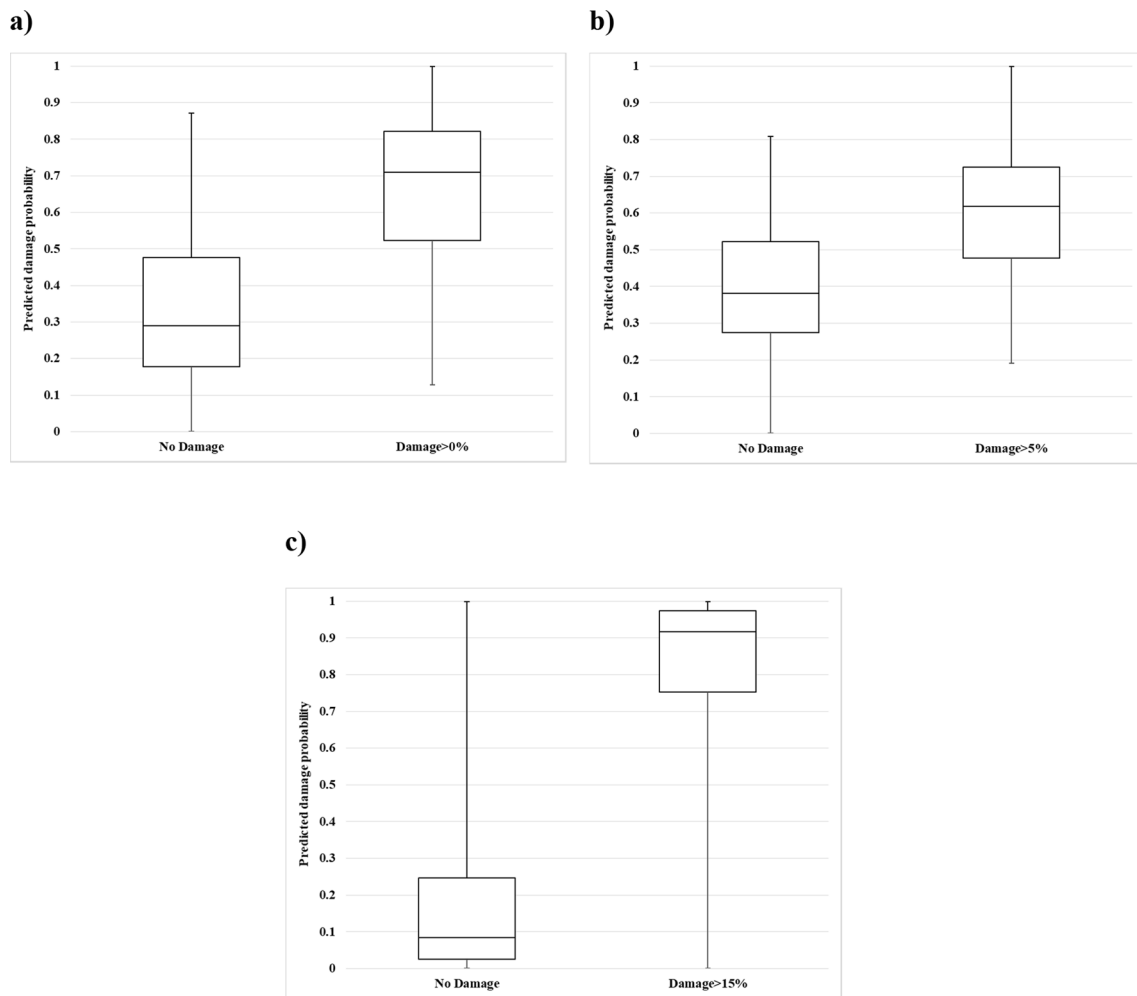


Fig. 5. Predicted damage probability versus 2020 measured data for (a) damage > 0%, (b) damage > 5% and (c) damage > 15% models.

other *Eucalyptus* spp. (*E. nitens*, *E. camaldulensis*, *E. gomphocephalus* A. Cunn., *E. robusta* Sm. and *E. viminalis* Labill.).

The selected sample comprises 264 plots belonging to the national LIMP and RMN (46 and 222 respectively) networks in which the presence of *Eucalyptus* spp. was registered between 2005 and 2020 (Fig. 1). Bioclimatic regions were defined following Rivas-Martínez et al. (2004). The extent of defoliation damage in *Eucalyptus* spp. per plot/year is shown in Fig. 2 for the reference period 2005–2020. The year 2005 was chosen as the initial year for the data set because *G. platensis* has only been included as a damage agent since 2003 in LIMP network.

The modelling data set was composed of data measured from 2005 to 2019. The data set collected in 2020 was used to test the performance of the proposed model.

2.2. Spanish forest Map (SFM)

We used the Spanish Forest Map (SFM) to identify the distribution area of *Eucalyptus* spp. in Spain. The SFM is the basic forest cartography at national level, with data on the distribution of Spanish forest ecosystems being continuously gathered and regularly updated (at least every 10 years) (MAGRAMA, 2006). The SFM provides detailed and homogeneous vectorial information for each polygon regarding forest structure, the main species (up to three), the degree of coverage and the development stage, among others. We used the most up-to-date SFM, that is, the SFM at a scale of 1: 25,000 (SFM25, minimum polygon size of 1 ha) for the regions that are already available at that scale (Northern populations, 75% of the eucalypt distribution area) and the SFM at a

scale of 1: 50,000 (SFM50, minimum polygon size of 2.5 ha) for the rest.

The distribution area of *Eucalyptus* spp. was established by identifying SFM polygons in which *Eucalyptus* spp. was present as either the main or secondary species (Fig. 1), comprising monospecific and mixed stands respectively. Monospecific stands were defined as those where 70 percent or more of the total tree crown cover is comprised of *Eucalyptus* spp.

2.3. Climatic information

To study the factors driving the spread of *G. platensis*, we collected the most up-to-date climate data based on temperature and precipitation measurements for the reference period 2005–2019 from meteorological stations belonging to the Spanish State Meteorological Agency (www.aemet.es). Climate data for 2020 was estimated using Universal Kriging geostatistical models to test the performance of the proposed model. Average seasonal and annual temperatures and total seasonal and annual precipitation were taken into consideration as possible explanatory variables.

2.4. Geostatistical methods

Universal Kriging geostatistical models (Matheron, 1973) allow the space–time structure of the variance as well as the effects of climatic (seasonal and annual climatic variables) and forest structure (monospecific and mixed stands) to be included in the model as auxiliary variables, improving the prediction accuracy in terms of bias and error

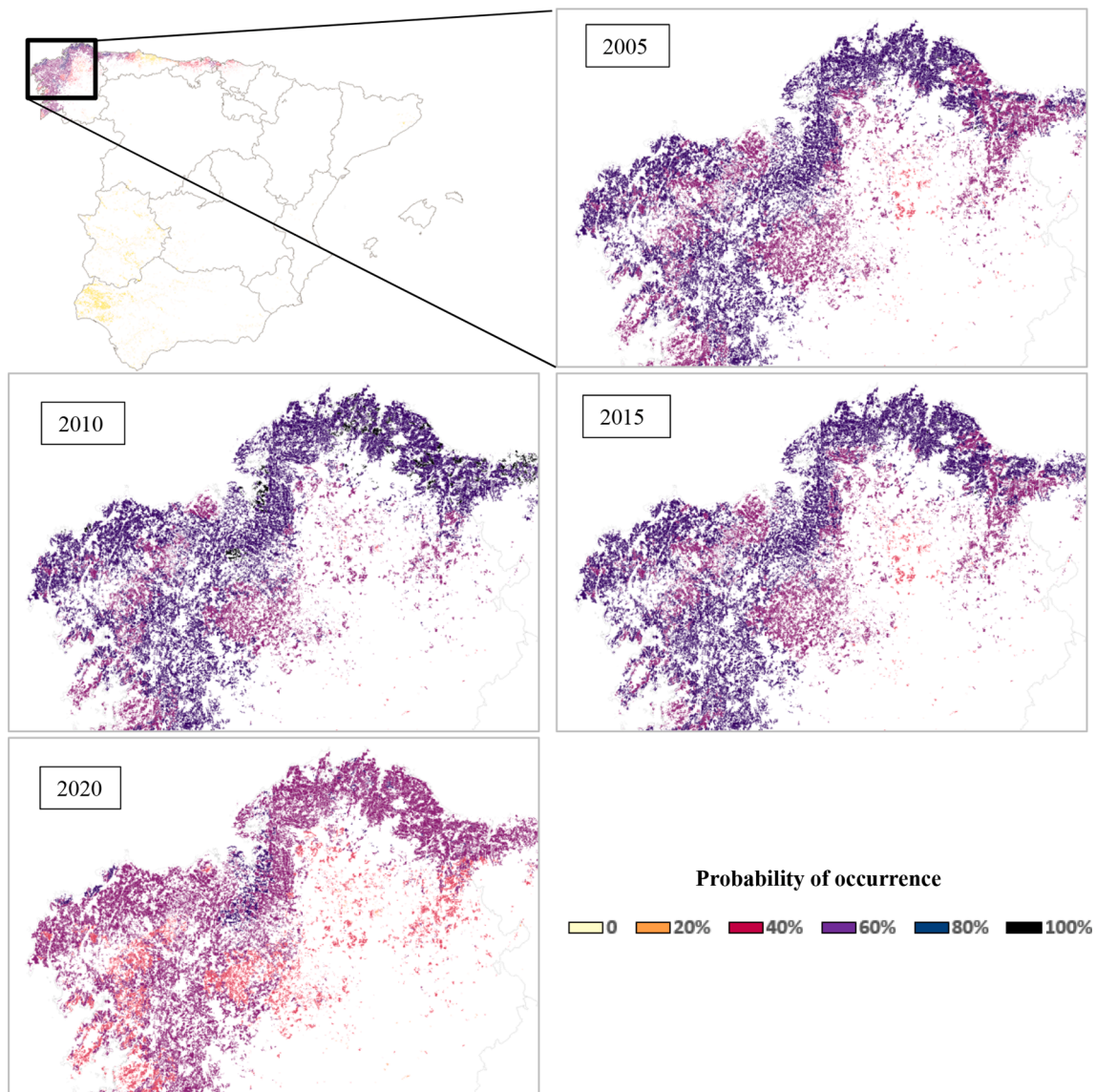


Fig. 6. Probability of occurrence of *G. platensis* between 2005 and 2020 for defoliation damage > 0% in North-western Spain.

(Lappi, 2001). These methods are variogram-based, describing the correlation among neighboring values as a function of the geographic distance between the points, therefore the farther apart two points, the lower the likelihood that their values will be similar.

Kriging techniques predict the value of the variable $Z(s_0)$ at an unsampled location s_0 from the value of the variable at various observation points $Z(s_1), Z(s_2), \dots, Z(s_n)$. UK models assume the mean $E(Z(s))$ shows a deterministic drift following an unknown linear combination of $p + 1$ known (in sampled and unsampled locations) auxiliary spatially structured variables (usually denoted $f_k(s)$) and spatially correlated random process $\delta(s)$ (Montes and Ledo, 2010):

$$Z(s_0) = \sum_{k=0}^p \beta_k f_k(s_0) + \delta(s_0)$$

The value prediction $p(Z, s_0)$ of the variable Z at point s_0 is then performed by estimating the optimal weight defined by the coefficients λ_i for each observation s_i while considering this autocorrelation structure (Armstrong, 1998; Oliver and Webster, 2015):

$$p(Z, s_0) = \sum_{i=1}^n \lambda_i Z(s_i)$$

The autocorrelation structure of the observations can be expressed abstractly by the semi-variogram or variogram $\gamma(d)$, which is defined as half the expected squared difference between paired (intrinsic) random functions (Matheron, 1973) at a distance d (Atkinson and Lloyd, 2007; Goovaerts, 1997), and the associated covariance function, which has to be fitted to the observation points. The estimation of the optimal weights λ_i involves modelling the variogram $\gamma(d)$. Several approaches can be used to estimate the variogram parameters and the β_k coefficients. For spatio-temporal variogram modeling we used the generalized product-sum model (De Iaco et al., 2002). Spherical variograms were used for both temporal and spatial components assuming a common nugget effect for both components. Iteratively Reweighted Generalized Least Squares (IRWGLS) (Neuman and Jacobson, 1984) was then chosen to simultaneously estimate the variance-covariance matrix and the β_k coefficients of the auxiliary variables.

Climate variables were calculated at annual and seasonal resolution every five years for the considered time span. UK, with altitude, X and Y coordinates as well as their interactions as auxiliary variables were used to interpolate annual and seasonal climatic variables at the LIMP and RMN data plots and centroids of SFM polygons. We retained those auxiliary variables with $p < 0.05$. When no significant trend function was found, Ordinary Kriging (OK) was used instead of UK. In this case,

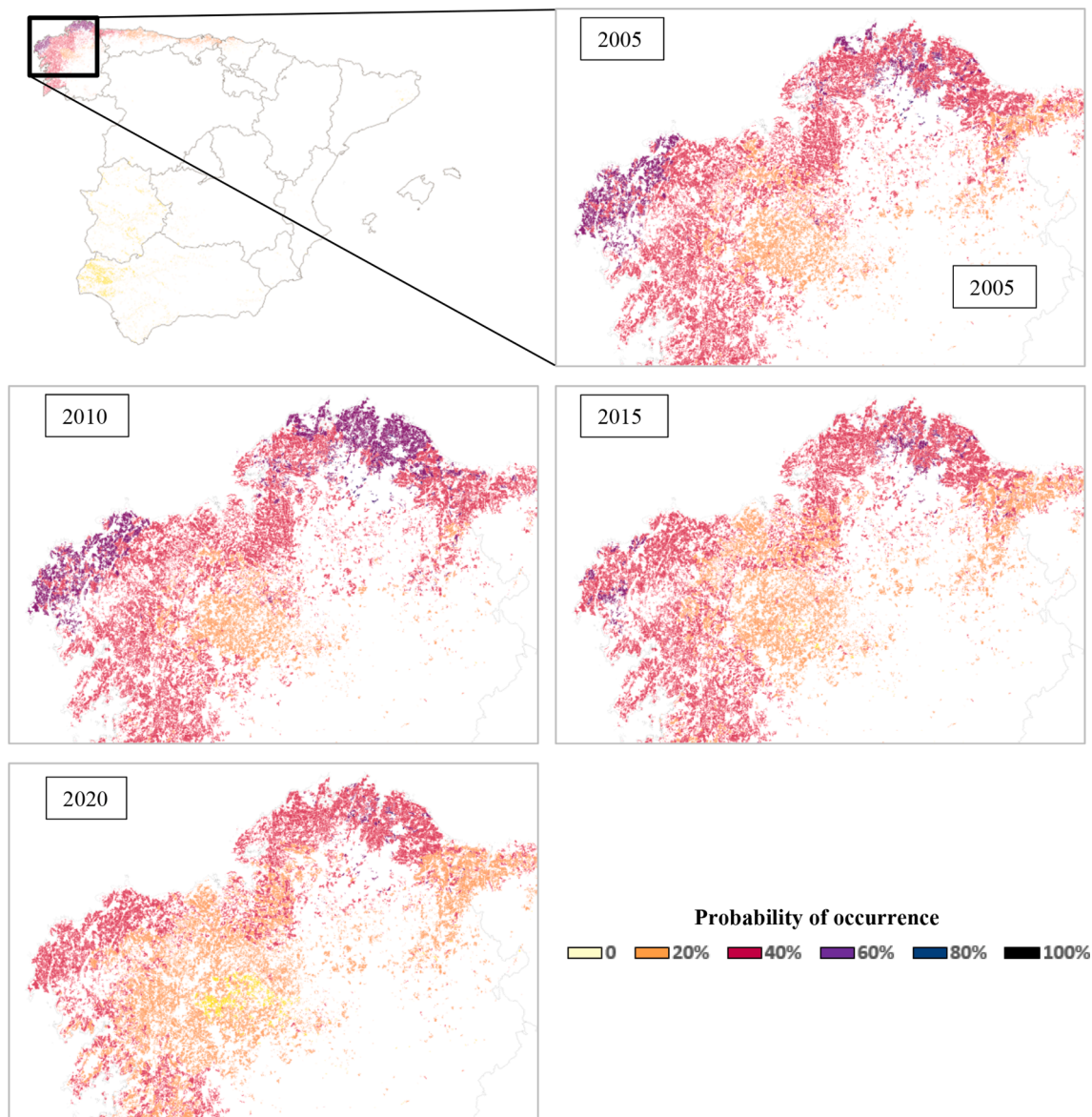


Fig. 7. Probability of occurrence of *G. platensis* between 2005 and 2020 for defoliation damage >5% in North-western Spain.

Weighted Least Squares (WLS) (Cressie, 1985) was used to fit the variogram parameters with OK.

Indicator Kriging provides probability maps from an indicator variable and has been used for pest risk assessment (Mohammadi et al., 1997). By adding temporal autocorrelation, Indicator Universal Kriging (IUK) can predict the dynamics of the outbreaks, allowing us to determine the spatio-temporal autocorrelation of the pest progress, as well as the geographical and temporal trend linked to climatic or geomorphologic variables (Montes and Ledo, 2010).

The distribution of *G. platensis* was evaluated using an indicator variable that took a value of 1 or 0 depending on whether the average defoliation damage caused in the *Eucalyptus* plot was above or below a certain threshold. We fitted three IUK models, one for each defoliation damage threshold: damage > 0%, damage > 5% and damage > 15%. Cross-validation residuals and β coefficient p-values were analyzed to select the auxiliary variables for inclusion in the IUK models.

To test the performance of the IUK models for predicting the following year's risk, we estimated the probability of plots being affected in the case of the plots measured in 2020. For each k th plot in the dataset, we have fitted a model leaving out 2020 observations and all data series from that plot. Then, we test the model to check the

effectiveness for k th plot. The averaged IUK predicted values for plots affected to a level above or below the respective threshold for each model were then compared.

Finally, occurrence probability maps were plotted applying the same IUK model calculated with the LIMP and RMN data in the centroids of SFM polygons every 5 years (2005, 2010, 2015 and 2020). These maps show the dynamics of the *G. platensis* pest in the area of the *Eucalyptus* stands in Spain.

The geostatistical analyses were conducted using MatLab® software developed by the authors and freely available by contacting the corresponding author, and raster calculations and map drawings were carried out using QGIS ver. 3.10.12-A Coruña (QGIS Development Team, 2021).

3. Results

3.1. Dynamics of *G. platensis* spread based on LIMP-ICP and RMN networks information

The data set showed that defoliation damage caused by *G. platensis* had varied over the period 2005–2020 (Table 1). Stands belonging to the Atlantic region had been more affected by this pest than those in the

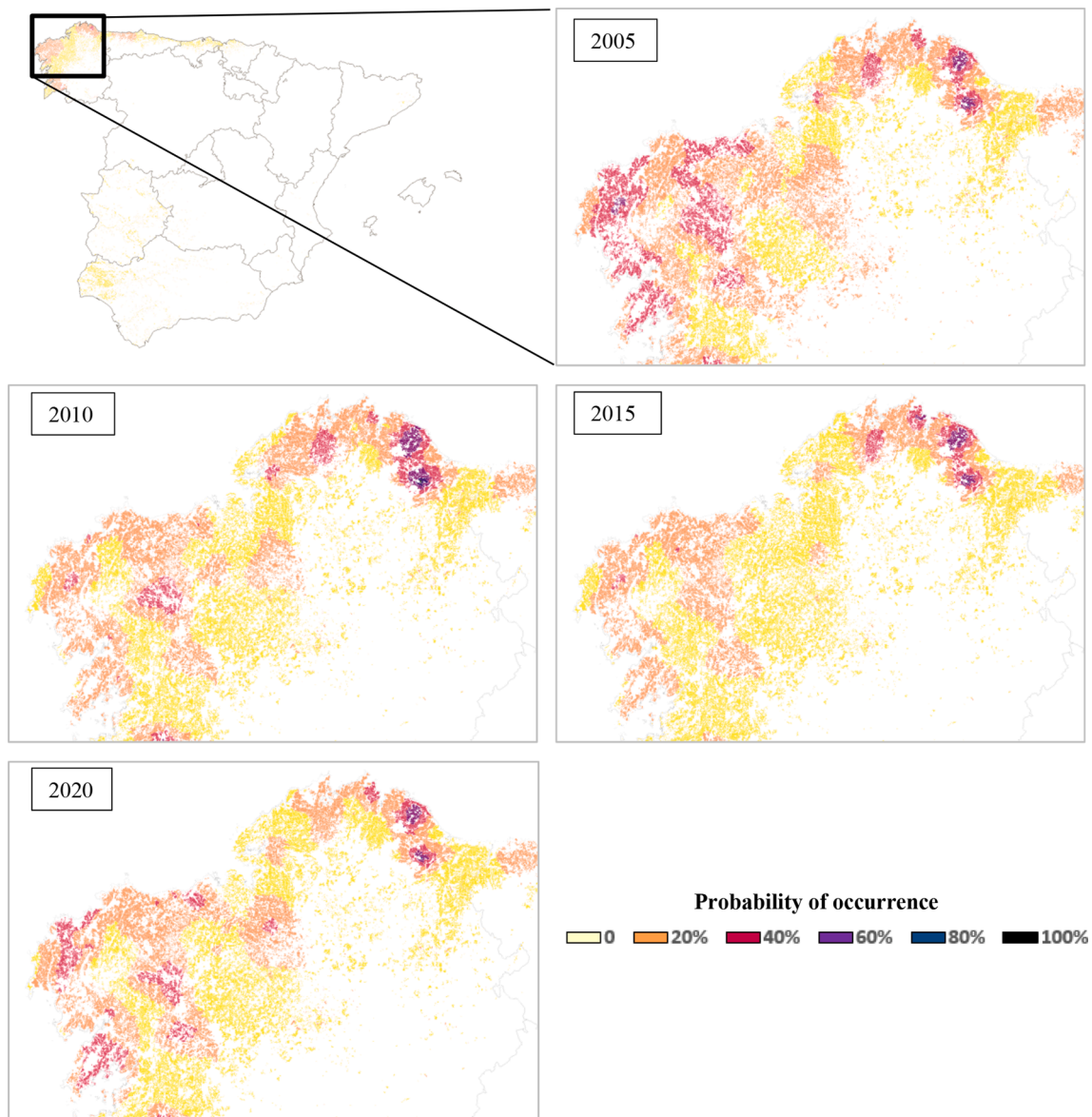


Fig. 8. Probability of occurrence of *G. platensis* between 2005 and 2020 for defoliation damage > 15% in North-western Spain.

Mediterranean region. 76% of the Atlantic plots had been affected at some time as opposed to only 4% of the plots in the Mediterranean area. Since 2005, average defoliation damage has reached maximums of 8.09% in 2009 and 12.35% in 2020, and minima of 3.11% in 2018 and 2.87% in 2019. *E. globulus* stands displayed a higher incidence and defoliation rate than other *Eucalyptus* spp. stands in all years. As regards forest structure, monospecific stands showed higher defoliation damage in all years, with the exception of 2006 and 2017.

3.2. Universal Kriging models for climate variables

Data from the National Meteorological Agency stations located close to the *Eucalyptus* distribution area reveal a rise in mean temperature and a decrease in annual rainfall between 2005 and 2019 (Fig. 3). Summer temperatures and spring rainfall for the studied area varied considerably, but there has been a clear negative trend in spring rainfall as well as increasing Summer temperature since around 2010 (Fig. 4).

UK, with altitude and Y coordinate as auxiliary variables, was used to interpolate all the mean annual and spring and winter seasonal temperatures at the points and centroids of the SFM polygons. The X and Y coordinates were included as auxiliary variables for mean summer and

fall temperatures, whereas the altitude, X and Y coordinates and the interaction of altitude with X and Y were employed as auxiliary variables for fall, winter and annual precipitation models. In the spring and summer precipitation models, no significant trend function was found so OK was used instead of UK.

The IRWGLS method used to fit the UK model variogram parameters and *b* coefficients reveals significant relationships between mean summer temperature and the X coordinate (increasing temperature towards the East) and latitude (negative relationship) as well as an autocorrelation range of 3,399 m and less than 1 year. OK was used in spring rainfall modeling due to the absence of a significant trend, the WLS estimations of space and time autocorrelation range being 187,952 m and 3.6 years, respectively.

3.3. Indicator Universal Kriging models for *G. platensis* damage

Based on previous exploratory analysis, *Eucalyptus* spp factor (*E. globulus* and other *Eucalyptus* spp.), forest structure (monospecific and mixed stands), previous summer mean temperature and spring precipitation were selected as auxiliary variables for the three IUK models.



Fig. 9. Average probability of occurrence of *G. platensis* and area of *Eucalyptus* spp. stands according to (a) Damage > 0% IUK model, (b) Damage > 5% IUK model and (c) Damage > 15% IUK model between 2005 and 2020 in Spain.

E. globulus stands showed significantly more damage than other *Eucalyptus* spp. stands in all three IUK models. As regards forest structure, monospecific eucalypt stands were more affected than mixed stands, while in the case of climatic variables, previous summer

temperature and spring precipitation were also found to be significantly related to the incidence of *G. platensis*. There was a significant, negative relationship between previous summer temperature ($p < 0.0001$) and the distribution of the eucalypt weevil in two of the three models

(damage > 5% and damage > 15%). Spring rainfall was identified as having a significant positive relationship with pest incidence in all three models. The spatial range of autocorrelation varied between 1000 km (damage > 0%) and 29 km (damage > 15%) and the temporal range varied from >5 years (damage > 0%) to less than a year (both damage > 5% and damage > 15%). In the three models, the sill of the spatial spherical variogram model (the maximum value of semivariance linked to the spatial distance between observations) was several times larger than the sill of the temporal spherical variogram model, indicating greater variability in space than in time. The variogram parameters as well as coefficients for the three models are included in Table 2.

The predicted probability of the three models for 2020, leaving out observations and auxiliary data, were compared with the data for that year measured in the field (Fig. 5). According to each model, the mean probability predicted in 2020 for plots with field-measured damage above the respective threshold was clearly higher than for those with field-measured damage below the threshold, pointing to the suitability of the proposed model for risk forecasting. The damage > 0% and damage > 15% models performed best.

3.4. Risk maps

Finally, risk maps for Spain were generated based on the SFM polygons to support decision making in pest prevention and control (see Supplementary Materials). The area most affected by *G. platensis* is North-western Spain, as can be seen from detailed examples of the risk maps, Figs. 6–8. South-western Spain is less affected (see Supplementary Materials). According to the UK prediction maps, the national area above the damage > 0% threshold increased between 2005 and 2010 (from an average of 46.7% to 51.4% of *Eucalyptus* spp. area affected) and decreased between 2010 and 2020 (average of 35.7%). This trend was quite similar where the damage was higher than 5% (24.3% in 2005, 26.4% in 2010 and 18.4% in 2020). When damage was greater than 15%, there was a clear diminishing trend from 2005 to 2015 (12.5% and 6.4%, respectively) and then a slight increase in 2020 (8.5%) (Fig. 9).

4. Discussion

This study presents a spatio-temporal IUK approach that allows us to identify the drivers associated with the presence and spread of *G. platensis* and to examine the dynamics of the pest in Spanish *Eucalyptus* spp. plantations through defoliation damage between 2005 and 2020. Given a set of observations irregularly distributed in space and time, geostatistical methods enable us to inspect and describe their statistical properties in order to perform optimal interpolation. These methods have proven to be suitable for stand density, growing stock or species distribution modelling from forest inventories (Aulló-Maestro et al., 2021; Hernández et al., 2014; Mandallaz and Ye, 1999). Expanding kriging techniques to model space–time survey data allows us to analyze changes in forest species distribution (Moreno-Fernández et al., 2016) or spread of animal diseases (Iglesias et al., 2018). Our findings show that these methods can also be used to examine changes in the spread of forest pests using long-term data and to assess the variance linked to environmental factors and intrinsic spatio-temporal factors, as well as to make one-year predictions for prevention strategy planning.

Along with the previous summer temperature, spring rainfall and monospecific *E. globulus* stands were found to be positively associated with the probability of *G. platensis* incidence. These results reveal that monospecific *E. globulus* stands in areas of Spain with milder weather (cooler summers and humid springs) are more prone to attack by *G. platensis*. This type of weather is typical of the Atlantic region in Spain, which is more affected by this pest than the Mediterranean region. Hence, climatic variables would appear to be of greater significance than forest structure. All the climate change scenario projections for Europe (IPCC, 2014) suggest that by 2100, temperatures will have increased, annual precipitation will be slightly lower and rainy seasons

will be longer. These scenarios are likely to result in positive responses of pest populations, such as increased development rate, increased chance of survival and reproductive potential as well as negative effects like decreased growth rate and reduced fecundity (Bale et al., 2002; Huberty and Denno, 2004; Hunter, 2001).

E. globulus is consistently found to be a preferred host in countries where *G. platensis* is present, even though several other eucalypt species have also been identified as susceptible (Cordero Rivera, 2000; Hanks et al., 2000; Lanfranco and Dungey, 2001). Furthermore, differences in susceptibility between species are less pronounced at high attack intensity (Gonçalves et al., 2019). Our results confirm a positive association between *E. globulus* and the probability of *G. platensis* incidence for all levels of damage in Spain. *E. globulus* is the main species in 56% of the Spanish *Eucalyptus* area (61% in Atlantic areas and 44% in Mediterranean areas), so plantations with less susceptible plant material would help to reduce the incidence of *G. platensis*.

Our results indicate that monospecific stands are more susceptible to defoliation than mixed stands. *Eucalyptus* spp. plantations in Spain are generally monospecific, planted in regular rows (generally 3 m × 3 m), with the aim of optimizing wood production. Homogeneous landscapes with high stand density can shorten the timescale and increase the frequency of pest dispersion by increasing the amount and connectivity of resources to the pest (Tscharntke et al., 2012). Abandonment of plantations caused by depopulation in rural areas, higher recurrence of fires and low productivity of small stands may lead to an increase in *Eucalyptus* mixed stands (Tomé et al., 2021). In this regard, several authors have stated that mixed stands are more resistant to natural disturbances caused by different agents, specialized insect herbivores among them (Jactel et al., 2017). Our results appear to support this statement, mixed *Eucalyptus* forests being less affected by *G. platensis* over all the period and regions studied. However, the productivity and profitability of mixed stands of *Eucalyptus* spp. could be diminished by competition with other species, depending on accompanying species, stand age and productivity (Forrester et al., 2011).

Our probability-of-occurrence maps reveal that the area with defoliation damage > 0% and defoliation damage > 5% by *G. platensis* increased until around 2010, then declined through 2020. Climate data in the study area, with a negative tendency for spring rainfall and a positive tendency for summer temperature since around 2010, show a high correlation with these results. These climatic variables were also significant when damage was greater than 15%, but showed a downward trend from 2005 to 2015 and then a slight increase in 2020.

Biological control through the introduction of parasitoids may also have had an impact on the spread of this pest. The egg parasitoid *A. nitens* is the main agent used worldwide to control *Goniapterus* spp. (Hanks et al., 2000; Reis et al., 2012). In the 1970s, it was successfully employed to control *Goniapterus* spp. in Italy and France, and later introduced into Spain at the end of 1993 (Mansilla and Perez, 1996). Success was restricted to a few areas despite successive releases of this parasitoid in Spain (Cordero Rivera et al., 1999; Reis et al., 2012). Santolamazza-Carbone et al. (2006) concluded that the effect of parasitism by *A. nitens* in some localities in NW Spain was to lower the *G. platensis* populations to levels below which the snout beetle could not be detected. Valente et al. (2017b, 2017a) assessed *A. inexpectatus* Huber as another possible *Anaphes* species to parasitize *Goniapterus* spp., reporting that it had good potential as a biological control candidate and that risk of negative environmental impacts due to the introduction of this parasitoid in Southwestern Europe is minimal.

The efficacy of the biological control organism is not always satisfactory and over 80% of organism release for biological control of arthropods is ineffective (Hall et al., 1980). Host density can be reduced by the action of parasitoids, but this in turn can shrink parasitoid density due to the lack of hosts (Begon et al., 1996). Understanding the spatio-temporal dynamics of pests and their natural enemies is important for the conservation and release of biological agents in the field (Park and Obrycki, 2004). Parasitoids and chemical treatments that influence the

spread of *G. platensis* have not been considered in this study.

Both the larvae and the adults of *G. platensis* feed on *Eucalyptus* leaves, causing defoliation damage in both development stages (Reis et al., 2012; Tooke, 1955). Mansilla and Perez (1996) reported that the insect lays eggs from March–June and from October–December in North-Western Spain, with an aestivation period from July–September. Cordero Rivera et al. (1999) found inter-annual variability in the number of egg-laying periods. These authors stated that this variability could be due to the *Anaphens nitens* parasitoid. Reis et al. (2012) observed that the population of adult weevils at the end of winter showed a significant, linear, positive relationship with the percentage of defoliation at the end of spring. Loch (2006) concluded that lower reproduction by *G. platensis* may be due to the limited availability from summer onwards of new flushing foliage, which is essential for feeding and oviposition. These findings are supported by our results, which reveal that high summer temperatures lead to a reduction in the incidence of damage in the following year. Thus, it may be concluded that hotter aestivation periods result in a lower ratio of survival of adults and consequently, a lower number of larvae.

Finally, forest management could also alter the future distribution of tree species, which will alter host distributions. The area occupied by *E. nitens* has increased substantially in the North of the Iberian Peninsula due to its suitability in frost prone areas and its lower susceptibility to defoliation by *G. platensis* (Gonçalves et al., 2019; Pérez-Cruzado et al., 2011). Likewise, land use change could alter forested land and urbanization patterns, both of which would affect pest spread (Hudgins et al., 2017). In Spain, most *Eucalyptus* spp. plantations are owned by small non-industrial private owners, a large majority of whom do not implement the management practices needed to obtain high productivity, or in many cases, any active forest management at all (Tomé et al., 2021).

Risk maps generated based on the SFM polygons help us to decide where to focus pest prevention and control. However, the results also indicate important synergies of biological control, climate change, site conditions and forest management that impact the dynamics of *Eucalyptus* spp. stands and *G. platensis* populations (Jordan et al., 2021; Rua et al., 2020). Our understanding of the adaptive capacity and vulnerability of *Eucalyptus* plantations to these variables is scarce, so further research efforts focusing on these aspects are required.

5. Conclusions

Our findings indicate that the incidence and occurrence of *G. platensis* in Spanish *Eucalyptus* spp. stands is strongly related to climatic conditions, especially the previous summer temperature and spring rainfall. Therefore, forecasted changes in climatic conditions could alter the influence of this pest on the profitability of *Eucalyptus* spp. stands. Monospecific *Eucalyptus globulus* stands in areas of Spain where weather conditions are mild, with cooler summers and humid springs, are more prone to attack by *G. platensis*.

This study establishes a methodology (LIMP-ICP and RMN permanent networks along with IUK geostatistical models) which enables us to understand and simulate the spread of *G. platensis*, generating risk maps, which are essential to the development of programs for controlling or preventing the spread, thus mitigating the economic consequences.

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CRediT authorship contribution statement

Patricia Adame: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Icieri Alberdi:** Writing – review & editing, Funding acquisition. **Isabel Cañellas:** Writing – review & editing, Funding acquisition. **Laura Hernández:** . **Ana Aguirre:** Writing – review & editing. **Antonio Ruano:** Writing – review & editing. **Daniel Moreno-Fernández:** Writing – review & editing. **Ana Isabel González:** Writing – review & editing. **Maria Belen Torres:** Writing – review & editing. **Fernando Montes:** Conceptualization, Software, Formal analysis, Writing – review & editing, Supervision, Funding acquisition.

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.

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Appendix A. Supplementary material

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References

- Armstrong, M., 1998. Basic Linear Geostatistics. Basic Linear Geostat. <https://doi.org/10.1007/978-3-642-58727-6>.
- Alvarez Taboada, M.F., Lorenzo Cimadevila, H., Rodriguez Perez, J.R., Picos Martin, J., 2004. Workflow to improve the forest management of *Eucalyptus globulus* stands affected by *Gonipterus scutellatus* in Galicia, Spain using remote sensing and GIS, in: Remote Sensing for Environmental Monitoring, GIS Applications, and Geology IV. <https://doi.org/10.1117/12.563507>.
- Atkinson, P.M., Lloyd, C.D., 2007. Non-stationary variogram models for geostatistical sampling optimisation: An empirical investigation using elevation data. *Comput. Geosci.* 33 (10), 1285–1300. <https://doi.org/10.1016/j.cageo.2007.05.011>.
- Aulló-Maestro, I., Gómez, C., Marino, E., Cabrera, M., De La Cueva, A.V., Montes, F., 2021. Integration of field sampling and LiDAR data in forest inventories: comparison of area-based approach and (lognormal) universal kriging. *Ann. For. Sci.* 78 (2) <https://doi.org/10.1007/s13595-021-01056-1>.
- Badalamenti, E., Cusimano, D., La Mantia, T., Pasta, S., Romano, S., Troia, A., Ilardi, V., 2018. The ongoing naturalisation of *Eucalyptus* spp. in the Mediterranean Basin: new threats to native species and habitats. *Aust. For.* 81 (4), 239–249. <https://doi.org/10.1080/00049158.2018.1533512>.
- Bale, J.S., Masters, G.J., Hodkinson, I.D., Awmack, C., Bezemer, T.M., Brown, V.K., Butterfield, J., Buse, A., Coulson, J.C., Farrar, J., Good, J.E.G., Harrington, R., Hartley, S., Jones, T.H., Lindroth, R.L., Press, M.C., Symrnioudis, I., Watt, A.D., Whittaker, J.B., 2002. Herbivory in global climate change research: Direct effects of rising temperature on insect herbivores. *Glob. Chang. Biol.* 8 (1), 1–16. <https://doi.org/10.1046/j.1365-2486.2002.00451.x>.
- Begon, M., Mortimer, M., Thompson, D.J., 1996. *Population Ecology: A Unified Study of Animals and Plants*, Third Blackwell Science Ltd, United Kingdom. <https://doi.org/10.1002/9781444313765>.
- Bennett, B.M., 2011. A Global History of Australian Trees. *J. Hist. Biol.* 44 (1), 125–145. <https://doi.org/10.1007/s10739-010-9243-7>.
- Bussotti, F., Feducci, M., Iacopetti, G., Maggino, F., Pollastrini, M., Selvi, F., 2018. Linking forest diversity and tree health: preliminary insights from a large-scale survey in Italy. *For. Ecosyst.* 5 (1) <https://doi.org/10.1186/s40663-018-0130-6>.

- Ciriani, M.-L., Dalstein, L., 2018. Forest Health Monitoring Highlights Progress in Forest Deterioration in France. *Water Air Soil Pollut* 229 (10). <https://doi.org/10.1007/s11270-018-3922-y>.
- Clark, A.F., 1937. A Survey of the Insect Pests of Eucalyptus in New Zealand. *New Zeal. J. Sci. Technol.* 750–761.
- Colautti, R.I., Ricciardi, A., Grigorovich, I.A., MacIsaac, H.J., 2004. Is invasion success explained by the enemy release hypothesis? *Ecol. Lett.* 7 (8), 721–733. <https://doi.org/10.1111/j.1461-0248.2004.00616.x>.
- Cordero Rivera, A., 2000. The effect of three species of Eucalyptus on growth and fecundity of the Eucalyptus snout beetle (Gonipterus scutellatus). *Forestry* 73 (1), 21–29. <https://doi.org/10.1093/forestry/73.1.21>.
- Cordero Rivera, A., Santolamazza Carbone, S., Andrés, J.A., Rivera, A.C., Carbone, S.S., Andrés, J.A., 1999. Life cycle and biological control of the Eucalyptus snout beetle (Coleoptera, Curculionidae) by *Anaphes nitens* (Hymenoptera, Mymaridae) in north-west Spain. *Agric. For. Entomol.* 1, 103–109. <https://doi.org/10.1046/j.1461-9563.1999.00016.x>.
- Cressie, N., 1985. Fitting variogram models by weighted least squares. *J. Int. Assoc. Math. Geol.* 17 (5), 563–586. <https://doi.org/10.1007/BF01032109>.
- da Silva, P.H.M., Poggiani, F., Sebbenn, A.M., Mori, E.S., 2011. Can Eucalyptus invade native forest fragments close to commercial stands? *For. Ecol. Manage.* 261 (11), 2075–2080. <https://doi.org/10.1016/j.foreco.2011.03.001>.
- De Iaco, S., Myers, D.E., Posa, D., 2002. Space-time variograms and a functional form for total air pollution measurements. *Comput. Stat. Data Anal.* 41 (2), 311–328. [https://doi.org/10.1016/S0167-9473\(02\)00081-6](https://doi.org/10.1016/S0167-9473(02)00081-6).
- Duarte, A., Whitlock, S.L., Peterson, J.T., 2018. Species distribution modeling. In: *Encyclopedia of Ecology*. Elsevier, pp. 189–198. <https://doi.org/10.1016/B978-0-12-409548-9.10572-X>.
- Duque-Lazo, J., Navarro-Cerrillo, R.M., 2017. What to save, the host or the pest? The spatial distribution of xylophage insects within the Mediterranean oak woodlands of Southwestern Spain. *For. Ecol. Manage.* 392, 90–104. <https://doi.org/10.1016/j.foreco.2017.02.047>.
- Eichhorn, J., Roskams, P., Potočić, N., Timmermann, V., Ferretti, M., Mues, V., Szepesi, A., Durrant, D., Seletković, I., Schröck, H., Nevalainen, S., Bussotti, F., Garcia, P., Wulf, S., 2020. Part IV: Visual Assessment of Crown Condition and Damaging Agents, in: UNECE ICP Forests Programme Co-Ordinating Centre (Ed.): *Manual on Methods and Criteria for Harmonized Sampling, Assessment, Monitoring and Analysis of the Effects of Air Pollution on Forests*. Thünen Institute of Forest Ecosystems, Eberswalde, Germany, p. 50.
- Ferretti, M., 2013. Concepts and design principles adopted in the international cooperative program on the assessment and monitoring of air pollution effects on forests (ICP Forests), in: *Developments in Environmental Science*. <https://doi.org/10.1016/B978-0-08-098222-9.00006-6>.
- Forrester, D.I., Vanclay, J.K., Forrester, R.I., 2011. The balance between facilitation and competition in mixtures of Eucalyptus and Acacia changes as stands develop. *Oecologia* 166 (1), 265–272. <https://doi.org/10.1007/s00442-011-1937-9>.
- Gonçalves, C.I., Vilas-Boas, L., Branco, M., Rezende, G.D., Valente, C., 2019. Host susceptibility to *Gonipterus platensis* (Coleoptera: Curculionidae) of Eucalyptus species. *Ann. For. Sci.* 76, 63. <https://doi.org/10.1007/s13595-019-0850-y>.
- Goovaerts, P., 1997. *Geostatistics for Natural Resources Evaluation (Applied Geostatistics)*. Oxford University Press, New York.
- Gumovsky, A., De Little, D., Rothmann, S., Jaques, L., Mayorga, S.E.I., 2015. Re-description and first host and biology records of *Entedon magnificus* (Girault & Dodd) (Hymenoptera, Eulophidae), a natural enemy of *Gonipterus weevils* (Coleoptera, Curculionidae), a pest of Eucalyptus trees. *Zootaxa* 3957, 577–584. <https://doi.org/10.11646/zootaxa.3957.5.6>.
- Hall, R.W., Ehler, L.E., Bisabir-Ershadi, B., 1980. Rate of Success in Classical Biological Control of Arthropods. *Bull. Entomol. Soc. Am.* 26 (2), 111–114. <https://doi.org/10.1093/besa/26.2.111>.
- Hanks, L.M., Millar, J.G., Paine, T.D., Campbell, C.D., 2000. Classical biological control of the Australian beetle *Gonipterus scutellatus* (Coleoptera: Curculionidae) in California. *Biol. Control* 29, 369–375. <https://doi.org/10.1093/ee/29.2.369>.
- Hengl, T., Sierdsema, H., Radović, A., Dilo, A., 2009. Spatial prediction of species' distributions from occurrence-only records: combining point pattern analysis. *Ecol. Modell.* 220 (24), 3499–3511. <https://doi.org/10.1016/j.ecolmodel.2009.06.038>.
- Hernández, L., Cañellas, I., Alberdi, I., Torres, I., Montes, F., 2014. Assessing changes in species distribution from sequential large-scale forest inventories. *Ann. For. Sci.* 71 (2), 161–171. <https://doi.org/10.1007/s13595-013-0308-6>.
- Huberty, A.F., Denno, R.F., 2004. Plant water stress and its consequences for herbivorous insects: A new synthesis. *Ecology* 85 (5), 1383–1398. <https://doi.org/10.1890/03-0352>.
- Hudgins, E.J., Liebhold, A.M., Leung, B., Early, R., 2017. Predicting the spread of all invasive forest pests in the United States. *Ecol. Lett.* 20 (4), 426–435. <https://doi.org/10.1111/ele.12741>.
- Huffaker, C.B., Simmonds, F.J., Laing, J.E., 1976. The theoretical and empirical basis of biological control. In: *Theory and Practice of Biological Control*. <https://doi.org/10.1016/b978-0-12-360350-0.50009-x>.
- Hunter, M.D., 2001. Effects of elevated atmospheric carbon dioxide on insect-plant interactions. *Agric. For. Entomol.* 3 (3), 153–159. <https://doi.org/10.1046/j.1461-9555.2001.00108.x>.
- Hurley, B.P., Gamas, J., Wingfield, M.J., Branco, M., Richardson, D.M., Slippers, B., 2016. Increasing numbers and intercontinental spread of invasive insects on eucalypts. *Biol. Invasions* 18 (4), 921–933. <https://doi.org/10.1007/s10530-016-1081-x>.
- Iglesias, I., Montes, F., Martínez, M., Pérez, A., Gogin, A., Kolbasov, D., de la Torre, A., 2018. Spatio-temporal kriging analysis to identify the role of wild boar in the spread of African swine fever in the Russian Federation. *Spat. Stat.* 28, 226–235. <https://doi.org/10.1016/j.jspasta.2018.07.002>.
- IPCC, 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC.
- Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B., Gardiner, B., Gonzalez-Olabarria, J.R., Koricheva, J., Meurisse, N., Brockerhoff, E.G., 2017. Tree Diversity Drives Forest Stand Resistance to Natural Disturbances. *Curr. Forestry Rep.* 3 (3), 223–243. <https://doi.org/10.1007/s40725-017-0064-1>.
- Jactel, H., Koricheva, J., Castagneyrol, B., 2019. Responses of forest insect pests to climate change: not so simple. *Curr. Opin. Insect. Sci.* 35, 103–108. <https://doi.org/10.1016/j.cois.2019.07.010>.
- Janik, G., Pödör, Z., Koltay, A., Hirka, A., Juhász, J., Kovács, G., Csóka, G., 2020. Effects of Meteorological and Site Parameters on the Health Status of Beech (*Fagus sylvatica* L.) Forests in Hungary. *Acta Silv. Lignaria Hungarica*. 16 (2), 67–78. <https://doi.org/10.37045/aslh-2020-0005>.
- Jordan, C., dos Santos, P.L., Oliveira, L.R.D.S., Domingues, M.M., Gêa, B.C.C., Ribeiro, M. F., Mascarin, G.M., Wilcken, C.F., 2021. Entomopathogenic fungi as the microbial frontline against the alien Eucalyptus pest *Gonipterus platensis* in Brazil. *Sci. Rep.* 11 (1) <https://doi.org/10.1038/s41598-021-86638-9>.
- Lanfranco, D., Dungey, H.S., 2001. Insect damage in eucalyptus: A review of plantations in Chile. *Austral Ecol.* 26 (5), 477–481. <https://doi.org/10.1046/j.1442-9993.2001.01131.x>.
- Lappi, J., 2001. Forest inventory of small areas combining the calibration estimator and a spatial model. *Can. J. For. Res.* 31 (9), 1551–1560. <https://doi.org/10.1139/x01-078>.
- Loch, A.D., 2008. Parasitism of the Eucalyptus weevil, *Gonipterus scutellatus* Gyllenhal, by the egg parasitoid, *Anaphes nitens* Girault, in Eucalyptus globulus plantations in southwestern Australia. *Biol. Control*. 47 (1), 1–7. <https://doi.org/10.1016/j.biocontrol.2008.07.015>.
- Loch, A.D., 2006. Phenology of Eucalyptus weevil, *Gonipterus scutellatus* Gyllenhal (Coleoptera: Curculionidae), and chrysomelid beetles in Eucalyptus globulus plantations in south-western Australia. *Agric. For. Entomol.* 8 (2), 155–165. <https://doi.org/10.1111/j.1461-9563.2006.00294.x>.
- López-Sánchez, C.A., Castedo-Dorado, F., Cámara-Obrigón, A., Barrio-Anta, M., 2021. Distribution of Eucalyptus globulus Labill. in northern Spain: Contemporary cover, suitable habitat and potential expansion under climate change. *For. Ecol. Manage.* 481, 118723. <https://doi.org/10.1016/j.foreco.2020.118723>.
- Lottering, R., Mutanga, O., Peerbhay, K., Ismail, R., 2019. Detecting and mapping *Gonipterus scutellatus* induced vegetation defoliation using WorldView-2 pan-sharpened image texture combinations and an artificial neural network. *J. Appl. Remote Sens.* 13 (1) <https://doi.org/10.1117/1.JRS.13.014513>.
- Machado, D.D.N., Costa, E.C., Perini, C.R., Ugalde, G.A., Saldanha, M.A., Leitão, J.V., Colpo, T.L., Arnemann, J.A., Rivera, A.C., 2019. The ongoing dispersion of the Eucalyptus bronze bug (*Thaumastocoris peregrinus*) in Spain. *For. Syst.* 28, eSC03. <https://doi.org/10.5424/fs/2019283-15353>.
- MAGRAMA, 2006. *Mapa Forestal de España 1:50.000 (MFE)* [WWW Document]. Minist. Agric. Aliment. y Medio Ambient.
- Mandallaz, D., Ye, R., 1999. Forest inventory with optimal two-phase two-stage sampling schemes based on the anticipated variance. *Can. J. For. Res.* 29 (11), 1691–1708. <https://doi.org/10.1139/x99-124>.
- Mansilla, J.P., Perez, R., 1996. *El defoliador del eucalipto Gonipterus scutellatus*. *Phytoma España VI* 36–42.
- Mansilla Vazquez, J., 1992. Presencia sobre Eucalyptus globulus Labill de *Gonipterus scutellatus* Gyll. (Col., Curculionidae) en Galicia. *Boletín Sanid. Veg. Plagas*.
- Mapondera, T.S., Burgess, T., Matsuki, M., Oberprieler, R.G., 2012. Identification and molecular phylogenetics of the cryptic species of the *Gonipterus scutellatus* complex (Coleoptera: Curculionidae: Gonipterini). *Aust. J. Entomol.* 51, 175–188. <https://doi.org/10.1111/j.1440-6055.2011.00853.x>.
- Matheron, G., 1973. The intrinsic random functions and their applications. *Adv. Appl. Probab.* 5 (3), 439–468. <https://doi.org/10.2307/1425829>.
- Miller, J., Franklin, J., Aspinall, R., 2007. Incorporating spatial dependence in predictive vegetation models. *Ecol. Modell.* 202 (3–4), 225–242. <https://doi.org/10.1016/j.ecolmodel.2006.12.012>.
- MITECO, 2018. *Anuario de estadística forestal*. Madrid.
- Mohammadi, J., van Meirvenne, M., Goovaerts, P., 1997. Mapping Cadmium Concentration and the Risk of Exceeding a Local Sanitation Threshold Using Indicator Geostatistics, in: Soares, A., Gómez-Hernández, J., Froidevaux, R. (Eds.), *GeoENV I — Geostatistics for Environmental Applications. Quantitative Geology and Geostatistics, Vol 9*. Dordrecht. https://doi.org/10.1007/978-94-017-1675-8_27.
- Montes, F., Ledo, A., 2010. Incorporating environmental and geographical information in forest data analysis: A new fitting approach for universal kriging. *Can. J. For. Res.* 40 (9), 1852–1861. <https://doi.org/10.1139/X10-131>.
- Moreno-Fernández, D., Hernández, L., Sánchez-González, M., Cañellas, I., Montes, F., 2016. Space-time modeling of changes in the abundance and distribution of tree species. *For. Ecol. Manage.* 372, 206–216. <https://doi.org/10.1016/j.foreco.2016.04.024>.
- Neuman, S.P., Jacobson, E.A., 1984. Analysis of nonintrinsic spatial variability by residual kriging with application to regional groundwater levels. *J. Int. Assoc. Math. Geol.* 16 (5), 499–521. <https://doi.org/10.1007/BF01886329>.
- Norberg, A., Abrego, N., Blanchet, F.G., Adler, F.R., Anderson, B.J., Anttila, J., Araújo, M. B., Dallas, T., Dunson, D., Elith, J., Foster, S.D., Fox, R., Franklin, J., Godsoe, W., Guisan, A., O'Hara, B., Hill, N.A., Holt, R.D., Hui, F.K.C., Husby, M., Kälás, J.A., Lehtikoinen, A., Luoto, M., Mod, H.K., Newell, G., Renner, I., Roslin, T., Soininen, J., Thuiller, W., Vanhatalo, J., Warton, D., White, M., Zimmermann, N.E., Gravel, D., Ovaskainen, O., 2019. A comprehensive evaluation of predictive performance of 33

- species distribution models at species and community levels. *Ecol. Monogr.* 89 (3) <https://doi.org/10.1002/ecm.1370>.
- Oliver, M.A., Webster, R., 2015. *Basic Steps in Geostatistics: the Variogram and Kriging*. Springer-Verlag GmbH.
- Park, Y.-L., Obrycki, J.J., 2004. Spatio-temporal distribution of corn leaf aphids (Homoptera: Aphididae) and lady beetles (Coleoptera: Coccinellidae) in Iowa cornfields. *Biol. Control.* 31 (2), 210–217. <https://doi.org/10.1016/j.bioccontrol.2004.06.008>.
- Pérez-Cruzado, C., Merino, A., Rodríguez-Soalleiro, R., 2011. A management tool for estimating bioenergy production and carbon sequestration in *Eucalyptus globulus* and *Eucalyptus nitens* grown as short rotation woody crops in north-west Spain. *Biomass Bioenergy* 35 (7), 2839–2851. <https://doi.org/10.1016/j.biombioe.2011.03.020>.
- Puletti, N., Canullo, R., Mattioli, W., Gawryś, R., Corona, P., Czerepko, J., 2019. A dataset of forest volume deadwood estimates for Europe. *Ann. For. Sci.* 76, 1–8. <https://doi.org/10.1007/s13595-019-0832-0>.
- QGIS Development Team, 2021. QGIS Geographic Information System. <http://qgis.org>.
- Queirós, L., Deus, E., Silva, J.S., Vicente, J., Ortiz, L., Fernandes, P.M., Castro-Díez, P., 2020. Assessing the drivers and the recruitment potential of *Eucalyptus globulus* in the Iberian Peninsula. *For. Ecol. Manage.* 466, 118147. <https://doi.org/10.1016/j.foreco.2020.118147>.
- Reis, A.R., Ferreira, L., Tomé, M., Araujo, C., Branco, M., 2012. Efficiency of biological control of *Gonipterus platensis* (Coleoptera: Curculionidae) by *Anaphes nitens* (Hymenoptera: Mymaridae) in cold areas of the Iberian Peninsula: Implications for defoliation and wood production in *Eucalyptus globulus*. *For. Ecol. Manage.* 270, 216–222. <https://doi.org/10.1016/j.foreco.2012.01.038>.
- Rivas-Martínez, S., Penas, A., Díaz, T.E., 2004. Bioclimatic map of Europe, bioclimates, cartographic service. Univ. León, León, Spain.
- Rodríguez-Soalleiro, R., Eimil-Fraga, C., Gómez-García, E., García-Villabrille, J.D., Rojo-Alboreca, A., Muñoz, F., Oliveira, N., Sixto, H., Pérez-Cruzado, C., 2018. Exploring the factors affecting carbon and nutrient concentrations in tree biomass components in natural forests, forest plantations and short rotation forestry. *For. Ecosyst.* 5, 35. <https://doi.org/10.1186/s40663-018-0154-y>.
- Rua, J.C.P., Barreiro, S., Branco, M., Tomé, M., 2020. Estimating defoliation impact of *Gonipterus platensis* on *Eucalyptus globulus* stands productivity using a forest simulator based on 3-PG. *For. Ecol. Manage.* 478, 118495. <https://doi.org/10.1016/j.foreco.2020.118495>.
- Santolamazza-Carbone, S., Rodríguez-Illamola, A., Cordero Rivera, A., 2006. Thermal requirements and phenology of the *Eucalyptus* snout beetle *Gonipterus scutellatus* Gyllenhal. *J. Appl. Entomol.* 130 (6-7), 368–376. <https://doi.org/10.1111/j.1439-0418.2006.01073.x>.
- Schröder, M.L., Slippers, B., Wingfield, M.J., Hurley, B.P., 2020. Invasion history and management of *Eucalyptus* snout beetles in the *Gonipterus scutellatus* species complex. *J. Pest Sci.* 93 (1), 11–25. <https://doi.org/10.1007/s10340-019-01156-y>.
- Sunder, S., 1995. The ecological, economic and social effects of *Eucalyptus*. *Proc. Reg. Expert Consult. Eucalyptus*. FAO Reg. Off. Asia Pacific, Bangkok.
- Toigo, M., Nicolas, M., Jonard, M., Croisé, L., Nageleisen, L.-M., Jactel, H., 2020. Temporal trends in tree defoliation and response to multiple biotic and abiotic stresses. *For. Ecol. Manage.* 477, 118476. <https://doi.org/10.1016/j.foreco.2020.118476>.
- Tomé, M., Almeida, M.H., Barreiro, S., Branco, M.R., Deus, E., Pinto, G., Silva, J.S., Soares, P., Rodríguez-Soalleiro, R., 2021. Opportunities and challenges of *Eucalyptus* plantations in Europe: the Iberian Peninsula experience. *Eur. J. For. Res.* 140 (3), 489–510. <https://doi.org/10.1007/s10342-021-01358-z>.
- Tooke, F.G., 1955. The *eucalyptus* snout-beetle, *Gonipterus scutellatus* Gyll: A study of its ecology and control by biological means. *Division Entomol. Entomol. Memoirs* 3.
- Tribe, G.D., 2005. The present status of *Anaphes nitens* (Hymenoptera: Mymaridae), an egg parasitoid of the *eucalyptus* snout beetle *Gonipterus scutellatus*, in the western cape province of South Africa. *Southern Afr. Forestry J.* 203 (1), 49–54. <https://doi.org/10.2989/10295920509505218>.
- Tscharntke, T., Tylianakis, J.M., Rand, T.A., Didham, R.K., Fahrig, L., Batáry, P., Bengtsson, J., Clough, Y., Crist, T.O., Dormann, C.F., Ewers, R.M., Fründ, J., Holt, R. D., Holzschuh, A., Klein, A.M., Kleijn, D., Kremen, C., Landis, D.A., Laurance, W., Lindenmayer, D., Scherber, C., Sodhi, N., Steffan-Dewenter, I., Thies, C., van der Putten, W.H., Westphal, C., 2012. Landscape moderation of biodiversity patterns and processes - eight hypotheses. *Biol. Rev.* 87 (3), 661–685. <https://doi.org/10.1111/j.1469-185X.2011.00216.x>.
- Valente, C., Afonso, C., Gonçalves, C.I., Alonso-Zarazaga, M.A., Reis, A., Branco, M., 2017a. Environmental risk assessment of the egg parasitoid *Anaphes inexpectatus* for classical biological control of the *Eucalyptus* snout beetle. *BioControl* 62 (4), 457–468. <https://doi.org/10.1007/s10526-017-9809-9>.
- Valente, C., Gonçalves, C.I., Monteiro, F., Gaspar, J., Silva, M., Sottomayor, M., Paiva, M. R., Branco, M., 2018. Economic Outcome of Classical Biological Control: A Case Study on the *Eucalyptus* Snout Beetle, *Gonipterus platensis*, and the Parasitoid *Anaphes nitens*. *Ecol. Econ.* 149, 40–47. <https://doi.org/10.1016/j.ecolecon.2018.03.001>.
- Valente, C., Gonçalves, C.I., Reis, A., Branco, M., 2017b. Pre-selection and biological potential of the egg parasitoid *Anaphes inexpectatus* for the control of the *Eucalyptus* snout beetle, *Gonipterus platensis*. *J. Pest Sci.* 90 (3), 911–923. <https://doi.org/10.1007/s10340-017-0839-y>.
- Valente, C., Vaz, A., Pina, J., Manta, A., Sequeira, A., 2004. Control strategy against the *Eucalyptus* snout beetle, *Gonipterus scutellatus* Gyllenhal (Coleoptera, Curculionidae), by the Portuguese cellulose industry. In: Borralho, N. (Ed.), *Proceedings of the IUFRO Conference Eucalyptus in a Changing World*. Aveiro, pp. 37–51.
- Wingfield, M.J., Brockerhoff, E.G., Wingfield, B.D., Slippers, B., 2015. Planted forest health: The need for a global strategy. *Science* 349 (6250), 832–836. <https://doi.org/10.1126/science.aac6674>.
- Withers, T.M., 2001. Colonization of *eucalypts* in New Zealand by Australian insects. *Austral Ecol.* 26 (5), 467–476. <https://doi.org/10.1046/j.1442-9993.2001.01140.x>.
- Wulff, S., Lindelöw, Å., Lundin, L., Hansson, P., Axelsson, A.-L., Barklund, P., Wijk, S., Ståhl, G., 2012. Adapting forest health assessments to changing perspectives on threats - A case example from Sweden. *Environ. Monit. Assess.* 184 (4), 2453–2464. <https://doi.org/10.1007/s10661-011-2130-7>.