Roger Moore, Joan Cottrell, Stuart A'Hara, Duncan Ray

Pine-tree lappet moth (*Dendrolimus pini*) in Scotland: Discovery, timber movement controls and assessment of risk

Summary

The pine-tree lappet moth *Dendrolimus pini* L. is a pest of pine forests across Europe but until recently was not known to be established in Britain. In 2009, we confirmed a small breeding population in pine plantations near Inverness. Populations have remained low since and are currently much lower than cause economic damage in Europe. Restrictions on timber movements appear to have been effective at preventing spread, but there are early signs of short-distance range expansion. DNA analysis of moths revealed the Scottish population belonged to the southern of three European lineages, and showed markedly lower diversity than a population in central Europe. Climate analyses predict a risk that with warming summers in eastern Scotland it will become increasingly favourable for damaging outbreaks. However, the impact of Scotland's unpredictable seasons and the role of potential predators and parasites are not understood. The Forestry Commission consider *D. pini* to be a potentially serious threat to Scotland's ancient Caledonian pinewoods and commercial forestry plantations, whereas some others suggest it to be a harmless, previously unrecorded, native component of our fauna. Opinions may be divided, but in the face of uncertainty over its origin and damage potential, an on-going precautionary approach is prudent.

© Göran Nordlander, SLU

Photo 1: Severe needle defoliation caused by pine-tree lappet moth, which led to extensive tree mortality on the Island of Furuskär in the Stockholm archipelago, Sweden, in 2012. (Photo credit: Göran Nordlander, SLU).

Introduction

The pine-tree lappet moth (*Dendrolimus pini* L) is periodically a serious defoliating insect pest in parts of continental Europe, where its caterpillars have been responsible for major damage to Scots pine forests (Malyshev, 1997). Outbreaks of this insect can occur over large geographical areas and, if left uncontrolled, often result in widespread tree death due to total needle defoliation (**Photo 1**). As a consequence of this threat, aerial insecticidal control is frequently employed to control it in countries such as Poland and Germany which have a history of outbreaks (Sierpińska, 1998; and Moeller *et al.*, 1998).

Shortly after a breeding population of pine-tree lappet was confirmed in Scotland, it was suggested that it was an overlooked and harmless resident species (Leverton, 2009) and Prescott (2009) reviewed the pest status of the moth in a range of European countries

THE AUTHORS

Roger Moore*, Joan Cottrell, Stuart A'Hara, and Duncan Ray

Dr Roger Moore is a senior scientist and entomologist with Forest Research studying and providing advice on insect pests of UK forestry.

Dr Joan Cottrell is a senior scientist and geneticist at Forest Research with interests in population genetics of trees and their associated flora and fauna.

Dr Stuart A'Hara is a research scientist with Forest Research specialising in using DNA-based approaches to help address questions in the areas of genetic conservation and tree breeding.

Duncan Ray is a senior spatial ecologist working in Forest Research. He studies the impact of climate change on woodlands and forests including changes in the provision of ecosystem services.

*Corresponding author: Forest Research, Northern Research Station, Roslin, EH25 9SY.

Email: roger.moore@forestry.gsi.gov.uk

Photo 2: (right) An adult male pine-tree lappet moth.
Photo 3: (below right) An adult female pine-tree lappet moth.
Photo 4: (below) Eggs of pine-tree lappet moth in Pulawy Forest, Poland in April, 2014. Eggs are easily transported into new areas and provide an instant starter source population for colonising new forests.

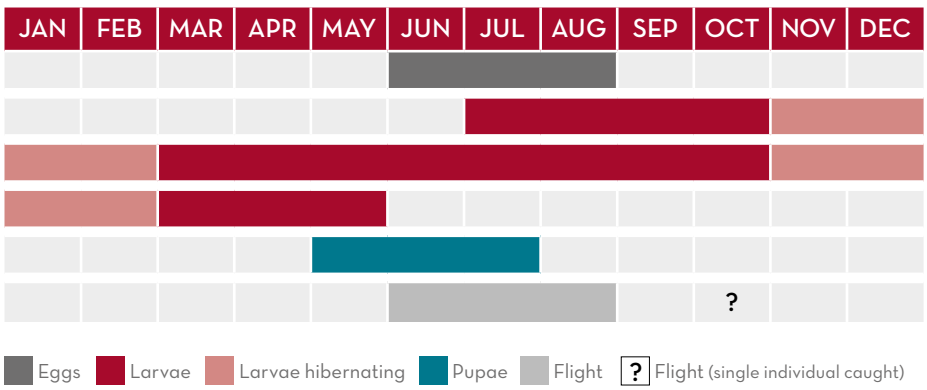

© Roger Moore


© Glenn Brearley/Forest Research


© Glenn Brearley/Forest Research

based on feedback from European lepidopterists. Prescott concluded that it was only considered a major pest in Poland and Germany, with records of some more limited historical outbreaks in Sweden and Norway. There have been no recorded outbreaks in many European countries where the moth is endemic. However, even infrequent outbreaks can be highly damaging and lead to tree death and encompass both small and large areas of forest. Indeed, since Prescott's review there has been a small, but significant and highly damaging outbreak that was confined to the tiny Swedish island of Furuskär in the Stockholm archipelago (Björkman *et al*, 2013). A large proportion of the mature trees on Furuskär suffered 80-100% defoliation during the outbreak and subsequently died as a result (Nordlander *pers comm*). There has also been an even more recent outbreak in Croatia in 2014 (Pernek *pers comm*) and the literature contains numerous other prior examples of *D. pini* damage across Europe. Hopkins (1907) records major outbreaks in Norway from 1900-1903 over an area of seven thousand acres, with glue banding of tree stems to intercept larvae successfully used to control populations. Csoka (1991) found that heavy damage by *D. pini* dramatically reduced height and diameter growth of Scots pine and that mortality of these trees was 50-60% with 100% death of totally defoliated trees. Selikhovkin (1998) suggested that *D. pini* should be considered amongst the most important defoliators of Russian Taiga forests and Mozolevskaya *et al* (2002). reported that outbreaks in Russian state forests during the period 1990-2001 killed 3-24,000ha of forest each year. Meshkova (2006) recorded the mean annual area of foliage loss during outbreaks in Ukraine to be in the region of 6000ha and Kondur (2006) lists it as a harmful insect in Turkey.

Figure 1: Lifecycle of the pine-tree Lappet moth (*Dendrolimus pini*) in Scotland.



Life-cycle and behaviour

Adult pine-tree lappet moths are large, conspicuous, night-flying and on the wing from June to August (**Figure 1**). Males and females (**Photos 2 and 3**) have similar markings but the latter is larger and wingspans measure 50-70mm and 70-90mm, respectively. The start time and duration of the flight period is variable and temperature dependent in Scotland but typically begins between mid-June and early July and lasts between 4-7 weeks. After mating, the female moths lay their eggs (**Photo 4**) on pine needles, twigs or bark in the canopy of Scots pine and other pine species in rows or as loose batches. The 150-300 eggs laid by each female begin to hatch within 1-2 weeks. The early instar larvae

Photo 5: A fully-grown, final instar pine-tree lappet caterpillar feeding on Scots pine needles.

feed on needles during late summer and at first autumn frosts descend from the canopy to the forest floor to hibernate in the needle litter or upper surface layers of unconsolidated soil. As the temperature rises in the spring the larvae become active again and, commencing in February and peaking in March, crawl back up the tree to the canopy to continue feeding. In ideal conditions, larvae can complete their development in a single year but in Scotland they continue to feed throughout the summer and autumn and descend for a second time to overwinter in the litter/soil.

A one-year development cycle predominates in southern European countries bordering the Mediterranean and in areas with very warm summers such as in Poland, Germany and France. However, a two-year or three-year life-cycle is more common in areas with more variable and cooler climates. Our monitoring surveys and rearing studies indicate that in Scotland, *D. pini* generally takes two years to complete its life cycle and the caterpillars overwinter twice. Notably, however, the length of the development cycle is not genetically fixed and under warmer conditions in laboratory trials, we have shown that development from eggs to adults in Scottish moths can be achieved in only five months with no over-wintering dormancy required, illustrating their plasticity and potential to respond to climatic change.

A full-grown female caterpillar can be up to 8 cm in length (**Photo 5**) but males are only about two-thirds of this size. Each caterpillar is estimated to consume 600-1,000 needles during the course of its entire growth period (Björkman, *et al.* 2013). On completion of larval development, the caterpillar spins a cocoon on either twigs, branches or the main tree trunk (**Photo 6**) thereby increasing the risk of human-mediated transport and dispersal via timber movement. The insect pupates within the cocoon and adults emerge 4-5 weeks later.

Previous records of pine-tree lappet moth in Britain and its discovery in Scotland

Adult male *D. pini* moths are very effective fliers and highly dispersive. In the past they have been recorded in southern England and the Channel Islands as rare migrants which have probably flown over during major outbreaks in Europe (Prescott, 2009) or with strong winds. In contrast, female moths, being much heavier due to their egg load, are very poor fliers making it unlikely that they could have recently colonised Scottish sites directly.

The first, initially unreported, capture of an adult male moth in Scotland occurred in 2004 during light trapping on the western edge of Inverness. Initially this was believed to be a migrant, but in 2007 and 2008 an amateur entomologist caught a further two and six male moths respectively, whilst light trapping in Ruttle Wood, near Kiltarlity, just south of Beauly (Kiddie, 2008) and 16.5km from the original capture site. This increase in captured specimens was highly suggestive of, but did not confirm, a breeding population.

The 2007 captures came to the attention of the Forestry Commission Plant Health Service (FC PHS) early the following year and they immediately established an Outbreak Management Team (OMT). The OMT rapidly commissioned a small pheromone trapping survey of eight sites in the area of the earlier captures to determine how widespread the moth might be. This exercise resulted in a further four moth captures in 2008, three in Ruttle Wood and a single specimen in Boblainy Forest.

The frequency and the year-to-year consistency of these male moth captures prompted concern and the commissioning of large-scale trapping surveys over a wide geographical area by FC PHS and Forestry Commission Scotland. The main aim of the surveys was to determine if *D. pini* was breeding in Scotland and, if so, whether it was increasing in numbers and/or extending its area of occupancy.

Surveys and monitoring: 2009-2016

Surveys were undertaken by Forest Research across an extensive network of 47 pine sites, identified in early summer 2009, which included both Forestry Commission and private woodland sites. All sites with a pine component greater than 20%, and that were within a 20km radius of, the then suspected centre of population near Kiltarlity in Inverness-shire, were selected for monitoring. In addition, this network of sites also included important key pine forests, out beyond 20km distance and up to 50km including Culbin and Glen Affric forest

© Roger Moore

© Roger Moore

Photo 6: Cocoons of Pine-tree lappet moth in Pulawy Forest, Poland, in April, 2014. Cocoons are highly cryptic and very difficult to see on both standing and felled timber.

SSSIs and Inshriach forest NNR. The initial intention was to monitor for adult moths and where these were captured, to subsequently monitor intensively for the presence of caterpillars, which would confirm a breeding population.

Three main entomological survey methods were used to detect pine-tree lappet: light trapping, pheromone trapping and glue banding (**Photos 7-9**, respectively). The first two methods aimed to capture adult moths on the wing during the two-month flight period in mid-summer. The third method, glue banding, aimed to monitor caterpillars – both those that were descending from the trees in the autumn to hibernate in the soil and those making their subsequent ascent back up to the forest canopy in the spring to continue feeding.

Adult monitoring

The light traps provided a generic method with the potential for catching large numbers of moths belonging to a range of different species including pine-tree lappet. The technique was very labour-intensive and hence only used to trap over a single night or small number of consecutive nights. Consequently, it only provided a 'snapshot' of the population, and catch tended to be highly susceptible to the prevailing weather conditions on the night, and thus provided less reliable estimates of populations than the pheromone traps described below.

The pheromone traps contained dispensers releasing synthetic versions of the highly specific pheromones produced by the female moths to attract males for mating. Consequently, all moths caught during pheromone trapping were male pine-tree lappet. The pheromone traps were left out for a period of 2-3 months, checked weekly and captures recorded throughout the entire flight period making catch less susceptible to weather variation. Two different types of pheromone traps were used during the course of the study: in the first year a 'mini-funnel' trap was used, in the second year this was used alongside equal numbers of delta traps. In subsequent seasons (2011 onwards) the delta trap type was favoured. This was a triangular, prism-shaped trap with two open ends and a pheromone dispenser positioned on a sticky flat

Photo 7: Light trapping in a Scots pine wood near to Kiltarlity.

© Roger Moore

surface onto which attracted male moths were captured (**Photo 8**).

Adult *D. pini* moth numbers caught during both pheromone and light trapping are shown in **Table 1**. In the first year of surveillance six pheromone traps were set up at each of the 47 pine sites centred round Kiltarlity with 282 traps installed in total.

The first summer of adult monitoring in 2009 revealed relatively large numbers of moths at a number of sites in the area, with eight moths caught using pheromone traps at five of the 47 sites, and 90 moths captured by light traps from five sites. All 98 individuals caught were male moths, including those caught in light traps, and came from seven different sites within 7km of Kiltarlity.

The number of moths caught in the first year by pheromone traps was low but this was due to the 'mini-funnel' trap used. In the second year, half of the trap bodies were of the original type and half of the delta type. This enabled a comparison to be made and showed that the delta was four times more efficient than the 'mini-funnel' trap. Consequently, in subsequent seasons, only delta traps were used. Factoring this knowledge into account, pheromone catches would have been reasonably high in 2009 but both 2010 and 2011 were the years with the highest pine-tree lappet populations. In 2012, 2013 and 2015, the numbers of trapped individuals dropped but in 2014 and 2016 the numbers rose again suggesting a recovery of the population (**Table 1**). The annual total numbers for moths caught during light trapping were relatively consistent with those caught in pheromone traps.

Confirmation of breeding

The large number of moths caught by light trapping at the seven sites in the summer of 2009 suggested that a breeding population existed in the area and, in an attempt to confirm this by verifying the presence of caterpillars, six Scots pine trees were selected to be felled at each site. Felling was undertaken in September 2009, after which each tree was hand-searched for the presence of caterpillars and immature life-stages of the insect. This exercise led to the first discovery in Scotland of a single pine-tree lappet caterpillar and a pupal cocoon. This discovery and glue band captures later in the autumn confirmed the existence of breeding populations at five of these seven sites.

The confirmation of breeding justified the implementation of the on-going annual surveys which have taken place since 2009 to determine whether the moth is spreading, to monitor for changes in density indicative of outbreak as well as to investigate the moth life-cycle in Scotland. We have now collected eight years of data and current plans are to continue monitoring into the foreseeable future.

Caterpillar monitoring

Glue bands are 15cm plastic bands coated with a sticky glue surface applied around the full tree trunk circumference at breast height. They take advantage of the protracted caterpillar growth period over several seasons in which the caterpillars climb down the tree trunks to overwinter and then climb back up the tree trunk to continue to feed in the spring. In Scotland, these two events occur at least once and normally twice during the course of caterpillar development. Where possible, when applying glue bands in the autumn, the tree trunks are 'scraped' to reduce the deeper pine tree fissures (which would otherwise provide a route by which the caterpillars could bypass the glue bands) and then the trunk bands are applied in advance of caterpillar descent. These autumn-applied bands are left on the trees over the winter and then replaced with fresh glue bands in mid-February, ahead of the spring ascent back into the canopy. Glue bands are checked on a weekly basis in the autumn (for caterpillars on and above the bands) as well as in the spring (for caterpillars on and below the bands). Caterpillars in fissures below the bands during their removal and replacement in mid-February band are also recorded.

Although caterpillars are only rarely captured on the sticky band itself, it creates a barrier that they are reluctant to cross and their natural instinct to

Table 1: Total numbers of adult pine-tree lappet moths caught in pheromone traps and light traps from 2009 to 2016 (excluding containment trapping).

PHEROMONE TRAPS			
YEAR	NO. OF TRAPS	TOTAL NO. OF ADULTS	MEAN NO. OF ADULTS PER TRAP
2009	282	8	0.028†
2010	288	40	0.139‡
2011	372	76	0.204
2012	348	29	0.083
2013	402	26	0.065
2014	384	47	0.122
2015	306	24	0.078
2016	294	55	0.187

LIGHT TRAPS			
YEAR	NO. OF TRAPS	TOTAL NO. OF ADULTS	MEAN NO. OF ADULTS PER TRAP
2009	54	90	1.67
2010	182	135	0.74
2011	109	69	0.63
2012	43	6	0.14
2013	56	22	0.39
2014	-	17	-
2015	-	-	-
2016	*	*	*

†Only mini-funnel trap used ‡50% mini-funnel and 50% delta traps used - Data unavailable * Light trapping only in containment area

climb causes them to accumulate above the bands in autumn and below the bands in the spring.

The number of caterpillars caught on glue bands was highest in 2009 followed by 2010 and then 2011 (**Table 2**). Considerably lower numbers were caught from the autumn of 2012 onwards. As expected there was a high degree of consistency between the number of autumn glue band captures of one year and spring captures of the same cohort the following year. There has been a progressive annual decrease in numbers caught at glue bands during the entire eight-year surveillance and monitoring programme. This may indicate that the glue bands are an effective though expensive control technique but further monitoring will clarify this.

Outbreak/ breeding area management

The first discoveries of adult male moths, and subsequently caterpillars, prompted the pine-tree lappet moth Outbreak Management Team (OMT) to put controls in place to restrict timber and foliage movement from these sites They were implemented where the moth had been captured, and later breeding confirmed, due to the risk of 'jump-spread' of life stages such as eggs and pupal cocoons (**Photos 4 and 6**)

Table 2: Total numbers of pine-tree lappet moth caterpillars caught by glue banding from 2009 to 2016.

YEAR	SEASON	NO. OF TREE BANDS	TOTAL NO. OF LARVAE	MEAN NO. OF LARVAE PER 100 TREES
2009	Spring	-	-	-
	Autumn	1900	101	5.3
2010	Spring	400	63	15.8
	Autumn	1900	56	2.9
2011	Spring	1900	48	2.5
	Autumn	1900	42	2.2
2012	Spring	2200	34	1.5
	Autumn	2300	2	0.1
2013	Spring	2300	8	0.3
	Autumn	2300	13	0.6
2014	Spring	2300	13	0.6
	Autumn	2200	7	0.3
2015	Spring	2200	8	0.4
	Autumn	2200	3	0.1
2016	Spring	2200	2	0.1
	Autumn			

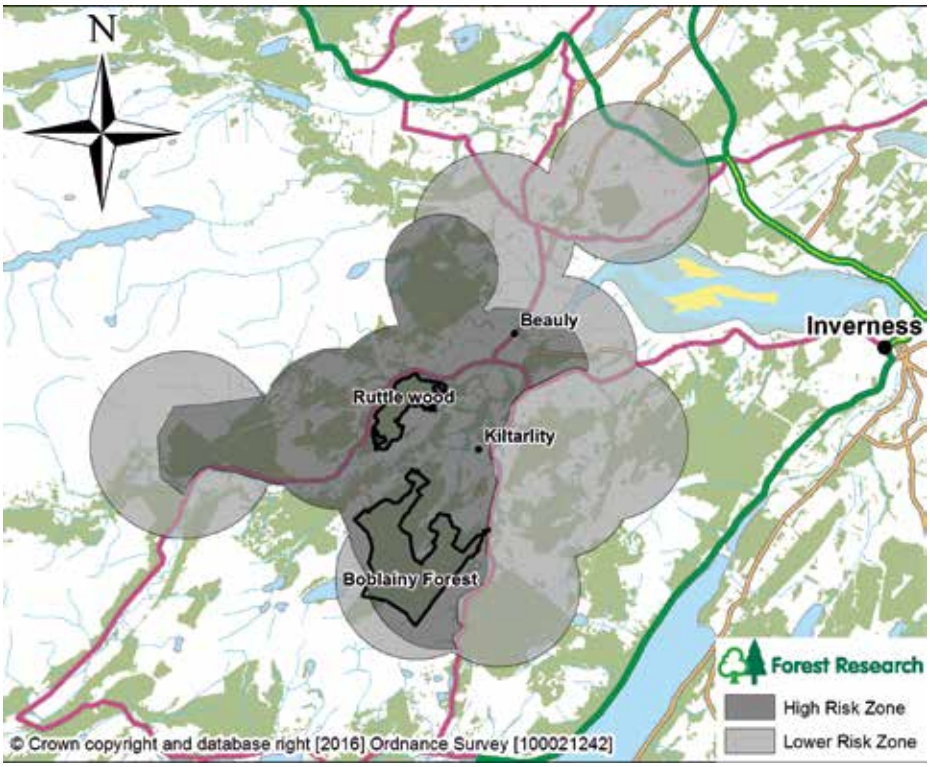


Figure 2: Map showing pine-tree lappet moth risk zones. The higher risk zones are areas where pine-tree lappet has been shown to be breeding or access to monitor has not been possible. The lower risk zones are areas where moths have been caught but no caterpillars have been caught to confirm breeding.

on the foliage and bark of felled timber (Moore and Evans, 2009). Movement of timber, to areas outside the suspected breeding area, was not permitted during the moth's 'active period' and bark-free timber movements were only allowed from 1 December to 28 February when the larval stages were overwintering in the ground. These preliminary controls allowed time to determine whether a breeding population was present, and if so, its size and distribution.

However, these initial precautionary controls severely hindered management activities (thinning and patch clear-felling) of pinewoods in the breeding area due to the difficulties of timber harvesting and haulage in potentially snow-bound conditions. Subsequent to these controls being implemented the programme of regular monitoring revealed that *D. pini* populations were low and that the moth was confined to a small part of the Beauly catchment around Kiltarlity. Based on this improved understanding, it was possible to categorize areas into higher and lower risk zones (**Figure 2**). The OMT considered that the level of timber movement controls could be partially relaxed so that woodland owners could resume more active management of their forests. The higher risk zone comprised the area where breeding had been confirmed by the presence of pine-tree lappet larvae. In this zone, the requirement to debark prior to transport has been relaxed and the time period during which timber can be transported has been extended to encompass the period between 1 September and 17 May (of the following year) subject to FC approval and adherence to biosecurity conditions. Timber movement is also allowed between 18 May and 31 August, but only if independent monitoring carried out to an approved protocol did not detect the presence of larvae during the spring (February/April) of the year of timber movement. The lower risk zone comprises the area where adult male moths had been caught but breeding had not been confirmed by presence of the larvae. In this latter zone, unrestricted timber movement under FC approval and biosecurity conditions is allowed. The relaxation of rules to allow more active management of pinewoods also benefits control of diseases such as Dothistroma needle blight (caused by *Dothistroma septosporum*) which could otherwise have impacted on the health and future resilience of pine woodlands in the area.

Photo 8. A pheromone trap in a Scots pine wood near to Kiltarlity in NE Scotland.

Origin of the pine-tree lappet moth in Scotland

It has been important to try to elucidate the origin of the Scottish pine-tree lappet moth to determine whether it is a native or non-native species. Scottish moths caught during pheromone and

Photo 9: Sticky glue bands being applied to Scots pine trees in Ruttle Wood near Kiltarlity.

light trapping by FR have undergone DNA analysis to define the genetic composition of the Scottish population. In addition, pine-tree lappet specimens were obtained from scientists, museums and moth enthusiasts from across its natural continental range and these also underwent genetic analysis of mitochondrial and nuclear DNA. This was with the aim of clarifying the genetic structure of the species across its distribution range in Europe and Western Asia and to compare the diversity present in the Scottish population with that of one in the centre of its distribution range in mainland Europe. Preliminary analysis of the mitochondrial DNA (A'Hara and Cottrell in prep) revealed three lineages which did not overlap in their distribution. The western lineage was restricted to Spain and western France. The northern lineage occurred throughout Scandinavia in the north, east towards the Caspian sea, west to the North Sea coast and as far south as Greece. The southern lineage included samples from as far north as Udmurtia in Russia, Mongolia in the east, north-eastern France in the west and Turkey and southern Italy in the south. All the Scottish samples belonged to the southern lineage.

These results indicate that the Scottish population does not originate from any of the areas where the northern or western lineages occur. Instead the Scottish population has its ancestral origins in the southern lineage.

Analysis of nuclear DNA based on highly variable microsatellite loci (A'Hara and Cottrell, 2013) indicated markedly lower genetic diversity in the Scottish population compared to that of a population in the centre of the distribution range on the European mainland. As there were never more than four alleles recorded per locus across the whole of the Scottish samples, the microsatellite work indicates that we cannot discount that the Scottish population has established from a batch of eggs laid by a female after a single mating event. Equally, it is possible that the number of breeding individuals in a natural population could have fallen to a very low level such that little genetic diversity remains in the relict population.

Despite carrying out pine-tree lappet moth surveys in the ten ancient Caledonian pine forests which have the most similar climate to that in the recorded breeding sites in Scotland, we found no specimens. These sites are particularly well suited to its growth and survival, being in the drier and warmer parts of NE Scotland, so if it has survived as a native in Scotland it is both surprising and fortuitous that it has not survived in the ancient forests most suited to its autecology.

Risk to Scotland's pine forests

The finding of the first male moth of pine-tree lappet in 2004, further captures in 2008, followed by the confirmation of breeding in 2009, has triggered much subsequent debate about not only its native/non-native status but also about its potential threat to Scotland's pinewood resource.

Populations and threshold damage densities

Overall the pheromone, light and glue band monitoring and surveillance have revealed some fairly consistent findings, with the highest pine-tree lappet catches – and hence largest populations – occurring in 2009-2011 and 2016, the lowest in 2012-13 and 2015; and intermediate population size in 2014. It is highly likely that the reason for the much lower captures in 2012, 2013 and 2015 was the extremely poor spring and summer weather conditions in these years, which would

have caused slow caterpillar growth and low survival, resulting in a subsequent drop in population density. These three years were also unfavourable for many other moth species. The weather in 2014 was considerably better for moths and appears to have aided a partial recovery of the pine-tree lappet population.

However, when compared with threshold damage densities defined for European pine-tree lappet populations, the Scottish populations have remained very low relative to their continental counterparts. Sierpińska (1998) records critical numbers caught below glue bands that signal the need for aerial spraying (following Burzynski, 1988) as between 8-20 larvae per tree for stands up to 20 years old, increasing to 101-150 larvae per tree for stands that are 81-100 years old. Zajac (2009) also showed that critical numbers of larvae varied in relation to stand age and site class. In marked contrast, the maximum density we recorded per tree on any Scottish site has been one caterpillar per three trees, indicating that the population would need to increase substantially before economic losses or ecological impacts might occur. That said, it is important not to be complacent as moth populations are often highly cyclic, exhibiting periods of low densities followed by dramatic increases and outbreak following periods of highly favourable environmental conditions. Indeed, this scenario has been shown for European pine-tree lappet moth populations (Varley, 1949).

Climate modelling studies

Forest Research has also been carrying out climate modelling work to help predict the impact and potential risk to Scottish forests from pine-tree lappet, both now and into the future (Ray *et al*, 2016). The results of this work suggest that climate conditions in Scotland are likely to become more suited to outbreaks in the future, especially in parts of eastern Scotland, close to the areas of confirmed breeding. Culbin Forest was identified in particular as an area where, if it were to colonise, climate conditions would become more and more conducive to promoting an outbreak during the course of this century. Forests on the Black Isle were also likely to be at increased risk of future outbreaks should it spread to these locations. Although the projected climate in Glen Affric over the next 80 years was not expected to significantly alter the risk of outbreak there, other ancient Caledonian pine reserves that are further to the east might be at greater risk should pine-tree lappet spread to these sites.

In addition to the greater potential for outbreak in the forest areas of north-east Scotland as climate warms, the frequency of outbreaks would also be likely to increase in these susceptible areas. If mass outbreaks and widespread tree death did occur in Scottish ancient Caledonian pine forests then they would be highly significant events. Indeed, even infrequent devastating events over relatively small areas of forest could have a significant impact on the total Caledonian pine resource.

"The debate continues about whether pine-tree lappet is native or non-native to Scotland as well as whether it represents a serious risk to Scotland's native forests"

It has been shown for another *Dendrolimus* species (*D. punctatus*) that populations were higher, damage greater and frequency between outbreaks shorter for pure compared to mixed tree species stands (Wang, 2005). These single or very restricted tree species situations are typical of those occurring in pine plantation forestry.

Vanette (2013) lists many species of pine, spruce and fir as hosts of pine-tree lappet as well as Himalayan cedar and juniper. This generalist feeding nature also introduces an increased potential risk to tree species that have not previously encountered it through evolutionary time and have not evolved constitutive plant defences to counter *D. pini* feeding attack. This highlights that it could potentially switch host food source to, for example, Sitka spruce which could have serious consequences for commercial forestry in Scotland.

Conclusions

Overall, the monitoring and surveillance of pine-tree lappet moth since 2009 has revealed that the Scottish population is confined to a relatively small area of north-east Scotland, that it has remained at a low density and that there is generally good agreement in terms of annual population cycles between the different trapping methods (pheromones, light and glue band traps).

Despite the low density recorded, there have been early indications during the first eight years of monitoring that the population is probably spreading, as the number of sites where the adult moths have been captured has gradually increased. Almost invariably the new sites where adults are captured are the closest to the known breeding areas of the previous year. It will take a number of years to be absolutely sure of spread given the low population sizes and hence numbers caught, as well as the fact that the suggested population expansion is based on adult males trapped and they are known to be highly dispersive. The potential for population expansion was highlighted by the discoveries of caterpillars, indicative of breeding, at sites where they were not located at the beginning of containment and monitoring. They were also discovered in Glen Strathfarrar in June 2014, although since trapping had only just commenced there that year it was not possible to be sure whether they had been present beforehand.

The debate continues about whether pine-tree lappet is native or non-native to Scotland as well as whether it represents a serious risk to Scotland's native forests and commercial forest industry, especially with more favourable climate conditions in NE Scotland predicted in the future. However, it is definitely worth maintaining a precautionary approach to pine-tree lappet given its impact on the continent, and the potentially serious environmental and conservation implications, by ensuring management of this potential pest species remains balanced and risk-based. With this in mind, Forestry Commission Scotland implemented a containment policy (June, 2014) to prevent the spread of the insect from its core breeding sites; this attempts to eradicate it from any newly colonised

forest and woodland sites where it has not previously been found. FCS has also indicated its continuing commitment to prevent spread to new areas via human-assisted transport and will monitor populations within the breeding area for any signs of increase towards densities indicative of potential outbreak.

Acknowledgements

The authors are grateful to Forestry Commission Scotland for funding this work, to Hugh Clayden for his involvement, Alistair Macleod and TSU staff at Lairg and Newton Field Stations for monitoring and surveillance, and Jordan Chetcuti for producing the risk zone map. We are also indebted to Butterfly Conservation Scotland, especially Dr Tom Prescott, and the many woodland and forest owners who have provided access to their land.

References

A'Hara, S. & Cottrell, J. (2013). Development and characterisation of ten polymorphic microsatellite markers for the pine-tree lappet moth *Dendrolimus pini* (Lepidoptera: Lasiocampidae). *Conservation Genetics Resources* 5: 1135-1137.

Baranchikov, Y.N., Pet'ko, V.M., and Ponomarev, V.L. (2006). The Russians are coming- aren't they? Siberian moth in European forests. *Proceedings 17th U.S. Department of Agriculture Interagency Research Forum on Gypsy Moth and Other Invasive Species. General Technical Report* NRS-P-10, 18-20.

Björkman, C., Lindelöw, Å., Eklund, K., Staffan Kyrk, Maartje J. Klapwijk, Frauke Fedderwitz & Göran Nordlander (2013). A rare event – an isolated outbreak of the pine-tree lappet moth (*Dendrolimus pini*) in the Stockholm archipelago. *Entomologisk Tidskrift* 134 (1-2): 1-9. Uppsala, Sweden 2013.

Buck, J.H. (2008). Effects of natural disturbances caused by the Siberian moth, *Dendrolimus superans sibiricus* (Tschetverikov), and fire on the dynamics of boreal forests in Krasnoyarsk Krai, Russia. PhD, The University of Michigan.

Burzynski, J. (ed.) 1988. *Instrukcja ochrony lasu* [Forest Protection Guide]. PWRiL, Warszawa.

Csoka, von G. (1991). Der EinfluB der Schadenerregung des Kiefernspinners (*Dendrolimus pini L.*) auf das Wachstum eines Kiefern-Jungbestandes. Anz. Schádlingskde., Pflanzenschutz, Umweltschutz, 64, 148-150.

EPPO, (2005). Data sheets on quarantine pests: *Dendrolimus sibiricus* and *Dendrolimus superans*. *OEPP/EPPO Bulletin* 35, 390-395.

Hopkins, A.D., 1907. Notable Depredations by Forest Insects. Reprint from *Yearbook of Department of Agriculture for 1907*, p147-164, Washington.

Kamata, N. (2002). Outbreaks of forest defoliating insects in Japan, 1950-2000. *Bulletin of Entomological Research*, 92 (2), 109-117.

Kharuk, V.I., Ranson, K. J., Kozuhovskaya, A.G., Kondakov, Y.P. and Pestunov, I. A. (2004). NOAA/ AVHRR satellite detection of Siberian silkmoth outbreaks in eastern Siberia. *International Journal of Remote Sensing*, 25 (24), 5543-5555.

Kiddie, R., 2008. Pine-tree Lappet *Dendrolimus pini* confirmed as a British Breeding Species. *Atropos* 35: 64–65.

Kimoto, T. and Duthie-Holt, M. (2006). *Exotic Forest Insect Guidebook*. Canadian Food Inspection Agency.

Kondur, Y., Oner, N., and Simsek, Z. (2006). Harmful insects and relationships between certain tree properties in Scots pine (*Pinus sylvestris L.*) of Ilgaz mountain, Cankiri, Turkey. *Journal of Biological Sciences*, 6 (6), 1065-1070.

Leverton, R. (2009). Pine-tree Lappet *Dendrolimus pini* (L.) (Lep.: Lasiocampidae) in Scotland: a previously overlooked indigenous species? *Entomological Records & Journal of Variation*, 120: 85–88.

Li, T. and Zhou, G. (1998). Evaluating the impact of insect communities on pine caterpillar density under different stand conditions. In McManus, M.L. & Liebhold, A.M. (eds). *Proceedings: Population Dynamics, Impacts, and Integrated Management of Forest Defoliating Insects*. USDA Forest Service General Technical Report NE-247, p122-128.

Malyshev, D. S. (1997). Disappearance of mass outbreaks of *Dendrolimus pini* L. (*Lepidoptera, Lasiocampidae*). *Acta Phytopathologica et Entomologica Hungarica*, 32 (1-2), 217-221.

Meshkova, V., (2006). Foliage browsing insects risk assessment using forest inventory information. *Proceedings of IUFRO Working Party* 7.03.10, 100-108.

Moeller, K., Haeussler, D., Majunke, C., Apel, K.H., Loeffler, S., Heydeck, P., and Wenk, M. (1998). About the Current Outbreak of the European Pine Moth (*Dendrolimus pini* L.) in the Northeast German Lowlands, page 353 in Proceedings: Population Dynamics, Impacts, and Integrated Management of Forest Defoliating Insects. *USDA Forest Service General Technical Report* NE-247 (editors M.L. McManus and A.M. Liebhold).

Moore, R., and Evans, H.F. 2009. Pest Risk Analysis for *Dendrolimus pini*. 1-35, Forestry Commission, UK.

Mozolevskaya, E.G., Utkina, I.A., and Matusevich, L.S. (2002). Dynamics of foci of forest pest insects in Russia over the last decade. Proceedings: Ecology, Survey and Management of Forest Insects (eds. McManus, M.L., and Liebhold, A.M.). *USDA Forest Service, GTR-NE-311*, p61-67.

Prescott, T., 2009. Pine-tree Lappet *Dendrolimus pini* – Friend or Foe? *Atropos* 37: 3-10.

Ray, D., Peace, A., Moore, R., Petr, M., Grieve, Y., Convery, C. and Ziesche, T. (2016). Improved prediction of the climate-driven outbreaks of *Dendrolimus pini* in *Pinus sylvestris* forests. *Forestry* 89: 230-244.

Sergeenko, V.N. (2005). Preliminary results of forest protection and renewal in 2003: Forest fire management. *International Forest Fire News*>(IFFN) 32, 5-11.

Selikhovkin, A.V., (1998). Defoliating insects: History of outbreaks in the coniferous forests of Russia. Proceedings: Population dynamics, impacts and integrated management of forest defoliating insects. *USDA Forest Service General Technical Report NE-247*, p340.

Shi, L. Zhao, Y. Zhang, Z-H, Xu, L-F and Wan, Y-M. (2004). Effect of compound microbial pesticide on controlling *Dendrolimus* spp. in large areas. *Forest Research*, 17 (4), 461-464.

Sierpińska, A., 1998. Towards an Integrated Management of *Dendrolimus pini* L. in McManus, M.L. & Liebhold, A.M. (eds). Proceedings: Population Dynamics, Impacts, and Integrated Management of Forest Defoliating Insects. *USDA Forest Service General Technical Report NE-247, 129-142*.

Vanette,, R.C. (2013). Pine commodity-based survey reference. *Cooperative Agricultural Pest Survey*. USDA Forest Service.

Varley, G.C. (1949). Population changes in German forest pests. *Journal of Animal Ecology*, 117-122.

Wang, G., Liu, X., Ge, F., and Li, Z. (2005). Population dynamics of *Dendrolimus punctatus* in different pine forest. *Chinese Journal of Ecology*, 24(4), 355-359.

Yuan, F., Luo, Y., Shi, J., and Kari, H. (2011). Spatial ecology niche of main insect borers in larch of Aershan. *Acta Ecologica Sinica*, 31 (15), 4342-4349.

Zajac, S. and Klocek, A. (2009). *A model of economic evaluation of forest protection treatments against defoliating pest insects*. XIII World Forestry Congress, Buenos Aires, Argentina, 18-23 October, 2009, p1-11.

Zhang, A., Wang, Z., Tan, S. and Li, D. (2003). Monitoring the masson pine moth, *Dendrolimus punctatus* (Walker) (Lepidoptera: Lasiocampidae) with synthetic sex pheromone-baited traps in Qianshan County, China. *Applied Entomology and Zoology*, 38 (2), 177-186.