# Developments in the integrated management of pine weevil, a pest of restocking in conifer plantations

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## Introduction

Integrated Forest Management (IFM) as a concept parallels the Integrated Crop Management (ICM) approach being adopted increasingly in agriculture. It examines all aspects of the forest crop production system to determine which have most influence on total productivity and survival. Within the overall approach to management of commercial and recreational forests, the direct and indirect effects of existing management practices on the impacts of pests on trees are considered dynamically in order to provide options for longer term management. When pest populations lead to unacceptable damage or tree mortality, the approach adopted by Forest Research scientists is to utilise conventional Integrated Pest Management (IPM) as the core tool to reduce these populations to a level below economic injury level. This concept has been adopted within an IFM programme which initially addressed a wide range of topics and disciplines, including entomology, pathology and silviculture.

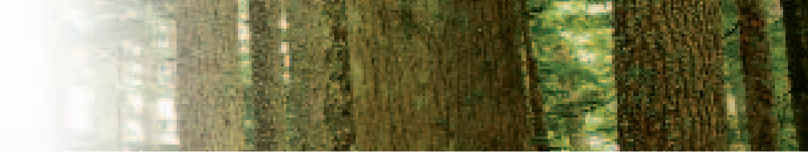
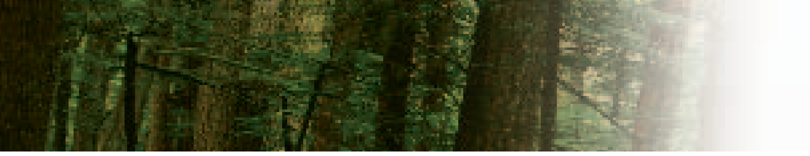


**Figure 1**

Adult pine weevil *Hylobius abietis* feeding on stem bark of conifer transplant.

After further evaluation of the IFM approach, work started on the most important insect pest of British forestry, namely the pine weevil *Hylobius abietis* (Figure 1), as a model system to develop IFM concepts towards a practical working system. As a result, existing projects on this pest were brought together. In developing a fuller understanding of the nature and dynamics of the *Hylobius* problem, it must be acknowledged that it is a man-made problem, which has been exacerbated by the introduction of efficient modern tree felling systems and replanting practices. The former have provided progressively more abundant breeding resources leading to greater *H. abietis* populations and the latter have led to greater damage by providing a preferred food supply for emerging adults within a clearfell area generally lacking in such resources. Conversely, the recognition that management practices are part of the primary cause of the problem also offers the potential to solve it, through changes in future management. Consequently, our approach to the challenge of developing a sustainable IFM system of management to counter the *H. abietis* threat includes the following key elements:

- Understanding and quantifying the links between felling dates and colonisation of the restock site by new populations of *H. abietis*.
- Quantifying the relationships between arrival of *H. abietis* colonising adults and subsequent breeding success and development in stumps, i.e. the net rate of population increase.
- Predicting the emergence periods of *H. abietis* populations on site, based on colonisation patterns relative to felling periods.
- Predicting the end-points of stump exploitation and *H. abietis* emergence to assess the magnitude and duration of risk over the period between felling and final restocking.
- Quantifying the links between *H. abietis* adult populations and damage to transplants to both determine risk and quantify the threshold population size for acceptable damage.
- Quantifying the impacts of insect parasitic nematodes on the survival of *H. abietis* in stumps treated with nematodes. This is the only strategy to directly reduce weevil populations towards the required threshold population size.
- Assessing and predicting the breeding success in stumps of different conifer species on a range of sites to aid the overall risk assessment model by quantifying the role of the previous crop on overall *H. abietis* dynamics on site.
- Assessing and predicting the relative resistance of transplants to *H. abietis* feeding pressure in relation to species, age, addition of fertilisers, etc. This is the final determinant of impact and links dynamically to threshold population size.



We are using acquired data and outputs of predictive models to develop options for management, with particular reference to reductions in the use of chemical insecticides. Currently, the emphasis is on spruce plantations, to reflect the importance of this genus in commercial forestry in Britain. While this places some constraints on the wider use of the particular models being developed, the general principles are also being adapted to upland and, more recently, lowland pine sites.

Key options that are being incorporated in the overall IFM strategy include:

- Use of chemical insecticides:
  - prediction of the need for pre-treatment
  - prediction of the need for top-up sprays.
- Guidance on the length of fallow period for delayed restocking (based on monitoring populations).
- Use of felling date information to predict exploitation and larval development in stumps to target nematode applications for maximum impact.
- Gradual reduction of *H. abietis* populations through use of nematodes in consecutive felling cycles within whole forest blocks. The key will be reduction in the source populations that constitute the pool of weevils for migration to new clearfells in the vicinity.
- Development of a Management Support System (MSS) based on known risk factors and, increasingly, predictive modelling supported by monitoring.

## Biology, population dynamics and migration of *Hylobius abietis*

Initial studies on the biology of *H. abietis* have concentrated on quantifying the population dynamics and damage caused by the weevil from the time of clearfelling to 5 years post-fell in upland spruce sites. During this period, timing and amount of colonisation and emergence of *H. abietis* and its movement between mature 'source' clearfells and newly felled 'sink' clearfells have been shown to be critical to prediction of events on a given clearfell site. The aim is to use the data to develop decision support systems for the management of the restocking problem by developing models of *H. abietis* populations and their associated damage and movement between felling areas. The ultimate aim will be to achieve sustainable reductions of *H. abietis* populations towards levels known to lead to acceptable damage as predicted by population dynamics models. These models will be further refined to incorporate data from other projects within the IFM programme.

Results from studies carried out at Ae Forest, Dumfries, Scotland, over the period 1995 to 2002, indicate that there are consistent and predictable patterns of population development and damage following clearfelling and that timing of felling plays a key role in determining the magnitude and timing of the peaks of *H. abietis* density (Moore, 2004; Moore *et al.,* 2004). It has also shown that there is a strong relationship between populations and transplant damage and that the majority of damage occurs during periods of emergence of new generation adults from stumps. For the first time under British conditions, it is now possible to relate transplant damage to the size of *H. abietis* adult populations on site and to link these dynamically to the availability, temporally and spatially, of breeding material. Work is continuing to build predictive models that forecast population trajectories and transplant damage on a site-specific basis (see Management Support System, page 82).

## Determining the length of the fallow period

Within the overall MSS concept, a number of 'tools' are being developed to provide managers with choices based on the improved information and predictability arising from the modelling approach. A low cost, low intervention approach is to predict the length of the fallow period which minimises the risk of *Hylobius* damage. This can lead to reductions in chemical treatments through minimising or eliminating the need for top-up sprays after restocking. This topic has been studied by assessing whether the patterns of population development found in Ae Forest (the length of the fallow period and size and dynamics of *H. abietis* populations) were similar to those at a range of sites across northern Britain. The work was carried out on 36 clearfell sites of known age since felling, in eight Forest Districts (FDs), and was also designed to determine our ability to predict damage (to treated and untreated transplants) from one year to the next, by monitoring *H. abietis* in the first year. On all sites, weevil densities and damage to transplants were monitored over a two-year period to determine the relationship between trap catches and damage (within and between years) as well as the length of the fallow period (i.e. the time taken post-fell before damage to transplants reduces to below 10%).

Initial results from the study showed that permethrin ED treated plants were well protected from damage on all sites in the first year after planting except on sites where the first emergence of *H. abietis* was occurring. The permethrin ED treated plants were not re-treated in the second year of the study and were badly damaged in that year, indicating little residual protection of the trees. This was the case for all sites except those that were aged from 4 to 5 or 5 to 6 years post-clearfell during the course of the work. In these cases little additional damage occurred, but this was as a result of general reductions in weevil populations associated with time since clearfell rather than continued insecticide protection. Damage to untreated trees was very high in sites of age 0, 1 and 2 (these being the year of colonisation, first and second emergence, respectively), intermediate on age 3 sites, but much lower and acceptable on sites of age 4 and 5. Damage levels varied in direct relation to catches of *H. abietis* at conifer billets and highly significant relationships were found between these variables 'within year'.

Models showed that it was possible to use billet captures in one year to predict damage in the following year ('between year' forecast). Precise knowledge of clearfell age significantly improved the ability to forecast from one year to the next. The highest *H. abietis* catches and damage occurred during late season (August/October) for the younger sites but during the early season (May/July) for older sites. These results were all consistent with those obtained in Ae Forest for the more detailed population dynamics work. It is likely that these models could be further improved by taking other site factors into account and this information is currently being collected. The data were analysed further and it was found to be possible to reduce the number of censuses and billets used to predict damage. This has made it possible to reduce monitoring costs for the *H. abietis* MSS.

## Development and testing of a Management Support System for restocking conifer forests

The success of the population dynamics work and the forest-scale trials described has led to the development of a new 'Management Support System' (MSS). The MSS is currently being co-ordinated within this programme and trialled, through Technical Support Unit, in Kielder, Dornoch and Coed y Gororau FDs (one FD in each of the three countries) from 2003 onwards. The *H. abietis* population dynamics project and forest trials have enabled the development of models that can be used to predict population dynamics trajectories and subsequent damage following the pre-emptive collection of minimal site-specific data (Figure 2). These models will be used to predict the likely success (or otherwise) of using the various management options (shown in green in Figure 2) and to provide advice to FD staff on the *H. abietis* threat to transplants in different years following the completion of felling operations.

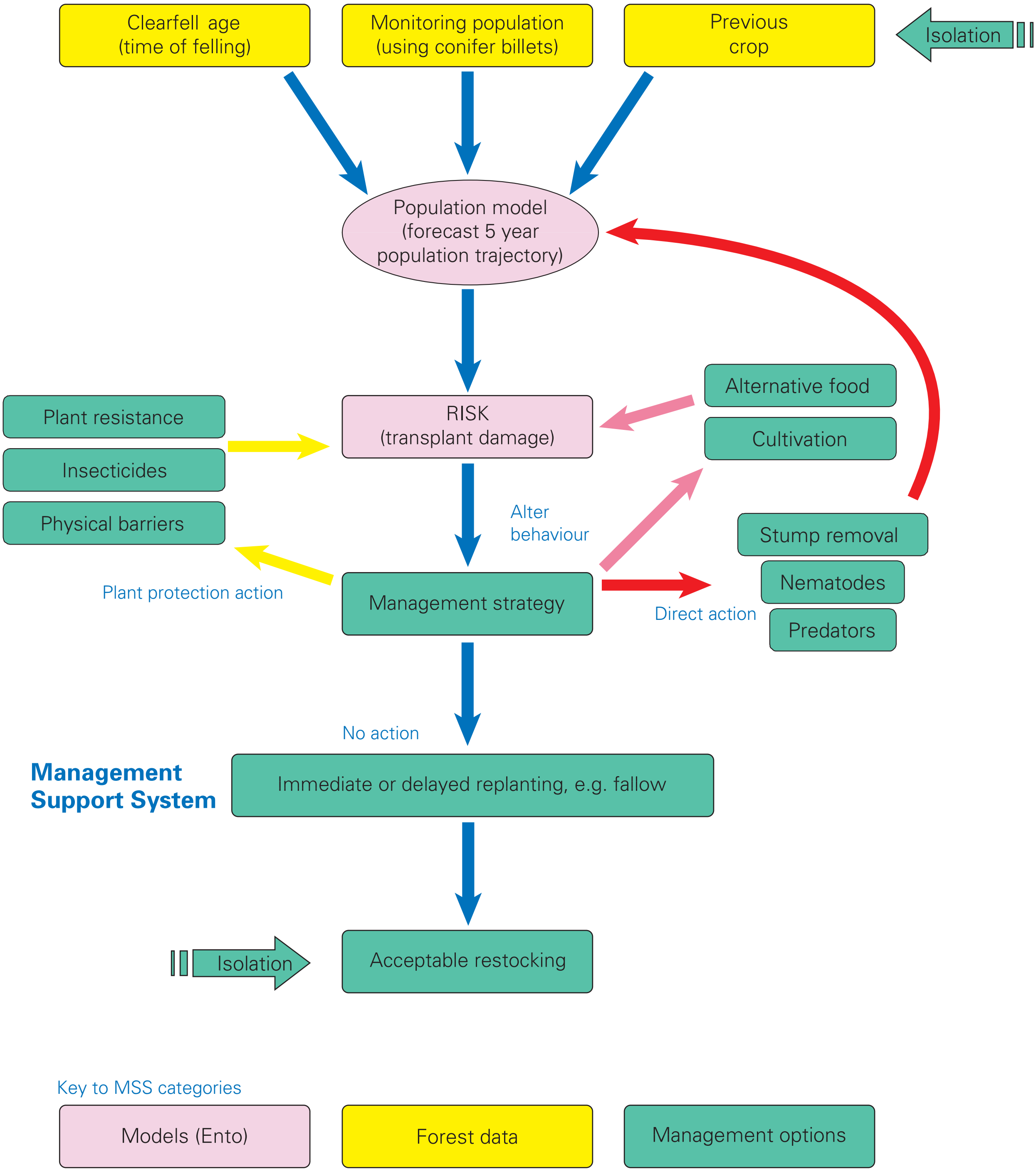
Protocols have now been developed for the site evaluation, data collection and temporal management of clearfell sites entering the MSS programme and initial *H. abietis* population monitoring started during two periods in the spring and autumn of 2003. The monitoring indicated that populations on individual clearfells were considerably different at these two times of year. However, when the 'independent' population data from these two time periods were analysed using the population model there was a very close agreement in damage levels forecast for subsequent years. The advice for each individual clearfell in the MSS will be presented to FDs during late 2003 for take up in 2004. At the end of 2004, the MSS recommendations made during 2003 will be evaluated by examining the variation in 2003 'predicted' and 2004 'observed' levels of tree damage.

## Plant resistance as a factor in determining weevil population size and damage to transplants

The project on plant resistance has the aim of reducing susceptibility of plants to weevil attack and of increasing their survival after attack. Success will depend on understanding the nature of defensive mechanisms in young trees, the relative importance of genetic and environmental factors in resistance expression and the significance of feeding in the reproductive behaviour of adult weevils. A study is also being made of the effect of root-stump 'quality' on weevil survival and development rate and how this interacts with the silvicultural management of the forest. Results will have a direct bearing on the survival and breeding success of pine weevil and so this part of the project is closely integrated with the other main components of the IPM programme – population dynamics, control of larvae with nematodes and the MSS. Methods of monitoring pine weevil populations that are specific to lowland forestry are also being developed.

**Figure 2**

Developing a model to predict population dynamics trajectories and subsequent damage to conifer transplants.



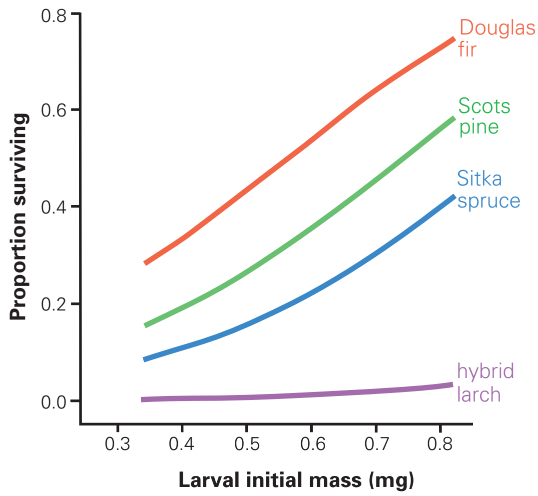
## The influence of the breeding resource on *H. abietis* reproductive success

Emphasis on the quantitative aspects of root-stump availability as a determinant of weevil population size has tended to obscure possible qualitative variation, both within and between tree species, in their 'suitability' for larval development. In living trees, both preformed and induced defences are highly effective in preventing colonisation of conifer bark by bark beetles and weevils. In the intact root-stump left in the ground after felling, preformed defences and even induced responses could remain partially effective and reduce establishment success of pine weevil larvae for a period after felling.

We found significant variation in larval survival on different conifer species (Figure 3). In addition, 'maternal effects' determine egg size and therefore the size of larvae that attempt to establish galleries in the bark of different species. Larger larvae are more successful than smaller ones in establishing in 'fresh' bark (Figure 3; Wainhouse *et al.*, 2001) providing indirect evidence for the importance of 'residual' resistance mechanisms within the bark of roots and stumps after felling. Resin appeared to be an important cause of larval mortality in pine, whereas in Sitka spruce, physical defence in the form of lignified stone-cell masses reduced the growth rate of larvae and probably also affected establishment success. We predict that the number of weevils emerging from clearfell sites will be determined both by the quantity and 'quality' of root-stumps available and this information could be of value in developing and interpreting monitoring methods within a MSS.

**Figure 3**

Predicted survival of pine weevil larvae inoculated onto logs of four different conifer species.




## Maturation feeding of adult *H. abietis* and damage to transplants

Adult female weevils emerge from root-stumps with undeveloped ovaries in which eggs develop only after a period of maturation feeding. In natural forest systems, these weevils will feed opportunistically on local food sources, especially the bark of branches and twigs within the crowns of mature conifers. At clearfell sites, initial feeding is likely to be on the bark of transplants although weevils also feed on the bark of logs and brash left at the site after felling operations as well as on standing trees in the vicinity. Adult weevils are large relative to transplants and because they feed on the bark of the main stem, relatively small amounts of damage can be lethal. As a result, significant damage to transplants is likely even at relatively low weevil population densities. Mass-produced conifer transplants (Figure 4) are, in general, highly susceptible to weevil attack and often require insecticidal treatment to ensure successful establishment. In addition, the use of highly susceptible plants makes the relationship between weevil population size and damage to transplants sensitive to relatively small changes in weevil abundance. This must be taken into account when using monitoring to predict potential damage to young transplants based on population size.

The aim of this part of the study has been to determine what factors influence the amount of feeding on transplants. To be of practical value,

**Figure 4**

Intensive production of young conifers in a forest nursery.

resistance in young conifers would need to be expressed through a reduction in the amount of feeding or an increase in the ability of the plants to tolerate and recover from a given level of feeding damage.

We have studied aspects of plant resistance by measuring weevil food consumption and rate of reproductive development when feeding on bark with differing nutritional and defensive characteristics. In order to understand the underlying processes, we have manipulated the growing conditions of young conifers to produce a range of phenotypes and, by analysing the main factors influencing the amount and distribution of feeding, identified likely resistance mechanisms (Wainhouse *et al.*, 2005, in press).

The amount of feeding on young conifers was influenced by a wide range of factors including the sex and size of weevils, stem diameter and the nutritional and secondary chemical content of the bark. One of the most important factors influencing the pattern of feeding on three seedling conifers (Corsican and Scots pine and Sitka spruce) was the inherent variation in the size of resin ducts in the bark of the main stem. The flow of resin from ducts severed during feeding appears to provide the main defence against pine weevil. Factors that influence the size of resin ducts during plant development and the amount of resin produced are currently under investigation.

## Direct intervention through reduction in *H. abietis* populations by application of insect parasitic nematodes

Building on several years' experimentation and field tests of the potential efficacy of entomopathogenic nematodes (EPNs) for biological control of *H. abietis* (Brixey, 1997), a programme of extended field trials and semi-operational use of nematodes commenced in 1999. Acknowledging that commercially available nematodes were significantly too expensive for operational use in forestry, a nematode production facility was constructed at Alice Holt during 1999, initially in collaboration with CABI Biosciences at Egham. Production was based primarily on techniques for the small-scale, low-technology production of nematodes developed by Australian scientists over the past few years. During this early phase of our work, a business model was prepared, demonstrating that nematodes may be produced at a cost considerably lower than those produced using commercial fermentation systems. During 2003, Forest Research embarked on development of its own variant of the Australian-based production technique.

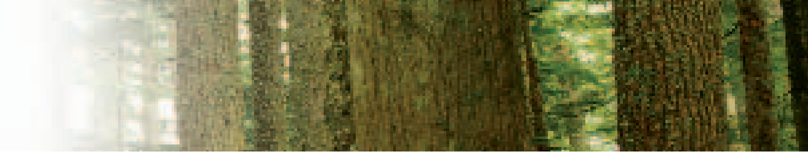
One of the key constraints to such techniques has been separation of the nematodes from the sponge medium during harvesting. To address this we have collaborated with BHR Group, Cranfield, in the design and production of a prototype separation system to remove nematodes from diet. This uses cyclone technology to separate the nematodes and is fully automated, offering the potential for considerable cost savings compared with conventional zonal centrifugation. Despite these encouraging developments in nematode production in-house, we are keeping our options open and have developed an excellent working relationship with Becker Underwood, the principal producer of nematodes in the UK and have used their nematodes for field trials in 2002 and 2003.

Field trials have been carried out over the past four years in order to provide baseline data on population reductions following direct application of nematodes to late larval/pupal populations in stumps. For optimum impact on the *H. abietis* populations, the nematodes must be applied to individual stumps in relatively high quantities of water at the correct stage of weevil development. Techniques and equipment have been developed to handle and apply the EPNs and use of a purpose built spray rig allows nematodes to be applied at costs per hectare competitive with the costs of treatment with insecticides. In addition, EPNs also offer the prospect of considerable cost savings over the longer term as the accumulated impacts of consecutive nematode applications become apparent on a forest-wide scale.

Over 100 ha were treated with EPNs during 2003. The development of new equipment allowed significant increases in the efficiency of application enabling the team to treat up to 10 ha per day. Results indicate that the application of nematodes not only reduced the emerging population of weevils in the few weeks after treatment, but surviving nematodes have a significant impact on late developing weevils the following year. Combined with previous results in both small and medium scale trials (up to 85 ha), we are increasingly confident that EPNs will be a key tool in reducing populations of *Hylobius* towards the levels predicted to be economically acceptable in our IFM programme.

An improved business plan for the use of nematodes in the management of restocking areas has been developed together with a number of information leaflets, CDs and fact-sheets to support forest managers in their adoption of this system.

The next phase of the work is to model the within-year effects of population reduction within the overall MSS system and to assess how this affects the size of the incoming weevil population to 'sink' clearfells at different distances from the treated sites. An important element of using EPNs is to consider their impacts over the longer term and on a forest-wide scale so that the efficacy can be measured based on how well the treatment reduces migrant populations to new 'sinks'.



## Conclusions

Taken together, the various elements of our work on sustainable management of *H. abietis* are now being integrated within the IFM approach so that, through monitoring and prediction, forest managers will be able to select options specific to local circumstances. Some of the tools will be low cost, but subject to temporal constraints, whereas others, such as use of nematodes to reduce pest populations and selection of transplants with improved ability to withstand attack, will directly affect overall damage levels. The current emphasis is on upland spruce areas but there is also encouraging progress on lowland pine sites indicating that the overall IFM concept is robust and likely to improve as our experience of the approach increases.

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