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The outbreak of the pine processionary moth in Venosta/Vinschgau: ecological and economic aspects

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Abstract

A sudden outbreak and range expansion of the pine processionary moth *Thaumetopoea pityocampa* (Lepidoptera, Notodontidae) was reported in 1999-2005 for Venosta/Vinschgau, an area or northern Italy where the species generally occurs at low density. The forests of *Pinus nigra* (introduced) and *Pinus sylvestris* (native) were attacked on a total area of several hundred hectares, on the southern slope of the valley. Repeated applications of a biological insecticide based on *Bacillus thuringiensis kurstaki* were necessary to limit the population growth and the consequent damage to the trees and the environment. We used a combination of ecological and economic variables to make predictions about the outcome of the present and future outbreaks. The insect is well adapted to cope with the extreme conditions at its range edge, especially because the possibility to enter extended diapause as a pupa in the soil. The presence of the insect in the pine forests threatens soil stability, landscape value, and tourism use of the area because of the allergenic hairs released by the caterpillars. The high persistence capability of the insects in the newly invaded stands and the generally strongly negative perception of the problem by the local community, make the Integrated Pest Management necessary. Profitability of IPM is shown when possible loss of the public functions of forests such as soil protection, carbon fixation and the risk of damages to public health, are taken into account.

Introduction

The pine processionary moth *Thaumetopoea pityocampa* (Denis & Schiffermüller) (Lepidoptera Notodontidae) is a univoltine oligophage on coniferous trees, firstly described in 1775 by the entomologists Denis & Schiffermüller (1776) on material collected in Tyrol (Masutti & Battisti 1990). The insect was however already known from a nearby area, the valleys of Non and Fiemme now in Trentino province, from a detailed description of the nests and caterpillars by Matthioli (1568). It is somewhat surprising that the oldest records of the presence of the insect come from the northern edge of the range. Outbreaks are generally known for the Mediterranean region, where *Pinus* spp. are main hosts, but also *Cedrus* spp. and the introduced *Pseudotsuga menziesii* (Roques *et al.* 2002).
Phenology of *T. pityocampa* varies with climatic conditions (Démolin 1969). Adult emergence, immediately followed by mating and egg laying, occurs between June, in colder mountainous areas, and October, in areas with Mediterranean climate. The larvae are gregarious and develop inside a conspicuous silk nest, which they typically build on a branch or treetop to maximize exposure to the sun. Larvae feed nocturnally on the needles throughout the winter, as long as the night temperature is above

0°C (HUCHON & DÉMOLIN 1971). In late winter or spring the larvae form a procession and move to pupate in the soil. A variable proportion of the colony enters an extended diapause, which may last up to six years (DÉMOLIN 1969). *T. pityocampa* frequently occurs at outbreak densities throughout the Mediterranean basin.

Late larval instars can reduce tree growth through complete defoliation (LAURENT-HERVOUET 1986), and their presence creates a public health risk due to the production of urticating hairs, which may cause allergic reactions (contact dermatitis) (LAMY 1990). Because of its economic and medical importance, *T. pityocampa* populations have been monitored for many years, by means of winter-nest censuses and pheromone trapping, as part of pest management programs throughout the Mediterranean region. Easy detection of the nests allows collection of accurate data on the distribution and abundance even at low population densities (GERI & MILLIER 1983).

Here we report about the first outbreak of *T. pityocampa* in Venosta/Vinschgau, a valley located at the northern edge of the range, where the species was present at low density in warm habitats (HELLRIGL 1995), as in many other parts of the nearby Trentino province (NICOLINI 1987). The expansion of the range and the development of the outbreak was likely related to the increase of the temperature observed in the last decades (BATTISTI *et al.* 2005). It has been shown that higher winter temperature enhance the survival of the colonies and promote the colonisation of the pine stands at high elevation. Survival is significantly related to the winter feeding and this resulted to occur when night temperature is above 0°C and nest temperature in the previous day is above 9°C. Thus an increase of the temperature causes a higher frequency of feeding and in turn a higher survival. The aim of this paper is to describe the dynamics of the outbreak in the area from 1999 to 2005, using monitoring and census data, and to carry out an economic assessment of the biological control methods used to limit the population growth in some areas.

Materials and methods

Study area

The Venosta/Vinschgau, located in the Northern part of the Province of Bolzano at the border with Switzerland and Austria, extends for about 60 km in a West-East direction. The altitude of the valley bottom is 660 m in Silandro/Schlanders and 957 m in Malles/Mals, while the main peaks around are above 3,000 m. About 60% of the land is located over 2,000 m. The climate is mainly continental with low annual precipitations (around 300-400 mm).

The total land area of the valley is 123,125 hectares, of which 75% is used agricultural area, the remaining rocks and sterile land. Total resident population in 2000 was about 31,100 inhabitants in 12 municipalities, with an population density ranging from 9 to 83 inhabitants/km^2 and positive population trends. The valley has a stable economy which employs 15,430 people: 24% in agriculture, 30% in small industry and handcrafts, 7% in trade, 12% in tourism, 14% in services, 13% employed in the public sector.

Agriculture is one of the most important economic sectors. Venosta/Vinschgau produces one third of the apple production of the whole Bolzano/Bozen province. Apple orchards have expanded in recent years taking the place of pastures along the mountain sides, up to over 1,000 m. Other agricultural products are apricots, strawberries, chicories and cauliflowers. In the valley bottoms also vineyards can be found, while the upper mountain sides host pastures for dairy cows for production of milk and local cheeses. All these crops have contributed in time to make the landscape of the valley very well maintained and pleasant.

Tourism is the other important source of income for the valley: a total of 1.5 million day-visits have been estimated by the local hotel syndicate. Tourists come in winter for skiing and in summer for walking, hiking and biking. During autumn and spring tourists mainly practice walking and hiking along the mountain sides, where a dense network of footpaths has been created along the ancient ditches of the irrigation systems, the *Waalwege*. It is just in these areas where most of the pine forests of the valley are located, and where *T. pityocampa* attacks are most frequent.

Pine forests in Venosta/Vinschgau

Conifer forests in Venosta/Vinschgau cover 35,829 ha, i.e. 29% of the total area. The main species are larch (*Larix decidua*), spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), and stone pine (*Pinus cembra*), growing mainly in mixed stands. Pure stands of pine, either native (*P. sylvestris*) or introduced (Austrian black pine *Pinus nigra*), occur mainly on the southern slope, extending up to 574 and 305 ha, respectively. Forest ownership is 90% public.

During the 19th century, when the valley was intensively grazed, pastures were burned in order to favour the re-growth of grass. This practice leaded, over time, to a loss of fertility and to the development of a steppic vegetation. In the period 1884-1912 the first reforestation works started and 80 hectares of forest were planted. A second reforestation phase took place in the period 1926-1935 (about 100 ha) and finally, starting from 1951, 5 million seedlings were planted within a specific *Venosta/Vinschgau Reforestation Plan*. The main purpose of this reforestation was to avoid erosion by strengthening the soil on the slopes. The dry climate together with the dry and incoherent soils and the steep slopes only allow pioneer species such as pines to be used. These actions resulted in a total reforested area of 1,263 ha, of which 50% with *P. nigra*. These pine forests are now 30-100 year old, have scarce economic impact but are very important for other reasons than timber production. Indeed, they provide a bundle of public goods, especially recreational and environmental benefits: a) they protect soils from erosion, b) they create the typical landscape of the area and are a recreation resort, since most of the ancient *Waalwege* now used as footpaths run through them, c) they form a Carbon sink, since Carbon is sequestrated through photosynthesis and is accumulated in the growing stock, in the pine needles and in the litter.

These goods are produced both on the site itself and off-site, involving a larger community than the residents of the valley. They cannot be bought on a market and therefore have no market price, but nevertheless are deemed very important by the society.

Thaumetopoea pityocampa in Venosta/Vinschgau

Beside old faunistic records of moths in the area, the first survey dates back to 1958, when the moth control started by clipping off and burning the winter nests (Hellrigl 1995). The control of the moth is regulated by a specific law approved in 1998 and taking into account previous existing laws. The owner of a forest attacked by the moth is requested to suppress the population whenever there is a risk for the health of humans and animals, or for the survival and productivity of the trees. The Forest Service is charged of surveying the status of the stands and assess the risk. Costs for pest control (e.g. treatments and prevention) are usually met through public funds. The compulsory pest control is supported by a strong perception of the moth as a problem by the public at large.

The start of the outbreak in 1998 had a very bad impact on landscape and recreational use, pushing the Forest Service to use a bio-insecticide based on *Bacillus thuringiensis kurstaki* (Btk) sprayed by an helicopter (Minerbi *et al.* 2001). Since then, two treatments per year had to be carried out to limit the population growth. The first one in autumn on the most intensively attacked areas (usually about 150-200 hectares), the second one in late winter on about 60-70 hectares. The areas attacked and treated and the average number of nests per tree (low: 0-4 nests, medium: 5-9 nests, high: >10 nests/tree) were recorded on a 1:10,000 scale map, together with direct costs for contractors (helicopter and purchase of insecticide). The areas were generally treated when trees with medium and high nest density were predominant in a stand.

The monitoring of the adult male flight was carried out by 5 pheromone traps at each of three sites on the southern slope. The traps were inspected weekly from June to August, because of the moth has an early emergence in the area (Minerbi *et al.* 2001). At the same sites, 3 large pupation cages (2x2x2 m) were built, and in each cage about 50 colonies were allowed to pupate in April 1999. The cages were inspected weekly during the flight period from 1999 to 2005, by counting the number of moths emerged.

This allowed to estimate the incidence of extended diapause in the 1999 cohort.

The phenology and extended diapause of the Venosta/Vinschgau population was also studied by raising colonies under outdoor conditions in the campus of the Padova University in Legnaro, belonging to the cohorts 2002-03, 2003-04, 2004-05. Thirty colonies with about 5,000 larvae in third and fourth instar were collected in winter on both the southern and northern slopes of the valley around Silandro/Schlanders and transferred to large, tunnel-shaped cages (6x4x2.7 m). A 1x1 mm mesh net (Artes Politecnica, Santorso Vicenza, Italy) allowed near-ambient light and temperature conditions, and a black landscaping tarp (Artes Politecnica, Santorso Vicenza, Italy) covered the floor of the cages. The colonies were supplied with pine branches from the host species from which they were collected (*P. nigra* on the southern slope and *P. sylvestris* on the northern slope). In late winter, the larvae were allowed to pupate in a 40 cm wide ditch running along the perimeter of each room, filled with sand (45%), peat (45%), and leaf mould (10%) to a depth of 15 cm. To facilitate adult emergence and their wing extension, wooden sticks (20 cm in length, 1.5 mm in diameter) were inserted in the ditch in vertical position. Emergence and oviposition were checked daily by counting and removing the dead insects and the egg batches laid.

Assessment of Integrated Pest Management (IPM) profitability: private and public viewpoints

The maintenance of a pest-free forest in Venosta/Vinschgau is very important from diverse perspectives. For the forest owner, fighting the pine moth means preserving the forest functionality in terms of present and future timber production, thus assuring the safeguard of the forest estate and its value. For the Forest Services, who are in charge of pest prevention and pest management, it means even more, namely to guarantee the continuity of the provision of public goods to the community and to the public at large. Not carrying out IPM can also have social costs in terms of dermatitis produced by the moth larvae to visitors of the pine forests.

On the other hand, IPM is provided at a cost for taxpayers. So its private and public profitability can be questioned if the benefits obtained are not large enough to offset such costs. Assessing the economic profitability of IPM by considering the interests of both the private and public sectors is the objective of this analysis. By casting light on this subject, its results can help us to improve pest management itself and to formulate more effective and efficient local forest policies. Deciding to carry out pest management can be considered as an *investment,* providing its revenues and having specific variable and fixed costs. The methodology through which economists usually approach investment assessment is Cost Benefit Analysis – CBA. This methodology is used for selecting projects or investments by valuing in monetary terms all its positive and negative effects. If the benefits outweigh costs, the investment under analysis is a potential gain in terms of social welfare. Since money is the only yardstick expressing the value scale in CBA, it is clear that – when the investment under analysis produces many public goods, having no market price – the evaluation of these goods can be very difficult. Indeed, this is the crucial challenge for researchers involved in CBA as well as one of the main criticisms brought about by detractors of the method.

CBA is also based on the principle of discounting future values into present values in order to make values commensurable. This is done by an appropriate discount rate. Discounted benefits and costs are then summed up in the Net Present Value (NPV) which is used as the indicator of profitability. The basic principle here is that future cost and benefits are worth less than present ones. The practice of discounting is another controversial issue of CBA, being its basic underpinning principle not universally accepted, especially in the light of future generations' needs and preferences. Despite its shortcomings, the method has been used since long by forest economists to assess the profitability of different forest projects. Although it cannot be considered completely exhaustive, at least it has the advantage of providing a framework for the analysis; although it cannot produce comprehensive and fine-tuned measurements of net gains, at least it can give orders of magnitude of benefits and costs involved.

The operational approach to CBA used in this work is a simplified version of the method proposed Cesaro *et al.* (1998), who attempted to design a codified stepwise procedure for including off-site and non-market environmental effects by extending progressively the range of benefits and costs considered in the CBA. The methodology is applied in three steps, each one corresponding to a step forward towards the TEV of natural resources, as well as a more reliable approximation of the *true* social costs and benefits, that is the welfare gain of the investment:

FA – Financial Analysis:
only monetary flows of expenditures and revenues are taken into account; prices are those observed in the market and market profit is the only objective
EEA1 – Extended Economic Analysis 1:
off-site market effects are taken into account, namely those external to the areas where IPM is executed but internal to the market; economic valuation techniques used are based on indirect market effects, such as productivity changes outside the area of intervention or possible off-site damages
EEA2 – Extended Economic Analysis 2:
in this step, effects external to the market – both on-site and off-site – enter the CBA; non-market values are estimated using economics techniques based on eliciting consumers' willingness to pay for specific environmental goods. In this way, the objective function includes people welfare.
The objective function therefore comes to include, step by step, an enlarged conception of the welfare gain. This operation seems to be acceptable because the overall project's objectives (economic, social and environmental) are to a large extent compatible, and not competitive, therefore additive.

Defining scenarios for IPM analysis in Val Venosta
CBA scenario for Venosta/Vinschgau compares the future evolution of the pine forests under IPM with a hypothetical situation without any treatment, leading to an uncontrolled expansion of the moth. The period of time considered in the analysis is fifteen years. Shorter periods would not have allowed the inclusion of the full positive effects of the treatments; longer periods would have forced us to estimate future values with too much uncertainty, therefore loosing accuracy in the analysis.
The data used in the analysis come from different sources. Forest stocks and increments come from forest yield tables of the area. Market prices for wood and forest harvesting and costs, as well as investment costs come from the Forest Services of the Bolzano/Bozen Province. The data used in the Economic Analyses 1 and 2 are partially elicited from literature and partially from experts' estimates.
The case-study is represented by the artificial pine forests located on the south slope, at an altitude ranging from 700 and 1500 m, where most of the pine moth attacks occur. The total area is 938 hectares, of which 575 is pure *P. nigra* and 305 is *P. sylvestris*. According to the Forest Management Plan, the average age of the pine trees in the case study area is 60 years and average growing stock 160 m^3/ha. Thinning should be carried out annually for management reasons. The wood could be used for chips and particles, with an average road side price of 15 €/m^3. Felling and harvesting costs range around 35 €/m^3: clearly thinning are a cost rather than an income. The analysis has been performed using a discount rate of 2%.

Results

Attacked area, Btk biocontrol, and phenology
The area infested by the moth and subjected to Btk treatment in 1999-2004 is given in Fig. 1. The attacked area was almost always larger than the treated area (Fig. 2). The nest density was not estimated for the cohort 1998-99, the first year with the outbreak causing an almost total defoliation on an area of about 150 ha. That cohort created a huge stock of diapausing pupae in the soil, which is in part responsible for the attacks in the following years, in spite of the repeated applications of Btk (Fig. 2). However, other cohorts from previous years and individuals coming from the low density areas not treated by Btk could have contributed to the maintenance of high population densities.
The frequency and duration of the extended diapause as a pupa varied among the three sites considered and was not related to the capture of adult males in

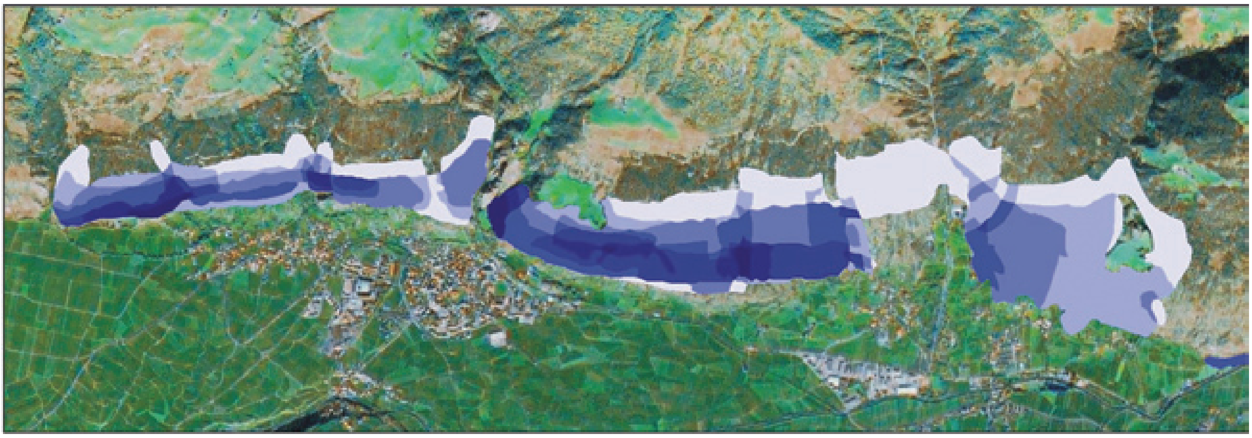

Fig. 1 Aerial view of the southern slope of Venosta/Vinschgau around the town of Silandro/Schlanders. The coloured areas are the forest stands heavily attacked and treated with *Bacillus thuringiensis kurstaki* during 1999-2004. Colour intensity is related to the number of treatments, from 1 (light blue) to 8 (dark blue). The forest above the treated area (dark green) was also colonised up to the height of 1450 m, but with a lower nest density.

pheromone traps in the same area (Fig. 3). From the comparison of nest density in Fig. 2 and male catch in Fig. 3, it results that the number of males caught in pheromone traps was not a good predictor of nest density in the next cohort. Thus, unpredictable diapause is the key to understand how the pine processionary moth is able of maintaining high population density, even when the Btk applications caused almost total mortality of the colonies. Recruitment of individuals from the neighbouring, untreated forests may also explain the maintenance of high density in the core outbreak areas. It is interesting to note that the treated area expanded up to 1300 m of elevation during the outbreak period, as shown in Fig. 1.

The cohorts of 2002-03, 2003-04, 2004-05 reared in the campus of the Padova University did maintain the same phenology observed in the field, with moths emerging between June and July (Fig. 4), with no differences between the slopes. The rate of extended diapause was around 50% of the individuals in the cohort 2002-03, whereas it increased to about 80% in 2003-04, with a higher incidence for the population of the northern slope, and reached 100% for populations of both slopes in 2004-05.

Economic analysis

The items included in the financial analysis are reported in Tab. 1 for the two alternatives with and without the IPM. Annual revenues to the landowner include incomes from possible sales of wood for chips and particles coming from thinning and the (implicit) land rent. Forest productivity remains stable in a pest-free forest, while it decreases if pine moth is not properly controlled, causing decreasing potential incomes from wood sales and diminishing land values. Annual financial costs include a variable costs linked to felling and harvesting – depending on whether and to what extent thinning is carried out – and a fixed management cost for land tax and surveillance. The investment costs of the with alternative include purchase of Btk, rent of equipment (helicopter) and labour costs of personnel involved.

The items included in the Extended Economic Analysis 1 are reported in Tab. 2. In addition to what already considered in FA, here off-site market effects have been accounted for. Social benefits include soil protection from erosion and carbon fixation. Estimates of the value of soil protection are based on literature data and refer to an average Italian

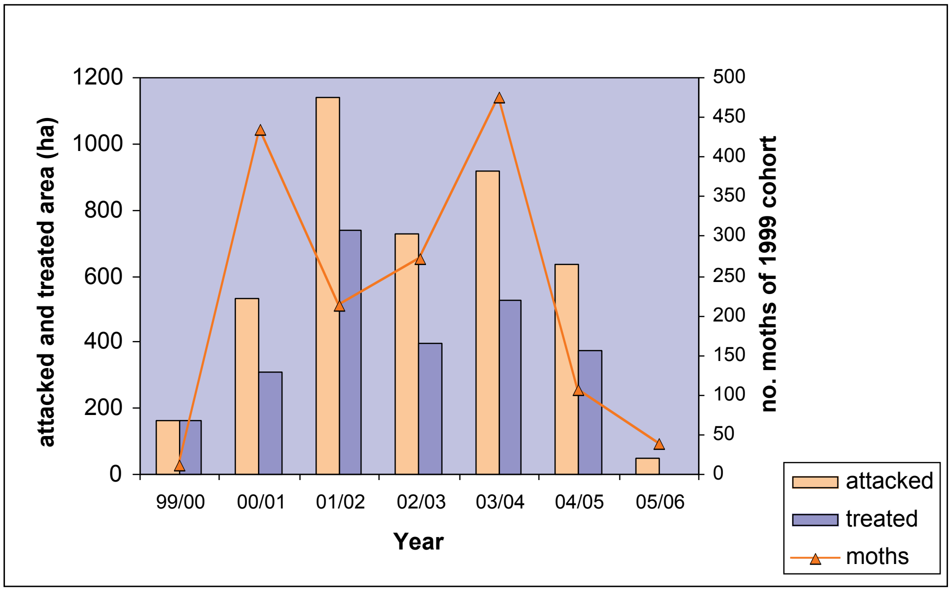

Fig. 2: Attacked and treated area in Venosta/Vinschgau during 1999-2006, compared with the total number of moths emerged from 3 cages where colonies of the 1998-99 cohort were allowed to pupate.

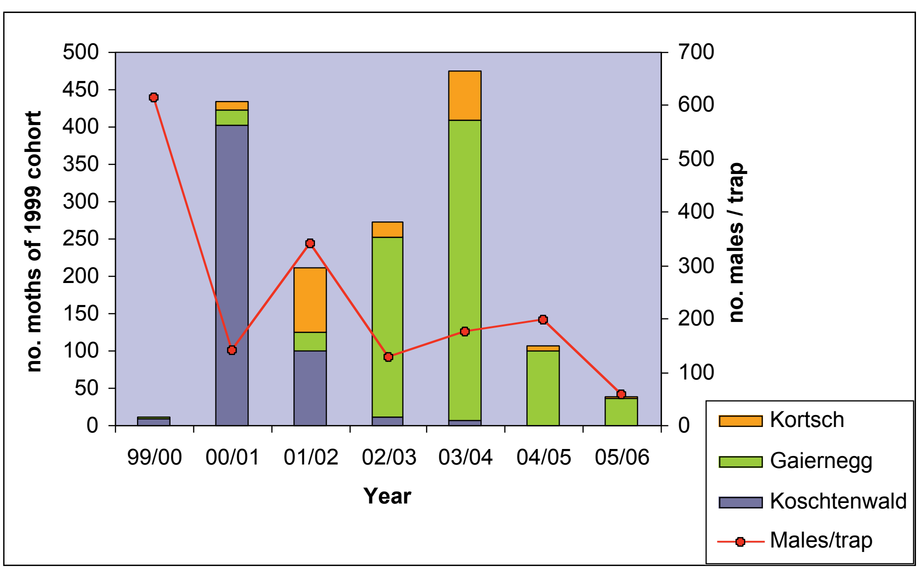

Fig. 3: Emergence of the moths of the cohort 1998-99 (pupated in April 1999) inside the experimental cages at 3 sites on the southern slope of Venosta/Vinschgau, compared with the number of adult males caught in pheromone traps in the same area.

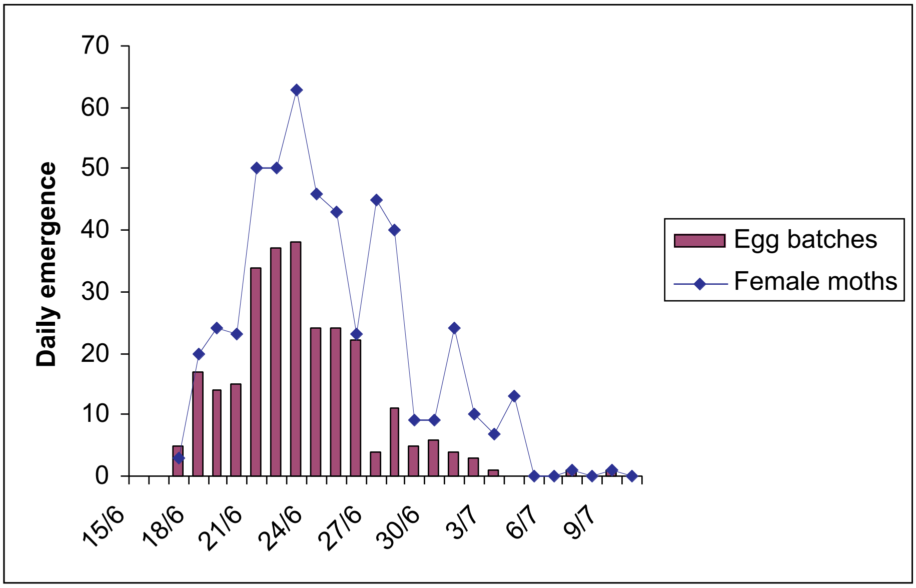

Fig. 4: Number female moths emerged daily and egg batches laid on potted trees by the cohort 2002-03 of the population from the southern slope of Venosta/Vinschgau, in the rearing under outdoor conditions in the campus of the Padova University. The total number of emerged moths (male and female, 910) corresponded to about half of the larvae successfully pupated in the cage.

situation. The value of Carbon sequestration is based on forest net growth and on the present market of C-quotas linked to the implementation of the Kyoto Protocol. Social costs are linked to the sanitary treatment of people being possibly injured through the contact with the pine moth, calculated on the basis of possible risks.

Off-site non-market benefits, accounted for in EEA2 and reported in Tab. 3, include social values such as recreation and landscape. Recreation estimates are based on the assumption that 10% of the tourists who visit the valley annually would spend some hours in the Waalwege and that they would be willing to pay 1.5 € per day spent in an healthy forest, but only 1 € in a unhealthy one (comparable data have been obtain in similar site where a specific survey has been carried out amongst tourists). In addition, a forest where pine moth expansion is not controlled would also attract a smaller number of tourists. On top of this, the typical landscape of the valley has a value also for residents and for the tourism sector who owes the attractiveness of the valley also to its features. Therefore we have assumed that each resident would be available to pay 0.5 € per year to keep the pine forests free from the moth.

Note that – despite these values are part of the social welfare function – they represent hypothetical figures and not real market transactions.

The results of the CBA application in terms of Net Present Value (NPV) are presented in Tab. 4. Financial Analysis gives negative results for both the with- alternative and the without- one. However the with- situation is worse: IPM costs are not paid back by a larger amount of wood production in the healthy forest, given the scarce profitability of the market for chips and particles. Profitability changes when the perspective shifts to consider social benefits and costs, bringing to positive results both in the cases of Extended Economic Analysis 1 and Extended Economic Analysis 2. In this case, IPM costs are covered by the higher social benefits – more soil protection, C-sequestration, recreation and landscape – produced by moth-free pine forests.

Tab. 1: Output of the Financial Analysis – FA.

Step of CBA	Benefit + Cost -	Item being valued	Physical Indicator	Monetary indicator	Annual value for the case-study area (Euro)	
					with IPM	without IPM
FA	+	Wood production from thinning	Volume felled 850-950 m^3 linked to annual increment	Market price of chips and particles: 15 €/m^3	12,800-14,400 depending on years	12,800-13,400 depending on years
	+	Estate value		Land rent 25 €/ha	23,450	19,500-12,100
	-	Management costs	Tax and surveillance	Unit cost 20 €/ha	18,760	18,760
	-	Felling and harvesting costs	Labour, purchases and overheads	Unit cost 35€/m^3	30,016-33,600 depending on years	30,000-31,400 depending on years
	-	Investment Costs	Purchases, equipment and labour	Unit cost per hectare	12,600-21,200 depending on years	0

Tab. 2: Output of the Extended Economic Analysis 1 – EAA1, with additional items to FA.

Step of CBA	Benefit + Cost -	Item being valued	Physical Indicator	Monetary indicator	Annual value for the case-study area (Euro)	
					with IPM	without IPM
EEA1	+	Soil protection from erosion		50-100 €/ha depending on forest functionality	93,800	50,300-78,800 depending on progressive expansion of the moth
	+	Carbon sequestration	Net C increment sequestered in forest biomass	Shadow price of Carbon : 13 €/tC	1,500-6,000 depending on forest growth	110-6,000 depending on forest growth
	-	Risk of dermatitis for visitors	Days of hospital treatment	Cost of daily hospital treatment	0	1,900-5,500 depending on progressive expansion of the moth

Tab. 3: Output of the Extended Economic Analysis 2 – EAA2, , with additional items to FA and EAA1.

Step of CBA	Benefit + Cost -	Item being valued	Physical Indicator	Monetary indicator	Annual Value/ha	
					with IPM	without IPM
EEA2	+	Recreation	150,000 day-visits per year in the with-situation, 120,000 in the without situation	Willingness to pay for 1 day-visit : 1.5 € in the with-situation, 1.0 € in the without situation	225,000 €	120,000 €
	+	Landscape	32,000 residents	Annual willingness to pay by each resident for an healthy forest: 0.5 €/year	16,000	0

Discussion

In this paper, we show that the expansion of the range and the outbreak area in a forest pest may cause considerable economic losses to the local community, unless a thorough control is carried out. Beside having pointed out that recreation and landscape are the most important benefits for pine forests in Venosta/Vinschgau, the results can also be used for designing specific policy tools to obtain control of *T. pityocampa* in the most efficient way. Of course, these must be based on the existing legislation and on the rather strong social perception of pine moth as a problem. In this context, the CBA results indicate that the private landowner has no incentive to carry out IPM since the costs for doing so are not counterbalanced by enough benefits in terms of timber production (which is low or inexistent in any case) or maintenance of the capital value of forest land. The profitability of IPM only turns up at the second level of the CBA (i.e. the Extended Economic Analysis 1), when the public goods produced by the pine forests are considered. The possible loss of the public functions of forests such as soil protection, carbon fixation and the risk of damage to public health justifies the use of public money to execute a control which would not be carried out otherwise, but whose benefits are enjoyed by a wide community of residents and tourists.

In addition to these economic issues, a number of predictable and less predictable variables may affect the population growth and the further expansion of *T. pityocampa* in the area. As temperature is predicted to increase according to global change scenarios (Houghton *et al.* 2001), we may expect a further expansion of the moth in the upper pine forests, according to the mechanism described by Battisti *et al.* (2005). The increase of temperature will also likely favour the survival of the colonies in the areas occupied recently, as large part of the forest where the outbreak of 1999-2005 occurred.

The early emergence of the moth is particularly adaptive under these conditions, as it allows the colony to grow up to the fourth instar before the winter, which is normally related to a higher probability of winter survival (Démolin 1969). The maintenance of the emergence time when the colonies were reared for three years in the campus of Padova University indicates that the mechanism is genetically determined, resulting perhaps from the selection of the trait in a native population of *T. pityocampa*, which probably existed on site for a long time before the development of the first outbreak. The old faunistic records (Hellrigl 1995) and the occurrence in alpine valleys of the nearby Trentino in the 16^{th} century (Matthioli 1568) may support the hypothesis that the Venosta/Vinschgau population is native. The outbreak would thus result from the increase of temperature and the consequent better winter survival. As at the beginning of the outbreak there were no specific natural enemies able to contain the population growth, we can hypothesize they were limited by the very low density of the host. Now we are facing an increasing mortality caused by specific natural enemies, mainly egg parasitoids (unpublished results), and this would hopefully drive the system under natural control, as it happens in several core areas attacked by the moth (Masutti & Battisti 1990).

However, the most important adaptive trait of the moth, and up to now almost impossible to predict, is the extended diapause of the pupae in the soil. This trait has been considered important in any population of the moth (Démolin 1969), but it appears to be the key for a population to establish itself under the most extreme climatic conditions. The stock of pupae present in a soil, where they can stay for up to 6 or perhaps more years as data from Venosta/Vinschgau show, is providing every summer a new cohort, independently on the success of the previous one. It may happen that a cold day with temperatures below –16°C for several hours, the lower lethal temperature determined by Huchon & Démolin (1971) for populations of southern France, kills all the colonies and brings a cohort to extinction, or that a cohort is killed by an extended starvation. The stock of diapausing pupae will provide new colonizers in spite of all these constraints to population growth. The strategy is challenging for natural enemies as well, because any relationships based on density-dependence is clearly negatively affected by the sudden change of the host density. Even when the cohort extinction is not observed, as during the outbreak years of Venosta/Vinschgau, the

contribution of the diapausing pupae can be of great importance in modifying the population density, as it happened in 2003-04. The prediction for that cohort was for a decrease of the attacked area, whereas we observed the highest attack during the outbreak. One reason can be possibly found in the extreme warm summer of 2003, which was responsible for a sudden shift of the moth populations in the Alps (Battisti *et al.* 2006).
The expansion of *T. pityocampa* and the occurrence of outbreaks in the newly occupied forests appear to be driven by mechanisms controlled by temperature. In spite of possible periodic extinctions in unfavourable years, populations can be maintained at sites outside the continuous range by emergence of individuals surviving as pupae in prolonged diapause. Based on the projections of climate change in the next decades (Houghton *et al.*, 2001, Anonymous, 2004), it is highly likely that *T. pityocampa,* and other organisms with distributions determined in part by temperature, will continue expanding their geographic range. While the projected mean rise in winter and summer temperatures could be used to approximate the rate of such expansions, we need to incorporate these effects in a quantitative, predictive framework combined with an assessment of the economic losses related to the expansion. For instance, in the case of *T. pityocampa*, forest management strategies based on the use of broadleaved tree species instead of pines could anticipate the measures needed to protect the forest ecosystem and public health.

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Zusammenfassung

Die Massenvermehrung des Kiefernprozessionsspinners im Vinschgau/Venosta: ökologische und ökonomische Aspekte

Ein plötzliches Massenauftreten und eine Arealausweitung des Kiefernprozessionsspinners *Thaumetopoea pityocampa* (Lepidoptera, Notodontidae) war im Vinschgau/Val Venosta in den Jahren 1999-2005 festzustellen; in diesem Alpen-Gebiet Nord-Italiens war die Art normalerweise bisher in niederer Dichte vorhanden. Betroffen waren Bestände von Schwarzkiefer *Pinus nigra* (künstlich) und von Weißkiefer *Pinus sylvestris* (natürlich) auf einer Fläche von einigen hundert Hektaren, vornehmlich auf den südexponierten Hanglagen (Sonnenberg). Es waren wiederholte Behandlungen mit einem biologischen Insektizid auf Basis von *Bacillus thuringiensis kurstaki* (Btk) erforderlich, um eine weitere Ausbreitung der Schädlingspopulation zu begrenzen und den Gesundheitszustand der Wälder zu gewährleisten. Unter Verwendung einer Reihe von ökologischen und ökonomischen Variablen, wurde versucht eine Einschätzung vorzunehmen über den weiteren Verlauf des derzeitigen Massenauftretens und einer möglichen zukünftigen Entwicklung. Der Kiefernprozessionsspinner scheint besonders befähigt zu sein auch unter den gegebenen Extrembedingungen überleben zu können, die bedingt sind durch den Umstand, dass er sich hier an der Nordgrenze seines natürlichen Verbreitungsareals befindet; dies besonders aufgrund der verlängerten Diapause der Puppen im Boden. Das Auftreten dieses Insekts bedroht zudem die Stabilität der Böden, die Landschaft und die touristische Nutzung des Gebietes, vor allem infolge der von den Raupen abgestossenen hautreizenden Gifthaare.
Die hohe Persistenzfähigkeit des Kiefernprozessionsspinners, sich im neu eroberten Gebiet halten zu können sowie die stark negative Wahrnehmung und Ablehnung des Problems seitens der lokalen Bevölkerungsgemeinschaft, machen die Anwendung von integrierten Bekämfungsmaßnahmen erforderlich. Diese Bekämpfung erweist sich auch aus ökonomischer Sicht als vorteilhaft, wenn man die Verluste und Risiken quantifiziert, die den Bodenschutz, die Bindung des Kohlenstoffes und die öffentliche Gesundheit betreffen.

Riassunto

La gradazione della Processionaria del Pino in Val Venosta/Vinschgau: considerazioni ecologiche ed economiche

Un'improvvisa pullulazione ed espansione dell'areale di processionaria del pino *Thaumetopoea pityocampa* (Lepidoptera, Notodontidae) è stato osservata nel periodo 1999-2005 in Val Venosta/Vinschgau, un'area dell'Italia settentrionale dove la specie era normalmente presente a bassa densità. Sono stati colpiti popolamenti di *Pinus nigra* (artificiale) e di *Pinus sylvestris* (naturale) su un'area di alcune centinaia di ettari, situata sul versante esposto a sud. Ripetute applicazioni di un insetticida biologico a base di *Bacillus thuringiensis kurstaki* sono state necessarie per limitare la crescita delle popolazioni e salvaguardare la salute delle foreste. Utilizzando una serie di variabili ecologiche ed economiche, abbiamo cercato di prevedere gli esiti della pullulazione in atto e di quelle possibili in futuro. La processionaria appare essere particolarmente adatta a sopravvivere nelle condizioni estreme poste dal fatto di trovarsi al limite del proprio areale, in virtù del meccanismo della diapausa prolungata delle crisalidi. La presenza dell'insetto inoltre minaccia la stabilità del suolo, il paesaggio e l'uso turistico del territorio, a causa della presenza di peli urticanti rilasciati dalle larve. L'elevata capacità della processionaria di persistere nell'ambiente di recente occupazione e la percezione fortemente negativa del problema da parte della comunità locale rendono necessaria l'adozione di misure di lotta integrata. Tale lotta si rivela vantaggiosa dal punto di vista economico se vengono quantificate le perdite e i rischi in merito alla protezione del suolo, fissazione del carbonio e alla salute pubblica.

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