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Is insecticide spraying a viable and cost-efficient management practice to control pine processionary moth in Mediterranean woodlands?

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ABSTRACT

Insect pests are a major threat to many forests worldwide, from boreal to tropical forest ecosystems. Some pests exhibit periodical outbreaks, after which their populations often crash as a result of natural biological control. To offset such outbreaks, several management techniques are used, including aerial spraying of insecticides. The question remains whether pest decline following an outbreak is the result of management practices or a natural consequence of the insect's population cycle. In this study, we assessed the performance of aerial spraying of insecticides on pine woodland stands to control pine processionary moth *Thaumetopoea pityocampa* (PPM) outbreaks in southern Spain. To achieve this, we compared the degree to which a forest stand recovers from defoliation from one year of severe damage by PPM to the following year (infestation index) in stands that were treated (i.e. subjected to aerial spraying) and untreated using a 4-years database from the Regional Environmental Council. The results revealed a significant similar recovery from infestation after a PPM outbreak of both sprayed and non sprayed pine woodland stands, for the four most representative pine species (black, Aleppo, maritime, and stone pine). It is concluded that insecticide spraying cannot be considered a prevention for outbreaks if it is applied once the outbreak explodes. Management practices that can help control PPM outbreaks include promoting spatial heterogeneity at the landscape level, fostering biodiversity in pine plantations, and reinforcing parasitoid insect and predatory bird populations that negatively affect the PPM. This study illustrates how simple sampling designs and statistical tests can be useful decision-making tools and can help improve the environmental viability and cost-efficiency of forest management practices.

1. Introduction

Herbivorous insects are integral components of forest dynamics, in which they play important roles (Dajoz, 2000). However, populations may occasionally grow rapidly into damaging proportions (Berryman, 2002). Such sporadic outbreaks can have catastrophic impacts on forests and trees, leading to the complete destruction of large areas of natural and/or planted forests, and considerable economic losses in some cases. In Europe, a number of insect species have achieved pest status over the last half century, since forestry plantations have become more important. One such pest is the pine processionary moth (*Thaumetopoea pityocampa*, Lepidoptera: Notodontidae; henceforth PPM; EPPO/CABI 1997). PPM is one of the most destructive pests in Mediterranean countries, where it attacks different pine species, some of which have been widely used in massive afforestations (Dajoz, 2000). In the last few decades, the area affected by PPM outbreaks in Europe has expanded northwards and upwards in the mountains, and the pest is now affecting higher altitude and latitude areas where it used to be absent (Hódar and Zamora, 2004; Battisti et al., 2005). This has resulted in high attack rates in areas hardly affected by this insect in the past (Battisti et al., 2005). Thus, the application of control methods for aggressive pests such as PPM is a key issue in Mediterranean forestry.

Foliage feeding insects often exhibit periodical outbreaks (Berryman, 2002). In the particular case of PPM, Robinet (2006) proved the existence of a roughly 6-year periodicity by long-term monitoring of nests in France, and similar results were obtained in southern Spain (Hódar and Zamora, 2009) and Italy (Battisti et al., 1998). This cycle, however, is not regular and may vary as much as from three to ten years (see Geri and Miller, 1985). To control PPM outbreaks, several management techniques have been used to date, including manual cutting and burning of nests, pheromone traps/mating disruption systems, and lethal mixtures of chemical and biological insecticides. Of these, aerial spraying of pine forests

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with insecticides is the most widely used option in most Mediterranean countries and has proved successful in preventing the pest multiplying, with apparently limited environmental effects (Sanchis et al., 1990; Battisti et al., 1998; Demolin and Martin, 1998; Dajoz, 2000). These insecticides target larval stages and are thus applied in late summer or early autumn provided that an outbreak of PPM has been detected during the previous winter. Given the proved efficacy of such treatment (Sanchis et al., 1990; Battisti et al., 1998; Demolin and Martin, 1998), aerial spraying of insecticides is thus expected to result in lower PPM incidence during the following winter. Application of insecticides is however implemented at a time when the moth's population is expected to crash as a result of natural biological control (predators–parasitoids, host plant, or both; Berryman, 2002). It follows to question whether PPM decline following aerial spraying of insecticides is a result of management practices or a natural consequence of the insect's population cycle. Despite of the simplicity of this reasoning, no attempt to answer this question has been done during the last two decades of control pest management practices in European forests and plantations. In this study, we assessed the performance of insecticide spraying by comparing the response of heavily infested stands that were either treated (with insecticide) or untreated. Our hypothesis is that, if PPM is effectively controlled by biological agents, we will find no differences in the response of heavily infested woodlands subjected to aerial spraying and untreated stands. Given the current range expansion and intensified virulence of PPM in Europe (Battisti et al., 2005), the implementation of tools that assess the effectiveness of pest management control practices are invaluable for forest management. The integration of forest management practices and scientific evidence is essential in order to ensure that the most environmentally sound and cost-efficient management practices are implemented.

2. Methods

2.1. Study area

The study area is the region of Andalusia (southern Spain). This area covers around 87,300 km^2 (ca. the size of Austria) and includes a wide variety of habitats, from lowlands and meadows on the western side to tall mountains (well above 3000 m.a.s.l.) in the east. Around 44,000 km^2 are forested, of which 19% are covered by both natural (1%) and afforested pine woodlands, mostly monocultures (99%) (Consejería de Medio Ambiente – Junta de Andalucía, 2003). In order to monitor PPM outbreaks, the Regional Environmental Council created a network of pine woodland stands scattered throughout the region (Carrasco et al., 2000). Five main pine species, black (*Pinus nigra*), Aleppo (*P. halepensis*), maritime (*P. pinaster*), stone (*P. pinea*), and Scots (*P. sylvestris*), represent the bulk of pine woodlands. Overall, there are 4389 pine woodland stands: 614 black pine, 1434 Aleppo pine, 657 maritime pine, 1137 stone pine, and 316 Scots pine, covering around 730,000 ha.

2.2. Life cycle of the PPM

In the adult phase, the PPM is a short lived moth which emerges in summer (June–August) and flies at night. The male moth is attracted to the female moth by pheromones that she emits. They will mate and a single female can then lay up to 300 tiny eggs which she attaches in a mass to a pine needle. Around one month later these eggs hatch into minute caterpillars. Caterpillars eat pine needles by night and build white silky nests on the tip of pine branches to take advantage of the sun's heat. These appear during the winter and a single pine tree may have many. This period of night time eating occurs during the winter months (October–March). At the end of the winter (March–April), the caterpillars leave the nest to burrow into the soil. The colony follows a leader, nose to tail, in a long procession. While searching out a pupation site, they may travel a distance of 30 or so metres to find soft soil to burrow into. Once underground they change into pupae and they will lay dormant until the summer months.

2.3. Data collection

At the end of every winter (February–April), trained rangers evaluate the degree of infestation in marked pine stands, according to six categories: 0 = no infestation, 1 = scattered nests, scant defoliation, 2 = defoliation and nests visible from the stand border, 3 = strong defoliation and numerous nests at the stand border, some defoliation in the center of the stand, 4 = very heavy defoliation both at the border and center of stands, and 5 = massive defoliation, almost no foliage remaining (Montoya and Hernández, 1991; Hódar and Zamora, 2004). Pine stands are surveyed by several hundred forest rangers from the Regional Forest Council each year. The application of treatments to control PPM outbreaks only occurs when a forest stand has a degree of infestation $\geq$3. Application of insecticides in earlier infestation stages is not practical because many woodland stands experience low levels of infestation that are not necessarily followed by a population outbreak. On the other hand, not all forest stands with a degree of infestation $\geq$3 are necessarily treated (Table 1), as for instance pine woodlands included in protected areas, which in general are not sprayed. Aerial ultra-light volume (ULV) spraying of insecticides (henceforth referred to as spraying) is the most frequent treatment, and it was applied to 96% of treated forest stands during the study period (Table 1). The main insecticide used to control PPM was diflubenzuron in a dose of 45 g diluted in 3 l of oil per hectare (DIMILIN 45 ULV) (Carrasco, 2008).

We used these data on the incidence of defoliation by PPM for the period 2002–2005. Although there is a climatic component that makes some years more prone to PPM infestation at a regional scale (Hódar and Zamora, 2009), we can assume that, in general terms, the PPM in each woodland stand follow its own cycle. Since our study focuses only on stands in later stages of infestation (which are those that are potential candidates for aerial spraying), there is no need to have information on earlier stages of the full 6-year cycle.

2.4. Data analysis

To compare the effects of spraying vs. no management of forest stands, we created a response variable, *PPM infestation index*, that reflects the degree to which a forest stand recovers from defoliation from one year of severe damage by PPM (degree of infestation $\geq$3) to the following year.

$$\begin{aligned}\text{PPM infestation index} &= \text{degree of infestation}_{t+1}\\ &\quad - \text{degree of infestation}_{t}\end{aligned}$$

Since the highest infestation value considered is 5, the *PPM infestation index* may vary between -5 and 5, where negative values indicate some recovery from PPM infestation as compared to the previous year, and positive values indicate an increase in the degree of infestation by PPM.

We first compared the *PPM infestation index* in woodland stands that were subjected to spraying vs. those non-sprayed provided they had suffered a degree of infestation $\geq$3 during any of the years within the study period for each of the pine species. Of the five main pine species, only the first four were considered for this study since data for Scots pine were insufficient. The total number of stands subjected to spraying vs. no spraying was 14 vs. 256 for black pine,

Table 1
Number of stands and pine forest area in Andalusia (southern Spain) between 2002 and 2005 for all pine forest stands, stands that have suffered a degree of infestation ≥3 (i.e. strong, heavy or massive defoliation, % total pine forest in brackets), and sprayed stands and those treated with other methods (including manual cutting and burning of nests, pheromone traps, and insecticides that are applied by means of ground based (truck or backpack) methods).

	2002		2003		2004		2005	
	N stands	km^2	*N* stands	km^2	*N* stands	km^2	*N* stands	km^2
Total pine forest stands	3350	6192	3597	6566	3639	6724	3656	6702
Degree of infestation ≥3	318 (9.5%)	639 (10.3%)	398 (11.1%)	715 (10.9%)	427 (11.7%)	813 (12.1%)	218 (6.0%)	453 (6.7%)
Total treated	170	312	138	250	118	223	111	250
Insecticide spraying	149	280	135	245	118	223	110	249
Other treatments	21	32	3	5	0	0	1	1

29 vs. 216 for Aleppo pine, 26 vs. 226 for maritime pine, and 71 vs. 438 for stone pine, respectively. Since this sampling design does not take into account the local variability of woodland stands (mostly climatic variability), we also compared paired samples. We chose stands that had suffered a degree of infestation ≥3 within the same year and compared sprayed vs. non-sprayed stands, pairing those that had a similar degree of infestation in the first year and were as close as possible to each other. Stands further away than 50 km from each other were discarded for further analyses (mean distance between stand centroids = 8.97 km). One of the advantages of a paired sampling design is that it has greater power than an unpaired design because the variance attributable to individual samples is negligible. By pairing samples using only neighbouring stands, sample size was reduced to 13, 23, 22 and 71 pairs of black, Aleppo, maritime and stone pine stands, respectively. Selection and pairing of woodland stands was undertook in late 2009, once we had full access to the Regional Environmental Council database.

We compared the distribution of *PPM infestation index* values from stands that were treated (i.e. subjected to spraying) and not treated using *t*-test and equivalence testing (Brosi and Biber, 2009), for both unpaired and paired samples. Scientists often assume populations are identical ("null hypothesis"), and then statistically test to identify differences (e.g. *t*-test); if a significant difference is not found, scientists usually accept the null hypothesis as true, when in fact it cannot be rejected. A better option in such cases is equivalence testing, which assumes that populations are different, and attempts to prove they are the same. Equivalence testing calculates a two-sample *t*-test for equivalence in means using confidence intervals, avoiding Type II errors (i.e. failing to reject a null-hypothesis when it should have been rejected). Confidence intervals in equivalence testing are estimated as follows:

$$\text{confidence limits} = \text{estimate} \pm \text{critical value} \times \text{standard error}$$

where the estimate is the difference between the means of the two sample distributions, which can be set in units of the data (e.g. metres) or in standard deviation units.

The critical value is the value that defines the limits of a standard normal distribution containing $(1-\alpha)$% (typically 95%) of the curve's area. For a two-tailed test with $\alpha = 0.05$, this critical value = 1.96. See Brosi and Biber (2009) for further details.

In equivalence testing, the null hypothesis is not that populations are equal, but that there is a difference between them. The experimenter must define a priori minimum difference between populations that is assumed as the null hypothesis (Brosi and Biber, 2009). This interval must be considered carefully, making sure that the expected minimum detectable difference is biologically meaningful. We set the minimum difference $\triangle$ in our study to a value of one, which was the unitary measure of our response variable. A detected difference between populations <1 is thus assumed to have no biological meaning in the context of our study. The method has the advantage of allowing the experimenter to simultaneously conduct an equivalence test and a traditional hypothesis test. All analyses were performed in R (R Development Core Team, 2010) with the 'equivalence' package (Robinson, 2010).

3. Results

The percentage of woodland stands that were strongly defoliated by PPM (degree of infestation ≥3) increased progressively between 2002 and 2004 from 9.5% to 11.7% respectively, suffering an abrupt decline to 6.0% in 2005 (Table 1). A similar pattern was detected for forest cover. The number of forest stands that were treated to control PPM outbreaks decreased during the study period, from 170 in 2002 to 110 in 2005 (Table 1). Total treated forest area also decreased progressively from 2002 to 2004 but increased slightly in 2005, indicating that fewer but larger woodland stands were treated in this year. Over 90% of the treatments throughout the study period consisted in the aerial application of insecticides (i.e. spraying), being almost 100% during 2004 and 2005.

Traditional *t*-tests applied to both unpaired and paired sampling designs showed no significant differences between sprayed and non-sprayed stands for all four pine species (Table 2). Equivalence testing applied to both unpaired and paired sampling designs allowed us rejecting the null hypothesis that there is a minimum difference of $= 1$ in the mean *PPM infestation index* between sprayed and non-sprayed stands for most pine species (Table 2). Only black pine under a paired sampling scheme resulted statistically non significant (Table 2). Consequently, there was not enough evidence to reject the null hypothesis of equal means (*t*-test) nor the null hypothesis of a minimum difference of $\triangle = 1$

Table 2
95% confidence intervals for the difference between means of the *PPM infestation index* in sprayed and non sprayed stands for four pine species using unpaired and paired sampling designs. *p*-Values are provided for traditional hypothesis testing (TT, where the null hypothesis assumes that means are not different) and equivalence testing (ET, where the null hypothesis assumes that difference of means is equal to one). Mean, minimum and maximum distance between paired stands is included.

	Unpaired sampling design			Paired sampling design			
	CI	*p*-Value (TT)	*p*-Value (ET)	CI	*p*-Value (TT)	*p*-Value (ET)	Distance between paired stands (km)
Pinus nigra	−0.894, 0.810	0.918	0.034	−1.086, 1.394	0.800	0.127	11.45 (1.69–34.14)
P. halepensis	−0.755, 0.175	0.214	0.007	−0.888, 0.453	0.517	0.028	15.55 (1.06–41.24)
P. pinaster	−0.729, 0.248	0.324	0.006	−0.904, 0.814	0.915	0.034	12.39 (0.77–47.50)
P. pinea	−0.292, 0.335	0.892	<0.001	−0.267, 0.577	0.469	<0.001	5.33 (0.32–34.69)

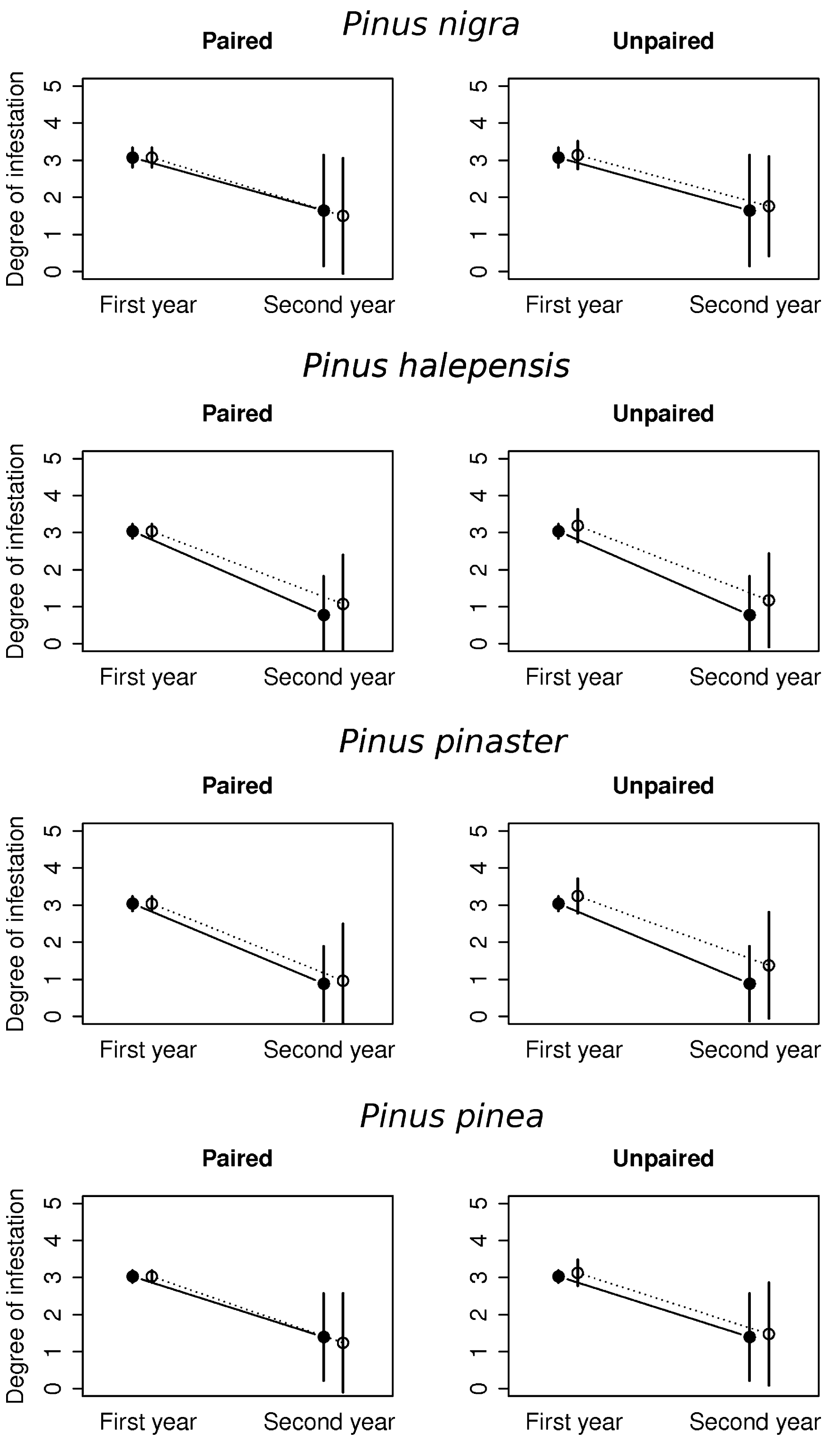

Fig. 1. Mean and standard deviation of the degree of infestation in sprayed (solid line) and non-sprayed (dashed line) pine woodland stands in years of high PPM incidence (first year) and the following year (second year). Results are shown for all four pine species: black (*P. nigra*), Aleppo (*P. halepensis*), maritime (*P. pinaster*) and cluster (*P. pinea*) as well as for paired and unpaired sampling designs.

in the mean *PPM infestation index* between sprayed and non-sprayed stands. This clearly indicates that more data are needed to reach a reliable conclusion. Fig. 1 shows no clear differences between the decrease in the degree of infestation after an outbreak of PPM (degree of incidence ≥3 in the first year) in sprayed and non-sprayed pine stands regardless of sampling design and species.

4. Discussion

The traditional view in forest pest control is that plant-feeding insects and pathogens are destructive agents that must be controlled to protect forest resources. In economic as well as environmental terms, however, pest management interventions must follow from a clear need to manage that pest, a decision that must be based on scientific evidence as much as possible. Our study provides a simple quantitative assessment that reveals a homogeneous response of sprayed and non-sprayed pine stands following an outbreak of PPM. We believe that this is not due to the inefficacy of insecticides used to control the pest, which have been indeed proved to be toxic to many forest insect pests, PPM among them (Sanchis et al., 1990; Battisti et al., 1998; Demolin and Martin, 1998; Dajoz, 2000), but to the timing of spraying, which takes place when the moth populations have reached a peak and are about to decline naturally. Such decline occurs not only because trees react to strong defoliation by producing inadequate food for the next generation of insects (Hódar et al., 2004), but also because there is an increase in insect parasitoid and predatory bird populations (Berryman, 2002; Barbaro and Battisti, 2011), all of which causes a collapse of the PPM population density. Similar results have been found for pheromone traps that aim to control bark beetle (*Ips typographus* L.) outbreaks in Poland (Grodzki et al., 2006), and massive releases of rodenticides that were used to control outbreaks of common voles *Microtus arvalis* between 2006 and 2007 in areas of north-western Spain (Olea et al., 2009). These authors attributed lack of difference between treated and untreated samples to natural declines of the pest populations due to exhaustion of resources and an increase of natural enemies (predators, parasitoids, etc.). Indeed, most potential pests are likely to be under natural biological control in forest and agro-ecosystems (van Lenteren, 2006), but this is rarely taken into account in forest management plans.

Our results can have both economic and ecological implications for forest management practices. The profitability of aerial treatments can be questioned if the benefits obtained are not significant enough to offset such costs (Aimi et al., 2006). The management and control of insect pests entails substantial monetary investments. With respect to PPM, between €1.0 and €1.5 million are spent annually on aerial spraying to control PPM outbreaks in our study region. In addition, because aerial spraying is conducted in the winter following strong, heavy or massive defoliation, treatments are unlikely to limit growth losses or prevent further damage to trees by other organisms. In this context, we advocate for more rigorous tests to evaluate the cost-effectiveness of pest control practices, combined with economic assessments (Gatto et al., 2009), instead of applying a routinary and unnecessary spraying protocol. Insecticide spraying cannot be considered a prevention for outbreaks if it is applied once the outbreak explodes. A promising path to research is forecasting outbreaks at the stand level, so control could be effectively applied in earlier stages of infestation. However, this possibility requires of a set of knowledge about the relative sensitivity of temperature of the insects and their hosts, and the biotic relationships in which they are embedded, that is still lacking (Netherer and Schopf, 2009).

This does not imply renouncing to control PPM when necessary. Although not acting will have similar results to spraying of insecticides in terms of reducing PPM populations, other forest management practices implemented at different scales can also help control PPM outbreaks. First, promoting spatial heterogeneity at the landscape level. Second, fostering biodiversity in pine plantations by, for instance, increasing the proportion of broadleaved trees and shrubs in forest stands (particularly at the stand borders), would increase the resilience of these systems to pest outbreaks (Jactel and Brockerhoff, 2007). This is particularly relevant in our study region, where the recuperation of woody species diversity is being considered as part of forest management plans targeting the next 50 years, forest logging is no longer a profitable activity, and forest values other than timber are gaining importance (Palahi et al., 2008; and references therein). Reinforcement of parasitoid insect and predatory bird populations that affect PPM could also be a highly recommendable option (Jactel and Brockerhoff, 2007); and parasitoids are also favoured by high forest diversity and heterogeneity (Jactel and Brockerhoff, 2007). A different but relevant case is when PPM larvae causes important health problems to humans (EPPO/CABI, 1997). This can be especially important in pine masses located close to or within populated areas. In such areas, aerial spraying is unpractical, but pheromone traps, hand removal, or application of high insecticide concentrations using truck or backpack methods is justified given the risks of PPM larvae for human health (EPPO/CABI, 1997).

Forest managers should shift from static to adaptive planning based on scientific evidence, monitoring systems and protocols (Palahi et al., 2008; Netherer and Schopf, 2009). Although our study addresses PPM in the Mediterranean basin, it clearly illustrates how simple sampling designs and statistical tests can be useful decision-making tools and can help improve the environmental viability and cost-efficiency of forest management practices worldwide. We conclude that science principles can and must be used as a regular tool in forest ecosystem management.

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