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**Spatio-Temporal Modelling and Analysis of Larch Bud Moth
Population Dynamics in the European Alps**

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TABLE OF CONTENTS

SUMMARY.....	VII
ZUSAMMENFASSUNG	IX
1 INTRODUCTION	1
1.1 The larch bud moth in general.....	1
1.2 Cyclic population dynamics	2
1.3 Spatio-temporal population dynamics	3
1.4 Scale issues in Ecology and Ecological Modelling.....	5
1.5 The research context	6
1.6 Objectives of this study.....	6
1.7 References	8
2 MATERIAL AND METHODS: MODELS	13
2.1 Simulation Environment	13
2.2 Existing models	14
2.2.1 LBM-M8.....	15
2.2.2 LBM-M9.....	17
2.3 Models developed in this research.....	20
2.3.1 LBM-M11	20
2.4 References	25
3 SYNCHRONY AND TRAVELLING WAVES OF LARCH BUD MOTH? TIME SERIES ANALYSIS WITH CHANGING SCALE	29
3.1 Introduction	30
3.2 Material and Methods	33
3.2.1 Study Area and Census Data.....	33
3.2.2 Time Series Analysis.....	37
3.3 Results.....	39
3.3.1 Valley scale	39
3.3.2 Alpine Arc scale	40
3.4 Discussion	44
3.5 Conclusions and Outlook.....	48
3.6 Acknowledgments	49
3.7 References	49
4 THE INFLUENCE OF OROGRAPHY ON LARCH BUD MOTH MIGRATION AT THE VALLEY SCALE.....	55
4.1 Introduction	56
4.2 Material and Methods	58
4.2.1 Study Area and Data.....	58
4.2.2 LBM-M8 and LBM-M9 Models.....	60
4.2.3 LBM-GIS	63

4.2.4 Comparison of Results.....	66
4.2.5 Sensitivity analysis	66
4.3 Results	66
4.4 Discussion	74
4.5 Conclusions and Outlook.....	76
4.6 Acknowledgments	77
4.7 References	77
5 SPATIO-TEMPORAL MODELLING OF LARCH BUD MOTH DYNAMICS IN THE EUROPEAN ALPS: THE IMPORTANCE OF DATA RESOLUTION	81
5.1 Introduction	82
5.2 Material and Methods	84
5.2.1 Study area.....	84
5.2.2 Models	85
5.2.3 Data.....	89
5.2.4 Comparison of Models Performance.....	94
5.3 Results.....	100
5.4 Discussion	105
5.5 Conclusion.....	108
5.6 Acknowledgments	109
5.7 References	109
6 DISCUSSION	115
6.1 The role of IPODLAS.....	115
6.2 Spatio-temporal dynamics of larch bud moth at differing scales.....	116
6.3 Influence of data resolution of modelling larch bud moth dynamics	116
6.4 References	119
7 CONCLUSIONS.....	121
7.1 Spatio-temporal dynamics of larch bud moth at differing scales.....	121
7.2 Influence of data resolution of modelling larch bud moth dynamics	121
APPENDIX	123
I Mathematical model LBM-M8	123
II Mathematical model migration sub model LBM-M9	126
III Modula-2 code LBM-M11	129
LBMMaster.....	129
LBMModel.....	133
LBMLifeCycle	141
LBMFlight	154
LBMFlyPars.....	167
LBMMonit	187
LBMValley	190
LBMObs	193
CURRICULUM VITAE.....	209

SUMMARY

The larch bud moth (*Zeiraphera diniana* GN.; Lep., Tortricidae) has caused large-scale defoliation of larch trees across the entire Alpine Arc every 8-10 years since at least Roman times. The temporal dynamics of the larch bud moth and its population cycles have been researched intensively, however the spatial patterns of larch bud moth population have received less attention. Some studies have noted the synchrony of population cycles within valleys, or, at the Alpine arc scale, travelling waves of larch bud moth (as a special case of synchrony). However, accurate quantification of these patterns has not previously been shown and the reasons for such patterns remain unclear. Recent research into synchrony suggests dispersal or regional environmental correlation (the Moran Effect) could result in such patterns of synchrony. Knowledge of spatio-temporal patterns of population dynamics is of general interest to ecologists and important for management and conservation purposes. As ecological field studies with high spatial and temporal resolution and extent are usually prohibitively expensive and time consuming, modelling studies are necessary for the management and understanding of systems over wide spatial and temporal grains and extents. However, knowledge of the appropriate grains and extents at which to model is necessary to achieve usable results.

The main aims of this research were to 1) to determine the spatio-temporal dynamics of larch bud moth populations at differing scales and 2) to investigate the influence of spatial data resolution on modelling larch bud moth dynamics and determine an optimum resolution for modelling larch bud moth dynamics in the Upper Engadine valley allowing for a balance between model complexity, output accuracy and simulation time.

Through time series analysis, in particular cross-correlation and cross-spectral analysis, we were able to confirm that patterns of synchrony at the valley scale and travelling waves at the Alpine arc scale in population cycles of larch bud moth are present but not consistent across all sites in the Upper Engadine valley.

At the Alpine arc scale, waves of larch bud moth travel from west to east across the Alpine arc. Wind-driven dispersal mechanisms in conjunction with a

gradient in habitat quality (possibly habitat connectivity) provide a feasible explanation for this phenomenon, whereas the Moran effect does not.

At the scale of the Upper Engadine valley, populations of larch bud moth are in close synchrony with one another with the exception of populations in areas to which migration is restricted due to orographical effects. This finding also confirms the hypothesis that migration is driving synchrony at the valley extent rather than the Moran effect.

We modelled larch bud moth population dynamics and migration under the same process models at the spatial extent of a single valley (The Upper Engadine valley) but with differing spatial grains: 1. that of the entire valley, 2. that of areas known as ‘sites’ which have an average area of 3.7km² and are homogeneous with respect to altitude, forest type and aspect, and 3. that of the forest compartment, which have an average area of 25 hectares. We revealed that for the larch bud moth, from these spatial grains, optimum modelling spatial grain is that of the ‘site’. However, dispersal appears to be more sensitive to wind conditions as influenced by orography at a higher spatial resolution than has been assumed previously. Thus, while larch bud moth populations should only be considered distinct at the ‘site’ level and therefore local dynamics modelled at this spatial grain, modelling of migration processes between the ‘sites’ taking into account orography at a higher resolution would produce more accurate predictions. Comparison of our time series analysis and modelling results revealed that migration is an important causal mechanism for observed patterns of synchrony in larch bud moth populations at the valley scale.

ZUSAMMENFASSUNG

Seit der Zeit des Römischen Reiches verursacht der Lärchenwickler (*Zeiraphera diniana* GN.; Lep., Tortricidae) alle 8-10 Jahre großräumige Entnadelungen der Lärchenbäume über den gesamten Alpenbogen. Die zeitliche Dynamik der Lärchenwickler ist intensiv erforscht worden, ihrer räumlichen Verteilungen wurde aber wenig Aufmerksamkeit geschenkt. Einige Studien haben die Gleichzeitigkeit der Populationzyklen innerhalb von Tälern oder Wanderwellen des Lärchenwickler über den Alpenbogen (als spezieller Fall von Synchronie) aufgezeigt. Eine genaue Quantifizierung dieser Muster stand allerdings noch aus und die Gründe für die Muster blieben unklar. Neue Forschungen legen nahe, dass Wanderungen oder regionale Umweltwechselbeziehungen (Moran Effekt) solche Muster von Gleichzeitigkeit erzeugen könnten. Das Verständnis raumzeitlicher Muster von Populationsdynamiken ist für Ökologen von allgemeinem Interesse, sowie für Management- und Erhaltungszwecke wichtig. Ökologische Feldstudien mit zeitlich sowie räumlich hoher Auflösung und grosser Ausdehnung sind normalerweise unerschwinglich teuer und mit hohem Zeitaufwand verbunden. Für das Management und für das Verstehen eines Systems mit räumlich und zeitlich hoher Auflösung und grossen Ausmassen sind daher Studien mit Modellierungsansatz notwendig. Um aussagekräftige Resultate zu erzielen ist die Kenntnis von angemessener Auflösung und Ausdehnung unentbehrlich.

Die Hauptziele der vorliegenden Forschungsarbeit waren 1) die Feststellung der Populationsdynamik des Lärchenwicklers auf unterschiedlichen Skalen in Raum und Zeit und 2) die Untersuchung des Einflusses der räumlichen Datenauflösung auf das Modellieren der Lärchenwicklerdynamik, sowie das Festlegen einer optimalen Auflösung für das Oberengadin, bei welcher Modellkomplexität, Genauigkeit und Simulationszeit im Gleichgewicht stehen sollen.

Durch Zeitreihenanalyse, insbesondere Kreuzkorrelation und Kreuzspektrumanalyse, konnten die Gleichzeitigkeit auf der Skala eines Tals und die Wanderwellen auf der Skala des gesamten Alpenbogens bestätigt werden, aber es könnte auch gezeigt werden, dass diese nicht konsistent an allen Standorten des Oberengadins auftreten.

Auf der Skala des ganzen Alpenbogens sind Wanderwellen des Lärchenwickler von Westen nach Osten festzustellen. Windgetriebene Verbreitungsmechanismen in Verbindung mit einem Gradienten der Lebensraumqualität (vielleicht Lebensraumverbund) stellen eine plausible Erklärung für dieses Phänomen dar, eher als der Moran Effekt.

Auf der Skala des Oberengadins verhalten sich die Lärchenwicklerpopulationen an verschiedenen Standorten synchron, es sei denn, die Wanderung an diese Standorte ist aus orographischen Gründen eingeschränkt. Dieses Ergebnis bestätigt auch die Hypothese, dass Migration eher die Ursache des synchronen Verhaltens auf der Talskala ist als der Moran Effekt.

Die Dynamik der Lärchenwicklerpopulationen und die Migrationsprozesse wurden innerhalb des gleichen Untersuchungsgebiets mit den gleichen Prozessmodellen modelliert, jedoch unter verschiedenen räumlichen Auflösungen: 1. ganzes Tal (Oberengadin), 2. 20 'Standorte', welche einer Durchschnittsgröße von 3.7 km² entsprechen und welche gleichartig bezüglich Höhe, Aspekt und Waldtyp sind, und 3. 424 Forstabteilungen, welche einer Durchschnittsgröße von 25 ha entsprechen. Die Ergebnisse zeigten, dass die räumliche Auflösung auf 'Standort'-Ebene die optimalsten Resultate liefert. Allerdings scheint die Verbreitung des Lärchenwicklers empfindlicher auf Windbedingungen zu sein als bisher angenommen, wenn diese bei einer höheren Auflösung durch die Orographie beeinflusst sind. Während daher die Populationen des Lärchenwickler nur auf der Skala von 'Standorten' einzeln betrachtet werden können, und das Modellieren der lokalen Dynamik bei dieser Auflösung erfolgen soll, würde die Modellierung der Wandervorgänge zwischen verschiedenen 'Standorten' präzisere Voraussagen erlauben, wenn die Orographie bei einer feineren Auflösung mit einbezogen würde. Der Vergleich unserer Zeitreihenanalyse mit Simulationsresultaten zeigte, dass Migration ein wichtiger Kausalmechanismus für die beobachteten Muster des synchronen Verhaltens des Lärchenwicklers auf der Skala einzelner Täler und des ganzen Alpenbogens ist.

1 INTRODUCTION

1.1 The larch bud moth in general

The larch bud moth (*Zeiraphera diniana* GN.; Lep., Tortricidae) has caused large-scale defoliation of larch trees across the entire Alpine Arc every 8-10 years since Roman times (Auer 1969, 1977, Fischlin 1982, Baltensweiler and Rubli 1999). The defoliation causes the larch trees to turn an unattractive brown colour during the summer months and was particularly considered a problem as a tourist deterrent post World War II (Baltensweiler and Fischlin 1987, 1988). Much research has been conducted into the larch bud moth and the causes of its regular cycles across the Alps, particularly in the heavily touristed area of the Engadine Valley in Switzerland (Baltensweiler and Fischlin 1987, Baltensweiler and Rubli 1990). The optimum habitat for the larch bud moth is mixed larch (*Larix deciduas* MILLER) – Swiss Stone pine (*Pinus cembra* L.) forests at altitudes of 1700 – 2000m a.s.l (Baltensweiler and Fischlin 1988). Although larch is usually considered the preferred host of larch bud moth, there exists both a larch race and a Swiss stone pine race. The latter prefers Swiss stone pine as its host, but both are known to feed on both kinds of host (Maksymov 1959, Fischlin 1982, Baltensweiler and Fischlin 1988, Emelianov et al. 2003).

The larch bud moth is a lepidopterous defoliator, the larvae emerge in spring, coinciding with the sprouting of the larch foliage (Baltensweiler 1993). There are 5 larval instars with the 5th being the longest and most destructive lasting 10-14 days (Baltensweiler and Fischlin 1988). The larch has the ability to produce a second set of foliage, but these needles are not able to mature properly and are susceptible to autumn frost. This can mean that nutrients are not well resorbed and the following year the needles will grow slowly and not reach the usual length (Baltensweiler and Fischlin 1988). If a larch tree is defoliated by more than 50%, needle regrowth the following year occurs in a similar manner as described above and it can take 2-7 years for the tree to regain its needle quality (Fischlin and Baltensweiler 1979, Fischlin 1982, Baltensweiler and Fischlin 1988). During the peak of the larch bud moth population cycle, high population densities and competition for food resources causes the larvae to leave

defoliated trees in search of better food and will often feed on less-favoured host trees such as Norway spruce (*Picea abies* K.), and Swiss stone pine in the understorey. The larch usually refoliates in 3-4 weeks and mortality of larch rarely exceeds 1%. However, if a young evergreen is more than 70% defoliated, it generally dies (Baltensweiler and Fischlin 1988).

1.2 Cyclic population dynamics

Many hypotheses have been developed to describe the dynamics of the larch bud moth, and there is no general agreement in the ecological community on which hypothesis might be considered closest to the truth (Auer 1969, Van den Bos and Rabbinge 1976, Fischlin and Baltensweiler 1979, Fischlin 1982, Baltensweiler and Fischlin 1988). The current emphasis of ecologists is on the food-quality hypothesis versus the antagonism hypothesis (Fischlin and Baltensweiler 1979, Fischlin 1982, Baltensweiler and Fischlin 1988, Bjornstad et al. 2002, Turchin et al. 2003).

The food quality hypothesis states that an increase in raw fibre content of larch needles occurs during a larch bud moth outbreak and has a strong negative effect on larval survival and female fecundity (Benz 1974, Baltensweiler 1993). In addition, bud moth feeding causes an increase in raw fibre content in the following season and the effect remains for several years (Fischlin and Baltensweiler 1979, Fischlin 1982, Baltensweiler and Fischlin 1988).

With the antagonism hypothesis the cycles of the larch bud moth are related to interactions with antagonists such as parasitoids, pathogens or predators. In the case of the larch bud moth a pathogen, in particular the granulosis virus, was considered to be very important in suppressing larch bud moth numbers during early studies (Martignoni 1957, Auer 1968, Baltensweiler et al. 1977, Anderson and May 1980). However, in later outbreaks large numbers of diseased larvae were no longer observed and, following continuing research, this idea was abandoned (Fischlin 1982, Baltensweiler and Fischlin 1988). The parasitoid hypothesis considers a complex of parasitoids that cause mortality of the larch bud moth, the most important of which being *Phytodietus griseanae* KERR. (*Ichneumonidae*), *Sympiesis punctifrons* THOMSON., *Didladocerus westwoodii* WEST. and *Elachertus argissa* WALKER (*Eulophidae*) (Baltensweiler 1955, Delucchi 1982). Delucchi (1982) suggests that parasitoid numbers are regulated

by the number of larch bud moth, rather than the other way around. However, recently the importance of the parasitoid hypothesis in describing the cycles of the larch bud moth has been reasserted by some researchers (Bjornstad et al. 2002, Turchin et al. 2003).

1.3 Spatio-temporal population dynamics

The temporal dynamics of the larch bud moth and its population cycles have been researched intensively, however the spatial patterns of larch bud moth population have received less attention. Some studies have noted the synchrony of population cycles amongst valleys (Fischlin 1982, 1983), or travelling waves (as a special case of synchrony) of larch bud moth across the Alpine Arc (Bjornstad et al. 2002, Johnson et al. 2004). However, accurate quantification of these patterns has not yet been shown and the reasons for such patterns are unclear. Fischlin (1983) cites dispersal as the cause for synchronised cycles among Alpine valleys. In this case, cycles within valleys across the Alpine arc are considered to be in close synchrony to each other, and can be explained by relatively small amounts of moth migration between valleys (Fischlin 1982, Baltensweiler and Fischlin 1988).

Migration is considered to be vital to guarantee establishment of the cycles if local extinction occurs, to stabilise the system and synchronise the fluctuations of the population over large areas (Fischlin 1982, Baltensweiler and Fischlin 1988). Recent research into synchrony suggests dispersal or regional environmental correlation (the Moran effect) could result in such patterns of synchrony (Hudson and Cattadori 1999, Kendall et al. 2000, Liebhold and Kamata 2000).

The Moran effect occurs where all sub populations have identical density dependant dynamics and are subjected to density independent (external) factors that are correlated across large distances such as synchrony in weather patterns (Moran 1953). Peltonen (2002) finds that at scales of over 100km such environmental correlations are a more likely cause of synchrony but at local scales dispersal is important. Distinguishing between dispersal and the Moran effect as causes of synchrony is difficult (Hudson and Cattadori 1999). Kendall et al. (2000) find that factors of dispersal and environmental correlation interact with each other and should be studied in combination.

Synchronous populations that have simultaneous widespread outbreaks can have devastating effects on forests and associated industries, especially when tree-mortality results. For example; the spruce budworm (*Choristoneura fumiferana* CLEM.; Lep., Tortricidae), which causes widespread damage to North American forests approximately every 30-35 years with outbreak periods of 5-10 years (Ludwig et al. 1978, Ludwig et al. 1979, Kettala 1983, Royama 1984, Williams and Liebhold 2000, Royama et al. 2005). In contrast, synchrony of populations can have negative implications for conservation, as global extinction of synchronised rare species can occur if local extinctions occur simultaneously (Williams and Liebhold 2000). Therefore, knowledge of the drivers of synchrony across varying scales is of importance for the management of systems for ecological and economic purposes.

Baltensweiler and Rubli (1999) have described a general dispersal pattern from west to east across the Alpine Arc, which could be considered to cause east-west travelling waves of population dynamics (Bjornstad et al. 2002). However, Baltensweiler and Rubli (1999) discuss the role of dispersal in driving the cycles of larch bud moth and have considered that long-range dispersal will only by chance affect a particular site as this dispersal is downwind. Dispersal on a local or regional scales contributes to the spatial population increases in the subalpine area and this dispersal is generally upwind in response to pheromones (Baltensweiler and Rubli 1999). At the valley scale local dispersal is dependant on wind conditions which, due to the mountainous, variable topography, may vary significantly over relatively small areas (Baltensweiler and Rubli 1999) and thus influence migration at fine spatial scales.

Travelling waves have been modelled by Bjornstad et al. (2002). Defoliation maps at the scale of the Alps from 1961-1998 give 135 time series of nominal data, which were analysed in this study. The study considered waves to be driven by larch bud moth-parasitoid interaction coupled with either directionally biased dispersal or variation in habitat productivity (Bjornstad et al. 2002). They found that the observed travelling waves matched well to the host-parasitoid model within a heterogeneous landscape with an east-west gradient in habitat quality, however they did not offer a functional candidate for this gradient in habitat quality. Johnson et al. (2004) also investigated travelling waves of the larch bud moth, concluding that waves across the Alpine arc travel from

epicentres which are determined by degree of habitat connectivity. This study was also based on the subjective defoliation map data.

1.4 Scale issues in Ecology and Ecological Modelling

‘Scale is characterised by grain and extent. Spatial grain is the finest possible spatial resolution within a given dataset. Extent refers to the size of the overall study area.’ (Turner et al. 2001). Ecological studies with high spatial and temporal resolution and extent are usually prohibitively expensive and time consuming, thus most studies are faced with a decrease in spatial grain as extent increases. However, it is in general unclear whether this can be justified or whether it occurs at the expense of relevant details. Although ecological modelling studies often face similar phenomenon, there is potential for models to overcome these limitations by modelling systems at spatial extents and grains that are not possible in field studies.

Spatial scale and in particular grain (as an aspect of scale) of input data are likely to influence results of ecological models significantly (Turner 1989, Wiens 1989, Levin 1992). There is likely an optimum spatial resolution to achieve most accurate model results depending on the ecological process being modelled (Levin 1992). However, it is unclear whether high resolution input data is required to make predictions and model processes at high spatial grains. For certain ecological processes it may no longer make sense to use input data at a higher spatial grain. This may only complicate computation without increasing the quality of the output or, at the worst, produce results that no longer make sense. However, using input data at low resolution only allows models to make broad predictions across large geographical areas. Small-scale processes may be disregarded, which may be of importance for understanding the bigger picture of the ecological process as a whole. Therefore, it is likely that for each ecological process being modelled there is an optimum spatial resolution for both input and output variables. This optimum spatial resolution would allow for highest accuracy in model predictions and takes advantage of any important small scale process but beyond which (at higher spatial grain) accuracy of results does not improve or perhaps declines (Mac Nally and Quinn 1998).

Scale is also relevant while studying synchrony and determining its causes. At local scales dispersal will often be more important for driving synchrony but at

global scales, with many species, dispersal effects can become negligible and environmental correlation is of more importance (Hudson and Cattadori 1999).

1.5 The research context

This research project forms part of the research project ‘Knowledge Based Dynamic Landscape Analysis and Simulation for Alpine Environments’, part of the Swiss National Research Project 48 (Landscapes and Habitats of the Alps) which aims to develop methodologies and tools for the integration of spatial (GIS and VISu) and temporal (Systems Modelling) modelling systems, resulting in an integrated system/tool: IPODLAS (Interactive, Process Orientated, Dynamic Landscape Analysis and Simulation). In order to develop such a tool, the project considers several ‘real-world’ ecological case studies that can provide data to be used to develop and test IPODLAS at various stages. The project takes a use case and case study approach. Due to the extensive history of research into larch bud moth dynamics, a great deal of data across varying spatial grains and extents is available for the larch bud moth, as well as accurate and accessible models describing population dynamics. Nevertheless, particularly in the context of spatio-temporal dynamics and the importance of scale, many interesting research questions remain open. Thus the larch bud moth provides an excellent case study to fulfil the requirements of the IPODLAS project as well as addressing relevant ecological research questions. The research from this Ph.D. work provides several use cases for the development of IPODLAS.

1.6 Objectives of this study

The temporal patterns of the larch bud moth dynamics and the resulting defoliation are well known, however, this Ph.D. research aims to investigate spatio-temporal dynamics. The goal was to determine quantitatively the spatio-temporal dynamics of larch bud moth at different scales and study whether larch bud moth populations exhibit synchrony at a variety of scales and whether this synchrony differs with scale. Given the importance of knowledge of the drivers of spatio-temporal patterns for population management, this research also considers the driving forces behind synchrony of larch bud moth populations, in particular migration versus the Moran effect. Using population dynamics models

we can study the larch bud moth system at a variety of spatial grains, and thus consider the influence of spatial grain and topography at higher spatial grains on larch bud moth migration processes. We investigate the ability of migration models to predict observed patterns of larch bud moth population dynamics at different spatial grains. Thus this work attempts to answer open ecological research questions with regards to the larch bud moth and provides an integration of spatial and temporal issues, which proved useful and important for IPODLAS.

The specific research questions addressed in this research are related to two general aims as follows:

- I. To determine the spatio-temporal dynamics of larch bud moth populations at differing scales
 - Is synchrony in population cycles quantifiable for larch bud moth and how does synchrony vary with scale?
 - At the Alpine arc scale, do larch bud moth travel in waves across the Alpine arc or spread from epicentres?
- II. To investigate the influence of data resolution on modelling larch bud moth dynamics and to determine an optimum resolution for modelling larch bud moth dynamics in the Upper Engadine valley allowing for a balance between model complexity, output accuracy, minimum uncertainty and simulation time
 - How does an increase in spatial resolution influence the migration patterns of the larch bud moth within the Upper Engadine?
 - Is Orography important in determining migration paths?
 - Does an increase in spatial grain of model input data increase the accuracy of modelled larch bud moth dynamics?
 - Can we better predict spatial pattern across a region by increasing the modelling spatial grain?

This thesis is a ‘paper thesis’ where the key research methods and results are presented within three papers submitted to scientific journals, each of these

papers forms a chapter (chapters 3-5) of the thesis. This Introduction chapter serves as an overall introduction to the general research questions addressed in the thesis and an introduction to how each chapter fits into the general context. Each paper contains its own introduction to the specific research question addressed and a discussion and conclusion based on the results specific to that chapter. Chapter 2 gives a more detailed description of the models used in this research than was possible or appropriate in the papers themselves. Chapter 3, ‘Synchrony and Travelling Waves of Larch Bud Moth? Time Series Analysis with Changing Scale’, addresses the research questions under point I above, relating to the determination of spatio-temporal dynamics of larch bud moth populations at differing scales. Chapters 4 and 5 relate to the questions under above point II. Chapter 4, ‘The Influence of Orography on Larch Bud Moth Migration at the Valley Scale’ addresses the first two questions under this point, relating to the influence of orography at a high spatial resolution on migration patterns. Chapter 5, ‘Spatio-temporal Modelling of Larch Bud Moth Dynamics in the European Alps: the Importance of Data Resolution’ considers the remaining two questions regarding the gains or losses in predictive ability associated with modelling larch bud moth at a higher spatial grain. Finally Chapters 6 and 7 provide an overall discussion and conclusion of the results placed within a general context with the intention of linking the findings of the separate chapters to the overall theme.

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2 MATERIAL AND METHODS: MODELS

There exists a variety of mathematical and associated simulation models to describe the population dynamics of the larch bud moth through time (Hassell 1978, Fischlin and Baltensweiler 1979, Fischlin 1982, Turchin et al. 2003). Some add spatial dynamics to a certain extent by including the influence of dispersal within and between valleys and at least three are spatially explicit models at the scale of the Alpine arc (Fischlin 1982, Bjornstad et al. 2002, Johnson et al. 2004). This research concentrates on models developed by Fischlin (1982) at the extent of the Upper Engadine valley that are considered relevant today, based on the food quality hypothesis.

Spatially explicit population models allow insect ecologists to incorporate habitat complexities, such as the distribution of species resources over space, into their population dynamics models (Brewster and Allen 1997). However, Brewster and Allen (1997) have found that use of such models has been limited within insect ecological research.

2.1 Simulation Environment

The larch bud moth models used in this study are described below and are implemented within the RAMSES (Research Aids for Modelling and Simulation of Environmental Systems¹) working environment. RAMSES is an interactive modelling and simulation software implemented in the Modula-2 programming language (Fischlin 1991). The RAMSES shell offers four sessions. The modelling session allows to declare models and model objects and to formulate model equations (Fischlin 1991). Within the experimental definition session the simulationist may specify an experimental frame and its association with a particular mathematical model (Fischlin 1991). The goal is to specify particular time domains, parameter and initial values associated with a given mathematical structure (Fischlin 1991). The simulation session supports the simulation and allows the simulationist to observe model behaviour in space, time or both. In

¹ Available as freeware from <http://www.sysecol.ethz.ch/SimSoftware/RAMSES/>

the post-analysis session the simulationist may analyse results from any interactive or batch simulation session interactively, without having to resolve the models again. RAMSES is considered to be well suited to the modelling and simulation of dynamic ecological systems, which are often ill-defined (Fischlin 1991). In an analysis conducted by Giorgetta (2002) RAMSES was evaluated alongside 41 other system simulation software packages against criteria relating to ease of use, robustness, power to simulate a variety of model types, possibility to develop and extend the system, availability of support and cost. The purpose of this analysis was to determine the most appropriate system simulation software for use in the development of the spatio-temporal modelling and analysis system IPODLAS. Giorgetta (2002) found that RAMSES ranked the highest, and is thus the most appropriate for such purposes.

The spatial data required as input to the spatially explicit larch bud both models are retrieved from a digital elevation model via the GRASS (Geographical Resources Analysis Support System) open source GIS software. In addition, GRASS is also used for calculation relating to orography dependant migration. GRASS was developed by the U.S. Army Corps of Engineers Construction Engineering Research Laboratory and is the largest open source Geographical Information System (Neteler and Mitasova 2002).

2.2 Existing models

This research uses larch bud moth population dynamics model based on the food quality hypothesis as developed by Fischlin (1979, Fischlin 1982). These models are readily available to the Terrestrial Systems Ecology research group including all source code so that they can be easily altered and extended. In addition, they have been found to model the larch bud moth system in the European Alps well with close fits to observed data (Fischlin and Baltensweiler 1979, Fischlin 1982, 1983). The original implementation of Fischlin's local dynamics larch-larch bud moth model was known as LBM-M1. Over the years LBM-M2 to M7 were developed with the new versions relating to implementations under new software systems and extensions to the model including the parallel display of observed data. LBM-M8 is the current RAMSES implementation of the local dynamics model under the food quality hypothesis. Here a local dynamics model describes the temporal cyclic

dynamics of a sub-population of larch bud moth for a given area. This area may be any size, but where larch bud moth dynamics are modelled as an average over the given area. LBM-M8 and LBM-M9 are described in further detail below. The model LBM-M10 describes local dynamics for a series of valleys along the Alpine Arc and migration between these valleys and is not used within this research.

2.2.1 LBM-M8

Fischlin (1982) developed a model of the local dynamics of the larch bud moth in the Upper Engadine valley based on the food quality hypothesis, named LBM-M8. The model considers the relationship between the larch bud moth and its main host, the larch. Each system component is both controlling and controlled by the other system component. Grazing by the larch bud moth causes an increase in raw fibre content of the larch needles, which results in a decrease in larch bud moth fecundity and thus causes a decrease in the larch bud moth population. The model deals with local dynamics only and treats an entire valley as a homogeneous area with no spatial structure (Fischlin and Baltensweiler 1979).

The local dynamics model is a deterministic mathematical model representing a second order SQM² system of coupled difference equations (Fischlin and Baltensweiler 1979, Fischlin 1982). It was also available as a RAMSES model definition program (MDP³) serving as a simulation model, which describes the dynamics of the larch bud moth at the scale of a forest stand to the scale of an entire valley such as the Upper Engadine. LBM-M8 is an autonomous system with no input variables. Variables of the model are given in Table 2.1. The model is described in full detail in Fischlin (1982) and (Fischlin and Baltensweiler 1979, 1982) and a generalised version of the mathematical model is reproduced for the reader's convenience in Appendix I.

² Sequential Machine – see also (Fischlin 1991, Fischlin et al. 1994)

³ Model Definition Program (cf. Fischlin 1991)

Table 2.1

Model variables for LBM-M8

Designator	Unit	Type	Meaning
r	%	state variable	raw fibre content (% fresh weight)
e	numbers	state variable	larch bud moth (individuals)
def	%	output variable	defoliation
springEggs	numbers	output variable	larch bud moth eggs in spring (individuals)
sl	numbers	output variable	larch bud moth small larvae (individuals)
ll	numbers	output variable	larch bud moth large larvae (individuals)
f	numbers	output variable	larch bud moth females (individuals)
y	/kg tree branches	output variable	larval density per kilogram tree branches
gmsl	%	auxillary variable	mortality of small larvae
gmsta	%	auxillary variable	starvation mortality of large larvae
gmllp	%	auxillary variable	mortality of large larvae and pupae
gfec		auxillary variable	fecundity of larch bud moth females
fol	Kg	auxillary variable	foliage

All variables are dependant on discrete time t , which due to the fact that the larch bud moth is a univoltine insect is measured in years. There are no input variables as the system is autonomous (Fischlin 1982).

2.2.2 LBM-M9

The model LBM-M9 (Fischlin 1982) couples the local dynamics model (LBM-M8) with a submodel for migration within a valley, in the case of the Upper Engadine valley between 20 'sites', which are considered to be homogeneous with respect to elevation, aspect and forest type.

The migration model is also a deterministic mathematical model and is conceived as a recursive process (Fischlin 1982), i.e. the behaviour of all female moths on a site is defined by a recursive formula relative to specific site conditions (Baltensweiler et al. 1977, Fischlin 1982, Baltensweiler and Fischlin 1988). The recursion process is limited by the number of females capable of flight. It is assumed that only mated females become airborne, and thus no interference between moths is considered. Therefore this recursive formula may be repeated for the females of all sites in sequence. With this approach the model for the local dynamics and the migration model are coupled and form a new system at a superior level (Baltensweiler and Fischlin 1979). With the coupled model:

- Immigration and emigration will determine the numbers of larvae in a given area
- Wind speed and direction determine where and how far moths migrate
- Distance between areas of larch forest determine to which areas LBM migrate

The model is further described in Chapter 5, and in its original form in Fischlin (1982) and Baltensweiler and Fischlin (1979). Variables of the migration submodel are given in Table 2.2 (variables for the local dynamics submodel are as given for LBM-M8, Table 2.1). A range of spatially explicit constant input data is also required as input to the LBM-M9 model and is listed in Table 2.3. A generalised version of the mathematical model is reproduced for the reader's convenience in Appendix II.

Table 2.2

Model variables for the migration submodel of LBM-M9

Designator	Unit	Type	Meaning
$f(k)$	number	state variable	females flying
$d(k)$	km	variable	distance to fly
L	number	variable	eggs laid
f_j	number	variable	females in target site
$D(k)$	km	parameter	distance already flown
fec_0		parameter	fecundity at the site of origin
$I=i(k)$	identifier	parameter	current site

where k represents the recursion level

Table 2.3

Spatially explicit data required as input to model LBM-M9 and LBM-M11 with sources

Constant	Source (LBM-M9)	Source (LBM-M11)
Frequency of turbulence in site i	MeteoSwiss, 1901-1990 (Fischlin 1982)	MeteoSwiss, 1901-1990
Frequency of still winds (0-0.5m/s) in site i	MeteoSwiss, 1901-1990	NUATMOS (Ross et al. 1988)
Frequency of calm winds (0.5-2.8m/s) in site i	MeteoSwiss, 1901-1990	NUATMOS
Frequency of strong winds in site i	MeteoSwiss, 1901-1990	NUATMOS
Frequency of calm winds in site i in direction j	MeteoSwiss, 1901-1990	NUATMOS
Frequency of strong winds in site i in direction j	MeteoSwiss, 1901-1990	NUATMOS
Area of neighbouring site n in direction j in sub-sector A resp. B	MeteoSwiss, 1901-1990	n/a
Area of neighbouring site n in sector j	n/a	Calculated in GRASS (Neteler and Mitasova 2002)
Air distance from site i to neighbouring site n in sub-direction A resp. B	MeteoSwiss, 1901-1990	n/a
Air distance from site i to neighbouring site n in direction j	n/a	Calculated in GRASS

where: for LBM-M9 i = 1-20, n = 1 – 20, j = NE,E,SE,S,SW,W,NW, N
for LBM-M11 i = 1-420, n = 1-420, j = as above

2.3 Models developed in this research

2.3.1 LBM-M11

The LBM-M11 model was developed within this research project.

Descriptive model

The LBM-M11 model describes local larch bud moth dynamics and migration within the Upper Engadine valley in a similar manner to the LBM-M9 but at a higher spatial resolution. The spatial grain of this model is the ‘Forst Abteilung’ (forest compartment) instead of the ‘site’ used in LBM-M9. The Upper Engadine valley was previously divided into 420 forest compartments based on forest management plans and these compartments have an average area of approximately 25 hectares. During larval census exact location of sampled trees has always been recorded on maps. This information was entered into the larch bud moth database: LBM Database (Fischlin in prep.), by tabulating the forest compartment to which each sample tree belongs for the years 1956 to 1977. Thus, modelling larch bud moth dynamics at this spatial resolution is convenient for comparison with observed data. In LBM-M11 local dynamics are modelled for each of the 420 forest compartments and migration is modelled between these compartments according to the same rules as defined for LBM-M9. The model structure and mathematical formulation is almost exactly the same as that of LBM-M9, the only exception being that flight is modelled in 8 compass directions instead of 16 directions. The LBM-M9 model originally modelled flight in 16 directions because the spatial arrangement of the ‘sites’ and large distances between them meant that a site often had more than 1 neighbour in a 45° compass sector. At a higher spatial resolution the smaller distances between forest compartments reduce this problem to a minimum and use of 16 compass directions would unnecessarily increase the number of required input parameters. The model variables and equations are therefore the same as LBM-M9, with the exception that for parameters c_{12} and c_{15} there is no subdivision into subsectors A and B.

The type of spatial data required as input to the model at this resolution is also the same as LBM-M9 (Table 2.3) and in this case has been retrieved by

digitising the forest compartment boundaries and calculation of the required values in the GRASS GIS system.

Wind data was retrieved from the NUATMOS wind model (Ross et al. 1988). NUATMOS is a “physically consistent three dimensional diagnostic model designed to minimize the difference between the initial interpolated wind field and the final wind field subject to a mass-consistent constraint”(Ross et al. 1988). NUATMOS produces a three dimensional mass-consistent windfield and based on a digital elevation model (DEM) and wind observations in the form of horizontal wind components (Ross et al. 1988). Wind direction and speed on the surface is calculated from the wind field produced (Bachmann 1998). In this study NUATMOS version 5N (07/31/91) (Ross et al. 1988) has been applied to a DEM with a spatial resolution of 50 m (DHM50 ©, Tydac AG).

The wind observation data used as input to NUATMOS was retrieved from the Swiss Federal Office of Meteorology and Climatology, MeteoSwiss. The six meteorological observation stations chosen to provide initial conditions were within and around the Upper Engadine valley (Bever, Bivio, Corvatsch, Robbia/Poschiavo, Sils Maria, and St.Moritz). Since topographical effects largely drive wind patterns within the Upper Engadine valley, average summer wind speed and direction values are considered constant through time by the LBM-M9 and LBM-M11 models (Fischlin 1982). Therefore, a period for which all of the relevant meteorological observation stations provide data, 1980 to 1982, was chosen from which to take data to drive NUATMOS.

As larch bud moth flight occurs only during a seasonal window of mid July to September in the early evening when temperatures are above 7°C (Baltensweiler and Rubli 1999), only wind measurements fitting these criteria were retrieved.

200 wind observation input files were generated from this data. Wind direction fields and wind speed fields were then interpolated in NUATMOS for 200 points in time. These wind fields were then applied to generate the wind statistics required for the larch bud moth models for the centre of each forest compartment.

Simulation model

The simulation model for LBM-M11 related to the mathematical model described above was implemented in Modula-2 as a MDP in the RAMSES environment (Fischlin 1991) on Macintosh® computers⁴ using MacMETH (Wirth et al. 1992). The MDP is a set of implementation and definition modules controlled by a master module. In Modula-2 programmes (or MDPs) are usually built from a library in which modules can be kept and each library module provides a set functions (Wirth 1983). A definition module represents the publicly available information of any library module and contains the declaration of all exported identifiers and all the related information that is required by modules that import them (Wirth 1983). Details concerning procedural operation and realisation are contained in the implementation module (Wirth 1983). The structure of the LBM-M11 simulation model is shown in Figure 2.1.

⁴ G4 RISC processor family

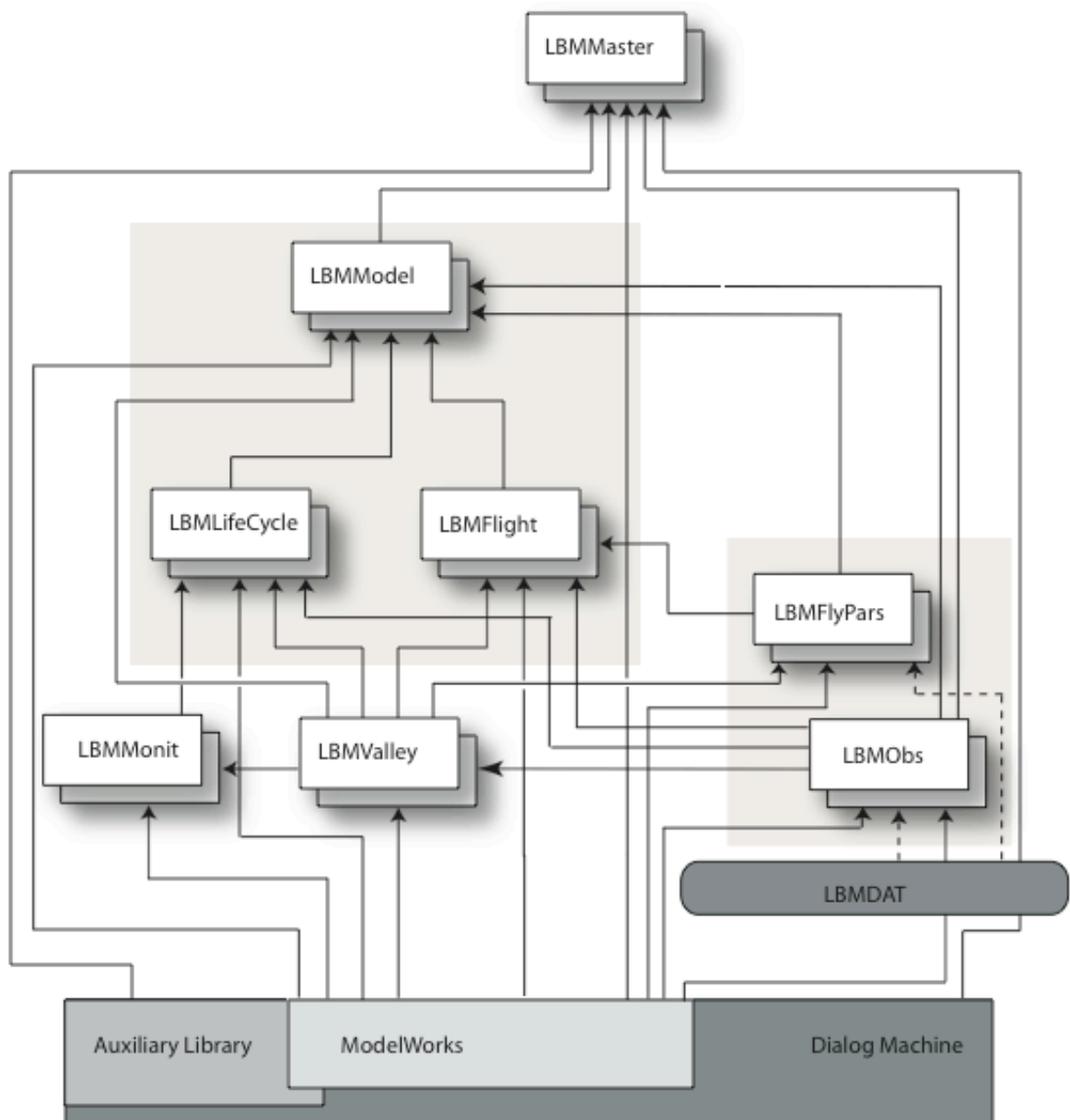


Figure 2.1: Structure of the simulation model LBM-M11 as implemented in the RAMSES (Research Aids for Modelling and Simulation of Environmental Systems) working environment. Arrows start from the exporting module and point towards the importing module. The libraries *Auxiliary Library*, *ModelWorks*, and *Dialog Machine* consist of many library modules and are shown only in summarized form. The oval denotes a data base system consisting of a collection of data files together with a dedicated data management library.

Here, the *Dialog Machine*, *ModelWorks* and the *Auxiliary Library* are all internal components of the RAMSES system. The *Dialog Machine* is a library of Modula-2 routines that allows for the easy programming of user-interfaces (Fischlin et al. 1987, Fischlin and Schaufelberger 1987, Fischlin and Thommen 2003, Keller 2003). *ModelWorks* is the simulation environment where processes are modelled through solving of dynamics systems while the *Auxiliary Library* is a library of auxiliary routines required by only some programmes (Fischlin et al. 1994). LBMDAT represents a larch bud moth database where files containing data required for the model such as observed larval densities and spatially explicit data for each forest compartment is stored.

The module LBMObs controls the retrieval of observed larval densities for initialisation of the system and comparison during simulation. LBMFlyPars retrieves spatially explicit time-independent data from the database and converts its format for use in the LBMFlight model – where the migration processes between the forest compartments are modelled. The module LBMValley controls the state of the valley, in particular the variables such as defoliation and eggs that are exchanged between the two dynamic process modules, LBMFlight and LBMLifeCycle. In LBMLifeCycle the local dynamics are calculated for each forest compartment. LBMMonit monitors the simulation results and manages the handling of files to which the simulation results are written. LBMModel controls the activation and deactivation of the dynamic process modules. Finally LBMMaster brings all program pieces together and provides the RAMSES MDP (Fischlin 1991). The full Modula-2 code for the simulation model can be found in Appendix 3.

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3 SYNCHRONY AND TRAVELLING WAVES OF LARCH BUD MOTH? TIME SERIES ANALYSIS WITH CHANGING SCALE

Bronwyn Price, Britta Allgöwer and Andreas Fischlin

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Abstract

Spatio-temporal patterns of cyclic larch bud moth population densities, for instance synchrony (valley scale) and travelling waves (Alpine arc scale), have been observed at different scales and may be related to distinct causes. In this study, quantification of population data through cross-correlation analysis and spectral analysis revealed that larch bud moth population cycles at the valley scale could be considered to be in close synchrony with one another. At the Alpine arc scale the presence of travelling waves could generally be confirmed. These results have implications for the understanding of the causal mechanisms behind the observed spatio-temporal patterns, suggesting that at the valley scale synchrony depends not only on distances between subpopulations, but is also affected by environmental/habitat characteristics that vary in space. At the Alpine scale, distance between populations is of greater importance in shaping spatio-temporal patterns than at the valley scale.

Keywords: larch bud moth, synchrony, travelling waves, time series, and spectral analysis

3.1 Introduction

The larch bud moth, *Zeiraphera diniana* GN. (*Lep.*, *Tortricidae*), is a conspicuous forest defoliator that exhibits distinctly regular population cycles peaking approximately every 9 years. These cyclic population dynamics are considered to result from a relationship between the larch bud moth and its host, the European Larch (*Larix decidua* MILLER) (food quality hypothesis) (Baltensweiler et al. 1977, Baltensweiler and Fischlin 1979, 1988), or an interaction with its parasitoids (parasitoid-prey hypothesis) (Baltensweiler et al. 1977, Baltensweiler and Fischlin 1979, 1988), or a tri-trophic relationship combining the food quality hypothesis and the parasitoid-prey hypothesis (e.g. Turchin et al. 2003).

Previous studies (e.g. Fischlin 1982, 1983, Bjørnstad et al. 2002, Peltonen et al. 2002) have described distinct spatio-temporal dynamics of larch bud moth, and these dynamics appear to change with scale. Synchrony of population cycles (nonlinear phase-locking) in spatially separated locations within valleys – in particular the Upper Engadine valley, has been observed qualitatively (Auer 1977, Baltensweiler and Fischlin 1979, Fischlin 1982, Baltensweiler and Fischlin 1988). Synchrony of larch bud moth populations along the Alpine arc has been investigated first by Fischlin (1983) and recently by Peltonen (2002). The possible existence of travelling waves of larch bud moth along the Alpine arc, has also been hypothesised by several authors (Ranta and Kaitala 1997, Baltensweiler and Rubli 1999, Feltham and Chaplain 2000, Bjørnstad et al. 2002, Johnson et al. 2004).

Perfect synchrony would result in standing waves, whereas lagged peaks from one location to another define travelling waves. Spatial synchrony can be considered to result from spatial correlations in the environment (the Moran effect) – where all sub populations have identical density dependant dynamics and are subjected to density independent factors that are correlated across large distances such as synchrony in weather patterns (Moran 1953), and/or dispersal (Fischlin 1983, Kendall et al. 2000, Liebhold and Kamata 2000). Additionally,

mobile natural enemies can cause regional synchronisation (Ydenberg 1987, Ims and Steen 1990).

Recognising spatial scale explicitly is important when studying synchrony of populations and the causal mechanisms of such synchrony. At local scales dispersal may be the dominant factor, whereas at regional to global scales the role of dispersal diminishes and environmental correlations may play a stronger role (Hudson and Cattadori 1999, Peltonen et al. 2002). Notably, Peltonen et al. (2002) have concluded that the Moran effect is the dominant factor explaining regional scale synchrony for six forest defoliators including the larch bud moth. However, their conclusion contrasts with that of an earlier study of larch bud moth, where dispersal, not the Moran effect dominated the observed synchrony in data and behaviour of models (Fischlin 1983).

At the valley scale, Fischlin (1982, 1983) found synchrony with few time lags, but without quantifying its parameters. At the Alpine arc scale, Fischlin (1983) found stable synchrony among valleys using a model resembling a metapopulation model, which consisted of several independent subpopulations linked through dispersal. Bjørnstad et al. (2002) have demonstrated waves travelling from west to east along the Alpine arc. Whereas, Johnson et al. (2004) argue that larch bud moth dynamics fit the epicentre hypothesis, spreading out from two different epicentres in the centre of the Alps and the south-west of the Alps respectively. Each of these findings have been based on defoliation data, recorded by a variety of foresters in four qualitative categories (no defoliation (0% of crown defoliated), light defoliation (1-33%), medium defoliation (34-66%) and heavy defoliation (>66%), Baltensweiler and Rubli 1999). This categorical data may be subjective and is more likely to be inconsistent than larval census data, although it does offer the advantage of covering a critically larger area, which would be prohibitively expensive for larval census data. Peltonen et al. (2002) have investigated larch bud moth synchrony along the Alpine arc with a focus on distinguishing the Moran effect from that of dispersal. However, they have also used defoliation data and have not taken into account temporal lags, therefore not considering the possibility of a travelling wave.

Using quantitative data (larvae per kg larch branches) from five valleys along the Alpine arc, one would expect significant spatial autocorrelation or lagged cycle peaks e.g. from west to east, if the hypothesized synchrony or travelling waves were to be present. However, the presence of such patterns is not obvious and requires careful analysis using the various kinds of larch bud moth data available (Figure 3.1).

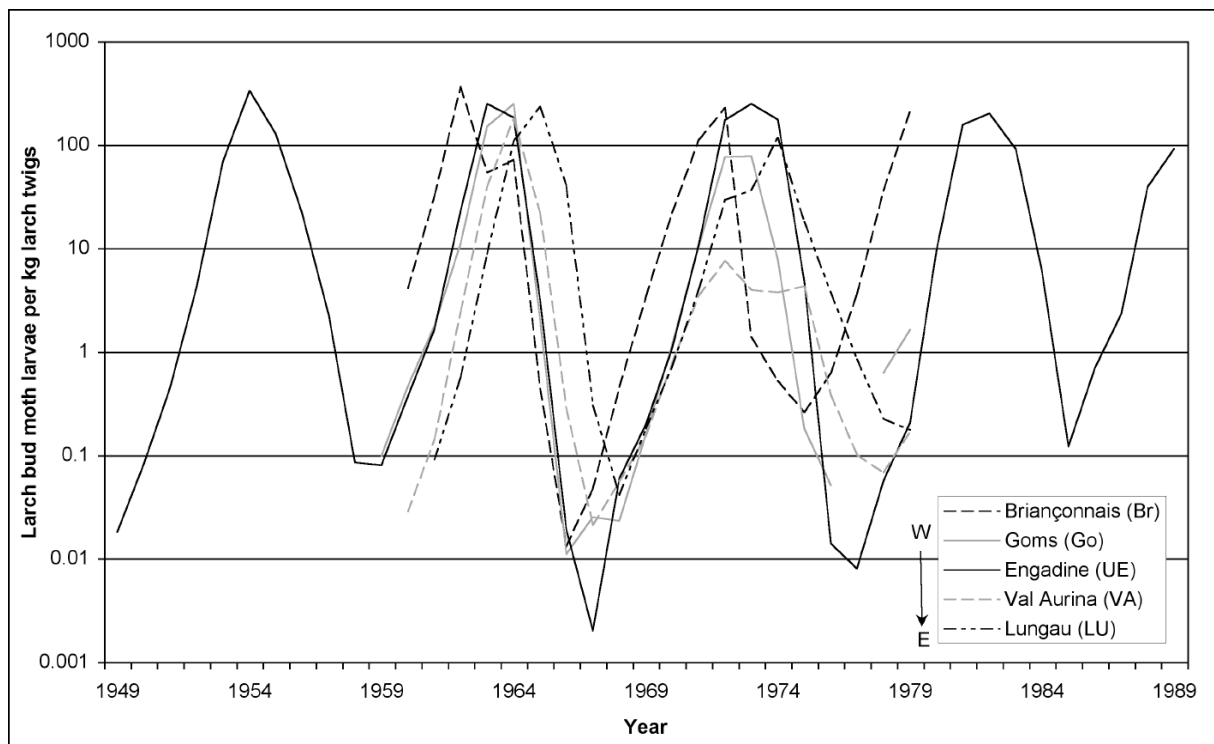


Figure 3.1: Larval densities in 5 valleys along the Alpine Arc from 1949-1989. 1949-1978, all sites, (Auer 1975, 1977). 1979, all sites: (Auer et al. 1981). 1980, Lu (Baltensweiler and Rubli 1999). 1980 Br, VA (Hoffmann and Auer 1989, Baltensweiler and Rubli 1999). 1980-81, UE (Baltensweiler and Rubli 1999). 1982-89, UE (Fischlin, unpublished).

While identification of spatio-temporal patterns, be it synchrony or travelling waves, is indeed only the first step in understanding spatio-temporal dynamics of a population system, it is a vital one. It enables one to speculate on causal mechanisms behind population dynamics, since we believe recognizing patterns is a prerequisite for understanding their causes. This research focuses on the analysis of time series of larch bud moth population census data (larvae per kg larch branches) in spatially disjunct locations in order to determine

quantitatively the spatio-temporal patterns of larch bud moth population dynamics at different spatial scales. In particular, this work aims to determine whether synchrony and/or travelling waves are present in larch bud moth dynamics with a view to distinguishing between migration and the Moran effect as causal mechanisms.

A common method to determine synchrony is the use of zero-lag pair-wise cross correlation (Bjørnstad et al. 1999). Employing (time-) lagged, pair-wise cross correlation between time series of abundance data from spatially disjunct locations permits to investigate synchrony among populations allowing for a temporal lag and a lag distance (i.e., travelling waves). In addition cross-spectral analysis allows us to demonstrate whether series in separate locations fluctuate similarly and whether series are phase shifted from one another.

With this approach we demonstrate that distinct spatio-temporal patterns are present in the larval census data of larch bud moth and that they may be explained by the dispersal capabilities of larch bud moth without being able to rule out some contribution from the Moran effect entirely. In this sense, because of the wealth of larval census data available, the population system of the larch bud moth can serve as a case study to tackle more general questions of theoretical value relating to the relative roles of the Moran effect and dispersal in causing spatial synchrony as found in many systems (e.g. Peltonen et al. 2002).

3.2 Material and Methods

3.2.1 STUDY AREA AND CENSUS DATA

The Upper Engadine valley is a sub-alpine valley located in the Swiss part of the European Alps (Figure 3.2) forested with larch (*Larix decidua* MILLER) - Swiss stone pine (*Pinus cembra* L.) forests. During development of a model for migration of larch bud moth within the Upper Engadine, the valley was divided into 20 ‘sites’, which are considered homogeneous with respect to forest type, aspect and altitude within each site (Figure 2, Fischlin 1982). The sites have an

average area of 3.7km² and are between 2 and 30 km apart (from site centre to site centre) (Fischlin 1982). Larval sampling is timed to take place when larch bud moth is predominately in the larval stages L3, L4 and L5, dependent on weather conditions (Fischlin 1993). Within the Upper Engadine valley, during the first phase of the larval survey (1949-1958) between 1000 and 2100 trees were sampled annually and the number of larvae per tree was determined (Auer 1961). From 1956-1979 the sampling method changed and approximately 400 larch trees were sampled annually according to a statistically sound random sampling scheme (Kälin and Auer 1954). Sample stratification was according to topographical features (altitude, exposure) and samples were weighted according to host-tree density per unit area (Baltensweiler and Fischlin 1988). During these annual population surveys approximately 3 kilograms of twigs and foliage (excluding cones) were taken from each tree; 1 kg from each of three levels within the crown. In 1956 and 1957 both sampling methods were employed to allow compatibility of the results. The larval censuses provide an average density estimate for the larval population (e.g. Auer 1969, 1978) and were converted to an annual absolute population estimate for each site and for the entire Engadine Valley (Fischlin 1982). Thus 20 time series for spatially disjunct populations (up to 30 km apart) are obtained (Figure 3, Fischlin 1982). The census method within the Upper Engadine changed after 1977, meaning that detailed data were no longer available for each of the sites within the Upper Engadine valley. Instead, three trees were randomly chosen within each of three specific sample sites. The sampled sites were chosen to be representative of the entire valley and were spread evenly along the length of the valley (Fischlin 1993). This allowed estimation of a mean population density for the entire valley.

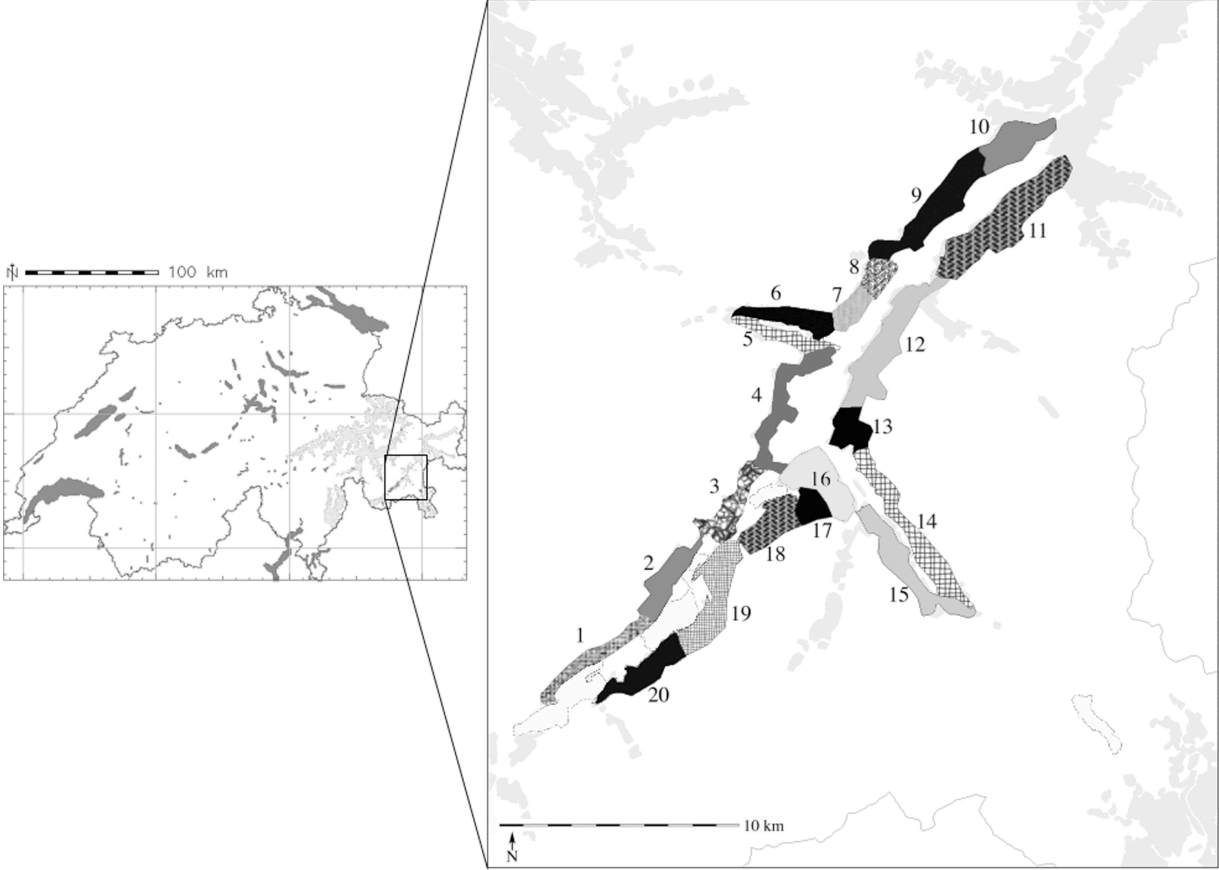


Figure 3.2: Location of the 20 sites within the Upper Engadine valley, Swiss Alps. Sites were delineated by Fischlin (1982) to be homogeneous with respect to forest type, exposure, altitude and aspect within site.

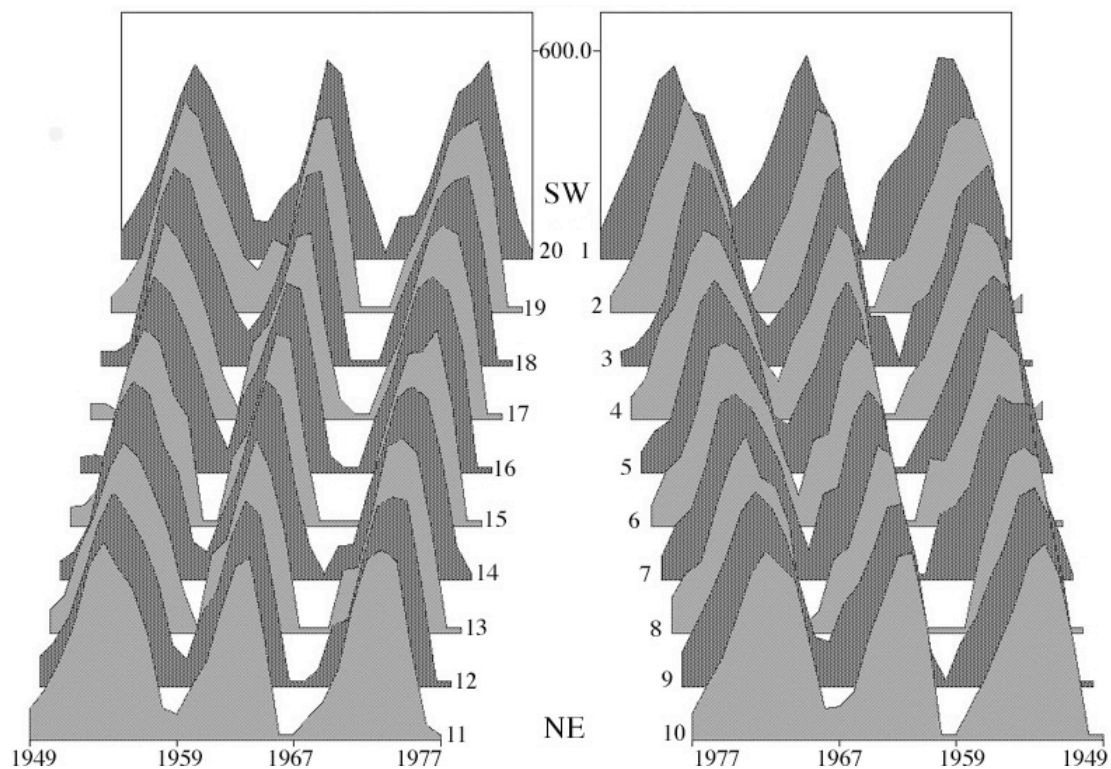


Figure 3.3: Observed larval densities in the 20 sites of the Upper Engadine valley for the period 1949-1977 (Fischlin 1982). The right-hand side of the graph represents site 1-10 along the east side of the valley with mostly south-eastern exposure. The left-hand side of the graph sites 11-20 with mostly north and north-western exposure. The observer therefore looks down the valley to the south-west. Cycles at this valley scale are in very close synchrony for the period 1949-1977.

Aside from the Upper Engadine valley, population surveys were also carried out in four other valleys along the Alpine Arc (Figure 3.4) in a very similar manner to that described above for population surveys between 1956 and 1979. Time series of annual numbers of larch bud moth larvae per kg of larch branches averaged across the valley are available for each of the following valleys (Figure 3.4): Briançonnais (Vallée de la Guisane and Val Névache, France, 1960-1979), Goms (Western Switzerland, 1959-1979), Upper Engadine (Eastern Switzerland, 1949-2004), Val Aurina (Italy, 1960-1979), and Lungau (Austria, 1961-1979).

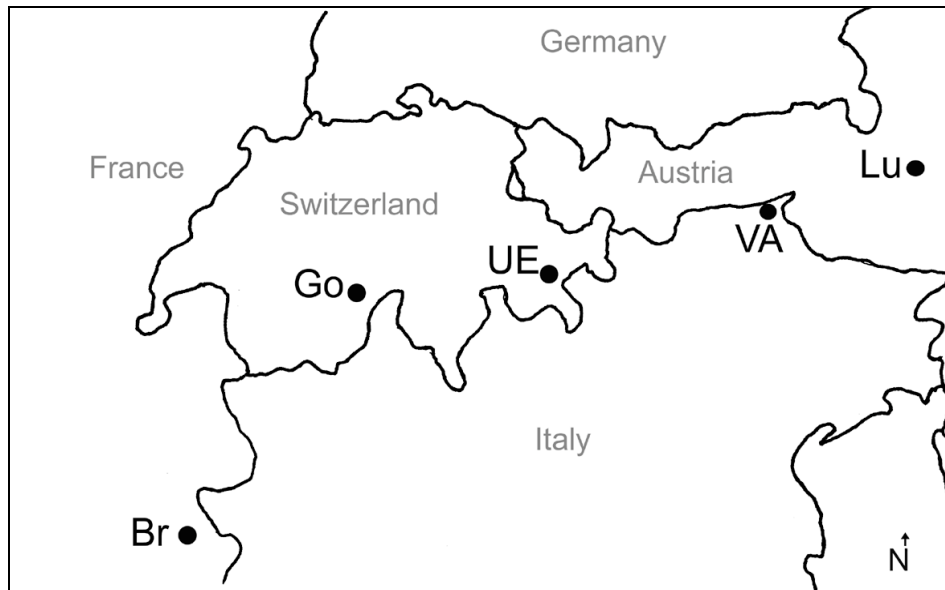


Figure 3.4: Locations of five studied valleys along the Alpine Arc. Br = Briançonnais (Vallée de la Guisane, Val Névache), France, Go = Goms, Switzerland, UE = Upper Engadine, Switzerland, VA = Val Aurina, Italy, Lu = Lungau, Austria.

3.2.2 TIME SERIES ANALYSIS

Spectral analysis examines a time series in the frequency domain, exploring cyclical patterns by reducing them to underlying sine and cosine functions with particular wavelengths (Wolfram 1996, Grover et al. 2000). Cross-spectral analysis would then allow us to determine the correlations between series at different frequencies.

Each of the 25 log-transformed time series (20 at the within valley scale and 5 at the Alpine Arc scale) were subjected to non-parametric spectral analysis. Log transformed data were used to render measurement errors additive, and to reduce skew and the correlation between the mean and the variance (Koenig 1999, Grover et al. 2000). During spectral analysis, relying on Fourier decomposition, cyclical components were mapped to sine and cosine functions. The periodograms calculated summarise in graph form estimated spectral density in function of frequency (Wolfram 1996, Grover et al. 2000). Spectral analysis assumes a stationary process (constant mean, variance and autocorrelation structure in time) (Priestley 1981, Grover et al. 2000). Thus all

time series were also de-trended prior to performing spectral analysis. A raw periodogram is not a consistent estimator of the spectrum, as it may fluctuate strongly and often has a large variance; therefore, we reduced fluctuations with weighted average smoothing using a Daniel window (moving average) with a width of 3 years (Wolfram 1996).

Using pair-wise cross-correlation, each of the 20 within valley time series were compared to one another, as were the 5 series along the Alpine arc. Cross correlation coefficients were calculated at temporal lags from 0 to 5 years for each pair of time series.

We estimated co-variation between the time series as a function of frequency using cross-spectral analysis (Platt and Denman 1975, Priestley 1981). The squared coherence and associated phase were derived from the cross-spectrum. Squared coherency - the squared correlation of cyclical components of two series for a given period (Platt and Denman 1975, Puckridge et al. 2000), served as a measure of explained variance. Squared coherence and phase spectra provided further information about the maximum cross-covariance function and the corresponding lag for each frequency (cyclic period) (Platt and Denman 1975).

The coherence and phase spectra showed us which time series were correlated with one another at which phase lag. According to Platt (1975), the behaviour of the phase function is an indicator for the accuracy of the coherence spectrum. Therefore, if the phase spectrum was a smooth function of frequency, we considered the squared coherence to be significantly different from zero, but when the phase spectrum oscillates rapidly with frequency, we assumed the squared coherence to be inaccurate (Platt and Denman 1975).

3.3 Results

3.3.1 VALLEY SCALE

As the area under a spectrum is proportional to the total variance in the time series, the highest peaks in a spectrum correspond to cyclic periods (or frequencies) that are of greatest importance in accounting for variation in the series (Haydon et al. 2002). The spectral analysis of our 20 series results in spectra with a maximum peak at frequency $\sim 0.11 \text{ a}^{-1}$, corresponding to a 9 year cycle for all time series (Figure 3.5).

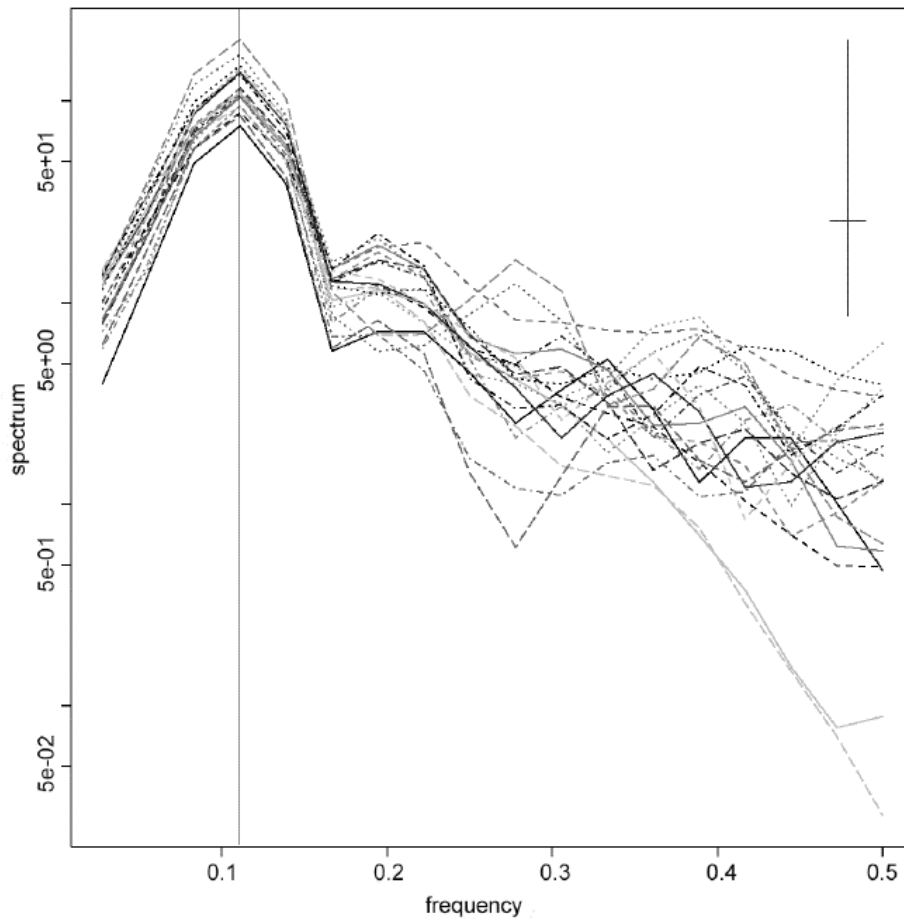


Figure 3.5: Spectrum for each of the 20 sites within the Upper Engadine valley. Maximum spectral peak is at $\sim 0.11 \text{ a}^{-1}$ (indicated by the vertical line) for each site and corresponds to a 9 year cycle. The line at the top right demonstrates the 95% confidence interval with the centre mark indicating the bandwidth of the Daniel smoothing window.

The cross-correlation analysis revealed highest significance for correlations between series at lag zero, where cross-correlation coefficients significant at the $\alpha = 0.05$ significance level ranged between 0.806 (sites 3 and 5) and 0.996 (sites 16 and 17). The exception was for site 3, which exhibited maximum correlation at a lag of -1 year (leading) with three other sites, 1, 6 and 7 (cross-correlation coefficients of 0.854, 0.852 and 0.786 respectively).

The results of the cross-spectral analysis of the 20 time series within the Upper Engadine valley showed that all spectra are in high coherency with one another, with coherency values in the range of 0.768 - 0.995, all significant at the $\alpha = 0.05$ significance level. The phase spectra were smooth functions at lower frequencies, below 0.2, allowing us to consider the coherency spectra accurate at our frequency of interest $\sim 0.11 \text{ a}^{-1}$, but inaccurate at higher frequencies where the phase spectra oscillate considerably. The corresponding phase lags were often not significantly different from zero, with some exceptions. Site 3 was found to be out of phase with all other sites at negative (leading) phase lags corresponding to values between 2 and 6 months. Such lags would correspond to an average lag over the entire time series, meaning that in some years the series peak in the same year and in some years with a 1 year lag. Sites 15, 16, 17, 19 and 20 are out of phase with almost all other sites (although in phase with one another) at lags corresponding to values between 2 and 4 months (trailing).

The cross-correlation method used calculates correlation coefficients only for whole integer values of lag, i.e. integer years, which partly explains the discrepancies between the results of the two analyses.

3.3.2 ALPINE ARC SCALE

The results of the cross correlation analysis are presented in Table 3.1. We observed a general pattern of increase in temporal lag for maximum correlation with distance along a west-east axis.

Table 3.1

Cross-correlation results Alpine arc

	Br	Go	UE	VA	Lu
Brianconnais (Br)	0	0.8	0.46	0.63	0.77
Goms (Go)	1	0	0.64	0.87	0.84
Upper Engadine (UE)	1	0	0	0.61	0.56
Val Aurina (VA)	2	1	1	0	0.9
Lungau (Lu)	2	1	1	1	0

Above the diagonal are maximum cross-correlation coefficients, all significant at the $\alpha=0.05$ level, for each of the 5 valleys along the Alpine arc and below the diagonal the corresponding temporal lag (years).

The spectral analysis yielded a maximum spectral peak at $\sim 0.11 \text{ a}^{-1}$ corresponding to a 9 year cycle for all series along the Alpine arc (Figure 3.6).

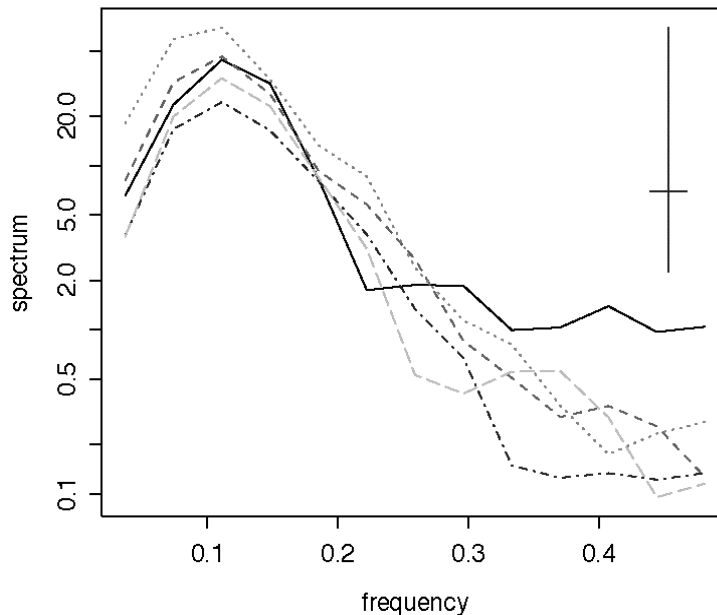


Figure 3.6: Spectrum for each of the 5 valleys within the Upper Engadine valley. Maximum spectral peak at $\sim 0.11 \text{ a}^{-1}$ for each valley corresponds to a 9 year cycle. The line at the top right demonstrates the 95% confidence interval with the centre mark indicating the bandwidth of the Daniel smoothing window.

Cross-spectral analysis revealed high coherency between all pairs of series for a 9 year cyclic peak (Figure 3.7). Examination of the phase spectra (Figure 3.8) showed that these high levels of coherency occur for phase lags increasing with distances in a west-east direction across the Alpine arc as summarised in Table 3.2. Again at lower frequencies the phase spectra were quite smooth, indicating accuracy of the coherency spectra at the $\sim 0.11 \text{ a}^{-1}$ frequency.

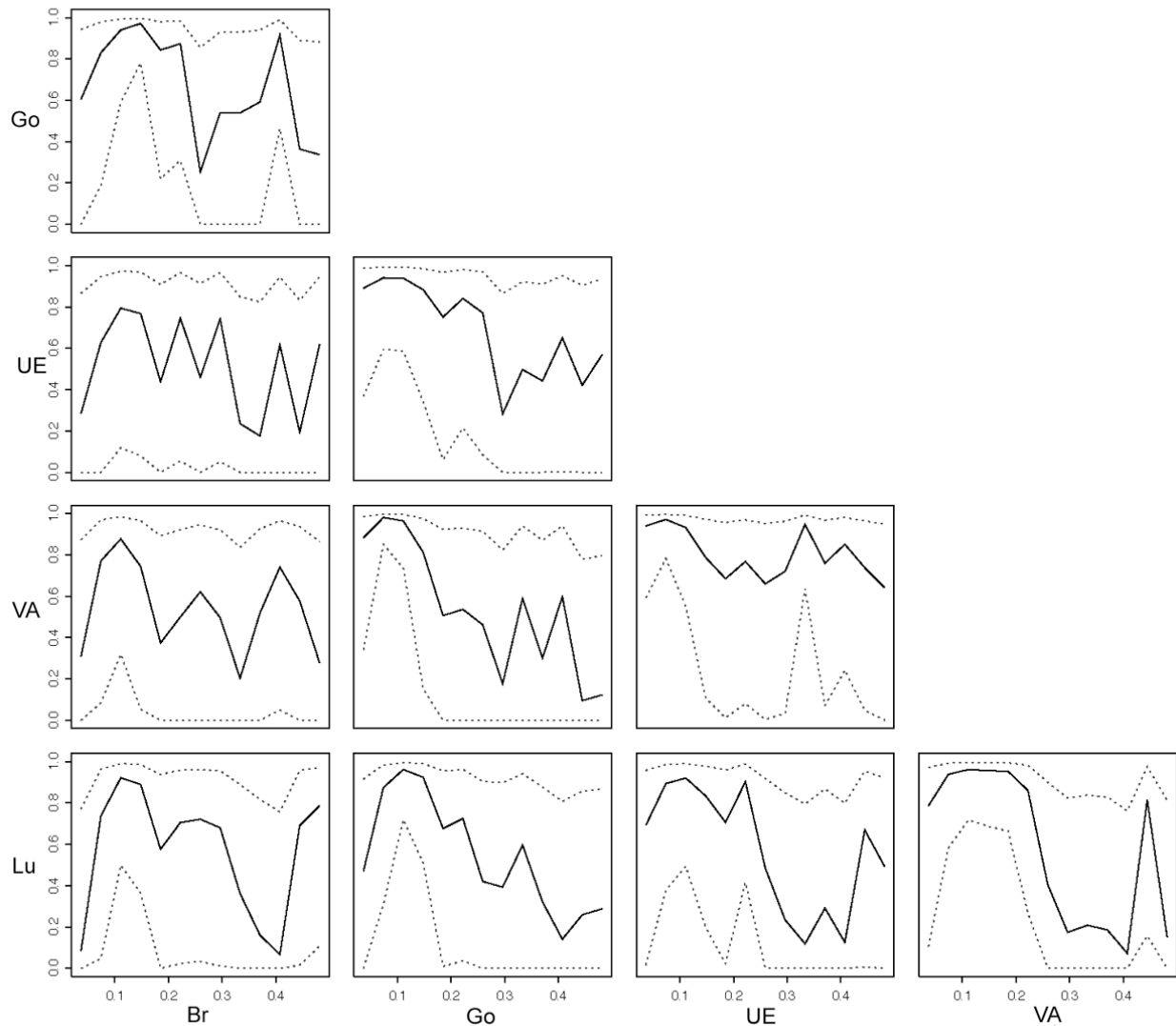


Figure 3.7: The coherency spectrums resulting from cross-spectral analysis between each of the 5 valleys along the Alpine arc. High coherency is present between all pairs of times series for spectral frequency representing a 9-year cycle ($\sim 0.11 \text{ a}^{-1}$). Dotted lines are 95% confidence intervals. For abbreviations see Figure 3.4.

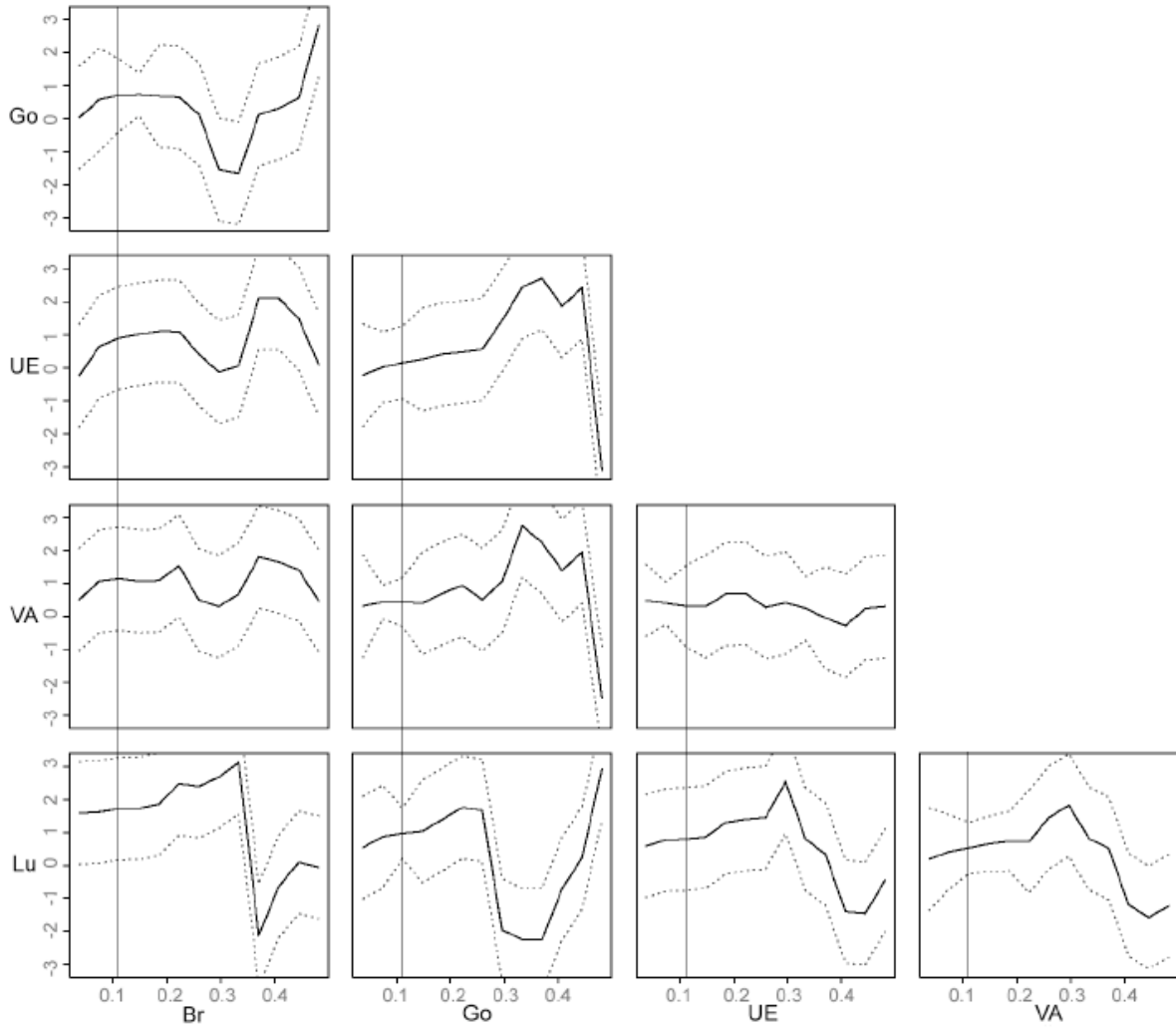


Figure 3.8: Phase spectrum resulting from the cross-spectral analysis between the 5 valleys along the Alpine arc. Dotted lines are 95% confidence intervals. The phase spectrum must be viewed in conjunction with the coherency spectrum. Note the phase lag values (years, y-axis) where coherency is highest and significant, here $\sim 0.11 \text{ a}^{-1}$, representing a 9-year cycle. High coherency between the spectra occur at a lag of 9 mo. for Briançonnais (Br) and Goms (Go), 1 a (year) for Br and the Upper Engadine (UE), 1 a for Br and Val Aurina (VA), 20 mo. for Br and Lungau (Lu), 3 mo. for Go and the UE, 5 mo. for Go and VA, 1 a for Go and Lu, 4 mo. for the UE and VA, 10 mo. for the UE and Lu, and 8 mo. for VA and Lu.

Table 3.2

Phase lags (months) relating to cross-spectral analysis results

Alpine arc

	Br	Go	UE	VA	Lu
Brianconnais (Br)	0				
Goms (Go)	9	0			
Upper Engadine (UE)	12	3	0		
Val Aurina (VA)	12	5	4	0	
Lungau (Lu)	20	12	10	8	0

All values corresponding to significant values ($\alpha = 0.05$) of coherence resulting from cross-spectral analysis of time series for each of the 5 valleys along the Alpine arc.

3.4 Discussion

Spatio-temporal dynamics of larch bud moth at the valley scale and the Alpine arc scale were quantified using cross-correlation and spectral analysis. The results reveal that at the valley scale (Upper Engadine), subpopulations have very similar cyclic fluctuations, even at large distances from one another (up to 30 km), and exhibit remarkably close synchrony. However, there are exceptions to this general pattern, in particular the time series for site 3 is out of phase with some other sites for negative temporal lags (leading) of 1 year (cross-correlation analysis), or negative temporal lags (leading) of 2-6 months (cross-spectral analysis). Sites 15, 16, 17, 19 & 20 are also out of phase with most other sites, by lags (trailing) of 2-4 months. Assuming that sites separated by as little as 5 km, are affected in a similar manner by similar conditions (i.e. weather conditions as typical candidates for the Moran effect), the observed temporal lags in synchrony are unlikely to result from the Moran effect. Previous studies (Auer 1961, Baltensweiler 1984, Baltensweiler and Rubli 1999) have reported observed lags in cyclic peaks and attributed this to different physical characteristics of areas. In particular, areas experiencing a lag were northern exposed with a higher proportion of Swiss stone pine (and lower proportion of larch), and thus less attractive to migrating larch bud moth (Vaclena and

Baltensweiler 1978, Baltensweiler and Rubli 1999). Populations in northern exposed areas also grow slower due to less insulation (Fischlin 1982). Indeed sites 15, 16, 17, 19 & 20 are northern exposed (Fischlin 1982) and this may explain the observed lag in synchrony as partly caused by biased dispersal. The key assumption of Moran's hypothesis is that all sub-populations are governed by the same density-dependant dynamics. Consequently, if populations on northern exposed sites experience different dynamics due to climatic or habitat variables, then Moran's hypothesis no longer holds (Moran 1953, Peltonen et al. 2002). However, not all time series from northern exposed sites showed a lag. Moreover, sites 2 and 4 are south-easterly exposed and also in other respects quite comparable to their neighbouring site 3 and yet lagged behind this site. Thus reasons for the negative lag are currently unclear, but may be due to unmeasured wind-aided dispersal patterns.

Due to relatively small distances between the sites and the high flight ability of the larch bud moth, the idea presented by Johnson et al. (2004) that habitat connectivity, as a function of inter-quadrat distance and moth dispersal ability, can also determine dispersal routes is of less significance at the valley scale. While long range migration of the larch bud moth is downwind and occurs once moths arriving at mountain ridges and passes are taken up by gradient winds, local and regional flight of larch bud moth is upwind and occurs in response to pheromones (Baltensweiler and Fischlin 1979). Therefore, habitat connectivity as a function of a moth's ability to traverse a landscape as determined by wind conditions and aspects of the terrain, is important. A recent modelling study (Price et al. in prep.) combining a wind driven dispersal model with a GIS model shows that physical components of the landscape, in particular slope, aspect and altitude, at the valley scale may determine migration paths and this may also affect spatial synchrony of populations.

At the Alpine arc scale, populations in valleys along the Alpine arc exhibit very similar cyclic properties (Table 3.1, Figures 3.6 and 3.7). It would be expected that if travelling waves were present, population cycles would be correlated to each other at increasing time lags with increasing distance. The results of this study (Tables 3.1 and 3.2, Figures 3.7 and 3.8) suggest that this is indeed the case, confirming a travelling wave of larch bud moth dynamics similar to that

described by Bjørnstad et al. (2002) based on defoliation data. Therefore, at the Alpine scale level, distance between populations appears to strongly influence the level of synchrony.

Baltensweiler and Rubli (1999) have hypothesised that west-to-east travelling waves could be driven by migration with the predominant westerly winds blowing in general along the Alpine arc. However, Bjørnstad et al (2002) found that models based on the food quality hypothesis with directional dispersal resulted in waves travelling in the opposite direction. Under the parasitoid hypothesis with directional dispersal, they found that modelled directional waves resulted for only narrow ranges of moth and parasitoid mobilities, but when dispersal depended on an east-to-west gradient of habitat quality, directional waves could be modelled for a wide range of model parameters (Bjørnstad et al. 2002).

Although synchronisation of mobile natural enemies can theoretically cause region-wide synchrony, larch bud moth parasitoids have relatively low mobility (Delucchi 1982) and are likely not able to cause such widespread travelling waves. In addition, Bjørnstad et al. (2002) found that the larch bud moth–parasitoid model with isotropic dispersal could not easily produce travelling waves. Since our results document high degrees of coherency at increasing phase lags with increasing distances between populations in a west-east direction, either the predominant westerly winds or an east-west gradient of habitat quality, e.g. in food quality, fit the evidence well. Both mechanisms require migration to explain the lagged spatial synchrony and contrast with any hypothesized Moran effect.

Moreover, spatial synchrony is expected to drop with distance, either due to exceeding the dispersal capacity of the involved organisms or due to uncorrelated characteristics of the environment. It is well known that variograms of temperature and particularly precipitation show significant declines in autocorrelation with distance, in particular in complex terrain such as the European Alps (e.g. Gyalistras and Fischlin 1999). Such effects also result in a decline in spatial covariance, e.g. in the Alps, temperature is usually no longer correlated at distances beyond 50 km (e.g. Gyalistras et al. 1997). Although Peltonen et al. (2002) report significant correlation in temperatures at lag

distances up to 400km in the European Alps, more detailed analysis of highly reliable records e.g. from Swiss weather stations (Gyalistras 2003) contradict these findings. The observed travelling waves also contradicts the assumption of a large range Moran effect covering all of the Alps, e.g. due to June common mean temperatures (Peltonen et al. 2002), as this conflicts with the lags we found increasing with distance in west-east direction, However, directional migration could easily explain those patterns.

The larch bud moth is known as a strong flyer, which can cover flight distances of over 200 km, meaning synchronisation of sites across large regions through dispersal is plausible (Fischlin 1982). Moreover, Peltonen et al. (2002) found spatial synchrony to decline more rapidly with distance when the environmental heterogeneity is spatially structured than would be expected from the decrease in correlation with distance of some weather variables alone. It follows that even at the regional scale, a mere decline in spatial covariance with distance is not conclusive for distinguishing between the Moran effect and dispersal as causes of synchrony, particularly not in the case of the larch bud moth.

Johnson et al. (2004) propose that larch bud moth dynamics at the scale of the Alpine arc could follow the epicentre hypothesis. They suggest two epicentres: a primary one in the south-western Alps, and a secondary in central north-eastern Alps. According to this hypothesis, larch bud moth is considered to spread from these epicentres via dispersal depending on the habitat density and connectivity. Our results are not conclusive with respect to the hypothesis proposed by Johnson et al. (2004), since there are only 5 time series available. Nevertheless, the results of our analyses would favour a west-to-east travelling wave which could be considered to start from the proposed primary epicentre, rather than the two epicentre hypothesis proposed.

The two epicentres described by Johnson et al. (2004) correspond closest to the valleys Briançonnais and the Upper Engadine. Under the epicentre hypothesis, should waves always spread from these valleys, one would not expect a correlation, lagged or otherwise, between populations at these valleys (unless we would assume a strong, superimposed Moran effect correlating only the epicentres, which however, would make it difficult to explain why areas in

between should not also be affected by the very same Moran effect). In fact, we found a strong, 1year lagged correlation between the valleys Briançonnais and Upper Engadine. Dispersal mechanisms can easily explain that finding, whereas a Moran effect faces considerable difficulties.

In addition, as long-range dispersal of larch bud moth occurs when moths are taken up by gradient wind (Baltensweiler and Fischlin 1979) moths usually lose touch with the canopy during such dispersal. This makes it difficult for them to distinguish 'high quality' from 'low quality' habitats. Nevertheless, both Johnson et al. (2004) and Bjørnstad (2002) using models, which assume dispersal within some kind of habitat quality gradient have been able to reproduce travelling waves. Therefore, dispersal, driven by wind dynamics in conjunction with habitat gradients, could be considered to be an important driver of the spatial dynamics of larch bud moth.

3.5 Conclusions and Outlook

Using time series analysis techniques of cross-correlation analysis and spectral analysis of larval census data, this study has been able to demonstrate and quantify the patterns of synchrony at the valley scale and travelling waves at the Alpine arc scale in population cycles of larch bud moth as have been hypothesized previously only from defoliation data. Although these spatio-temporal patterns are present they are not consistent, particularly not across all sites in the Upper Engadine valley. The results of this study suggest that differences in characteristics between sites could help determine the spatio-temporal dynamics of the larch bud moth at the valley scale. Our results indicate that at the Alpine Arc scale spatial synchrony is more likely attributable to synchronising dispersal effects than the Moran effect. However, particularly at the scale of the Alpine arc, further research is needed to identify the relevant environmental characteristics in order to more conclusively distinguish between the Moran effect and migration hypotheses. In addition, previous studies have suggested that dispersal can be driven by wind and/or gradients in habitat quality, therefore it would also be of primary interest to look further into those drivers of larch bud moth migration.

3.6 Acknowledgments

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4 THE INFLUENCE OF OROGRAPHY ON LARCH BUD MOTH MIGRATION AT THE VALLEY SCALE

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as submitted to *Oikos*

Abstract

Spatio-temporal patterns of insect population densities, for instance, spatial synchrony in population cycles, have been observed at different scales for several species and appear to be related to distinct phenomena of spatial and/or biological nature. In this study we investigated the hypothesis that migration processes determine the observable spatio-temporal synchrony in population dynamics of larch bud moth at the valley scale. We explored the effect of orography at a finer resolution on modelled potential dispersal ranges of larch bud moth by incorporating a high resolution GIS based migration model with a coarse resolution population dynamics simulation model. Modelled migration paths were affected considerably by inclusion of orography compared to predecessor models that ignored orographical effects. Our results demonstrate that geographical features such as orography are of importance for determining larch bud moth migration paths and resultant spatio-temporal population dynamics.

KEYWORDS: larch bud moth, migration, modelling, GIS, spatial dynamics, synchrony

4.1 Introduction

The larch bud moth, *Zeiraphera diniana* GN. (*Lep.*, *Tortricidae*), is a univoltine, conspicuous forest defoliator exhibiting cyclic population dynamics across the entire Alpine Arc with population peaks every 8-10 years (Auer 1969, 1977, Fischlin 1982, Baltensweiler and Fischlin 1988, Baltensweiler and Rubli 1999). During peaks of population cycles, crowding causes larvae to interrupt each other's feeding, which usually leads to partially eaten needles drying out and resulting in highly visible, large scale defoliation (Baltensweiler and Fischlin 1988).

Spatio-temporal dynamics of larch bud moth appear to change with scale of observation (spatial extent and resolution). Some studies have noted the synchrony of population cycles within valleys – in particular the Upper Engadine valley (Fischlin 1982, 1983), or travelling waves of larch bud moth across the Alpine Arc (Bjornstad et al. 2002).

Spatial synchrony occurs when populations in spatially separate locations fluctuate in a similar manner (Liebhold and Kamata 2000). Spatial synchrony is considered to be a result of either dispersal or spatial correlation in the environment (the Moran effect) – such as synchrony in weather patterns (Kendall et al. 2000, Liebhold and Kamata 2000). With a few exceptions (e.g. Clark 1979, Fischlin 1983) spatial synchrony has only come to be quantified in recent years, and identification of processes causing such synchrony is considered to be a great challenge to population ecologists (Liebhold and Kamata 2000).

Fischlin (1983) has found that dispersal may well explain the synchronised cycles of larch bud moth among Alpine valleys. Recent research into synchrony further suggests that dispersal or regional environmental correlation could result in patterns of synchrony as has been observed for larch bud moth (Hudson and Cattadori 1999, Kendall et al. 2000, Liebhold and Kamata 2000). Peltonen et al. (2002) have shown that dispersal may well be a causal mechanism of synchrony at local scales for several species, including larch bud moth.

If dispersal is a driver for synchrony among population cycles, the physical distance between sub-populations and migration ability of the species is of importance (Peltonen et al. 2002). The further apart the sub populations relative to the typical migration distance, the less likely that dispersal can cause synchrony. Therefore, knowledge of how far a species can migrate in given conditions is vital to understanding whether dispersal can be a driver for population synchrony.

While we know a great deal about migration behaviour of larch bud moth (Vaclena 1977, Vaclena and Baltensweiler 1978, Baltensweiler and Rubli 1999) and can successfully model that behaviour at coarse spatial scales (Fischlin 1982, in prep.), we know little about how larch bud moth migration is affected by landscape features at fine spatial resolution. Moreover, constructing population models at a high spatial resolution is challenging, since it requires site-specific values for a large number of model parameters.

Models of larch bud moth dynamics have already been developed for a variety of spatial scales, ranging from local scales to that of the entire Alpine Arc (Fischlin 1982, 1983, Bjornstad et al. 2002, Turchin et al. 2003, Johnson et al. 2004). While the focus of many existing larch bud moth models is on fluctuations over time (Kälin and Auer 1954, Auer 1971, Van den Bos and Rabbinge 1976, Fischlin and Baltensweiler 1979, Fischlin 1982, Turchin et al. 2003), some models incorporate spatially varying properties such as wind conditions, distances between sub-populations, habitat connectivity and forested area in order to examine spatio-temporal dynamics (Fischlin 1982, Bjornstad et al. 2002, Johnson et al. 2004). However, such models have only been able to take advantage of spatial data at a very coarse spatial resolution or subjective categorical defoliation data (Bjornstad et al. 2002, Johnson et al. 2004), and often assume that spatial data is constant over time (e.g. Fischlin 1982).

This research is based on Fischlin's (1982) spatially explicit model of migration throughout the Upper Engadine valley. This model is derived from species specific characteristics and thus lends itself well to consideration of spatial features such as orography at a high resolution. The model was initially formulated with a coarse spatial resolution of input data. Using this model, a GIS based larch bud moth migration model was developed at a higher spatial resolution. The research aims to determine how an increase in spatial granularity

would influence the migration patterns of the larch bud moth within the Upper Engadine valley and whether features of the landscape are important in determining migration paths. We show that migration is likely a relevant driver of synchrony and that incorporation of topographical features at an increased spatial granularity in the migration model influences synchrony within the same spatial extent.

4.2 Material and Methods

4.2.1 STUDY AREA AND DATA

The Upper Engadine valley is a sub alpine valley located in the Swiss part of the European Alps (Figure 4.1) forested with mixed larch (*Larix decidua* MILLER) - Swiss stone pine (*Pinus cembra* L.) forests. During development of a migration model for larch bud moth within the Upper Engadine, the valley was divided into 20 areas known as ‘sites’, which are considered homogeneous with respect to ecological and orographical characteristics such as aspect and altitude (Figure 4.1 Fischlin 1982).

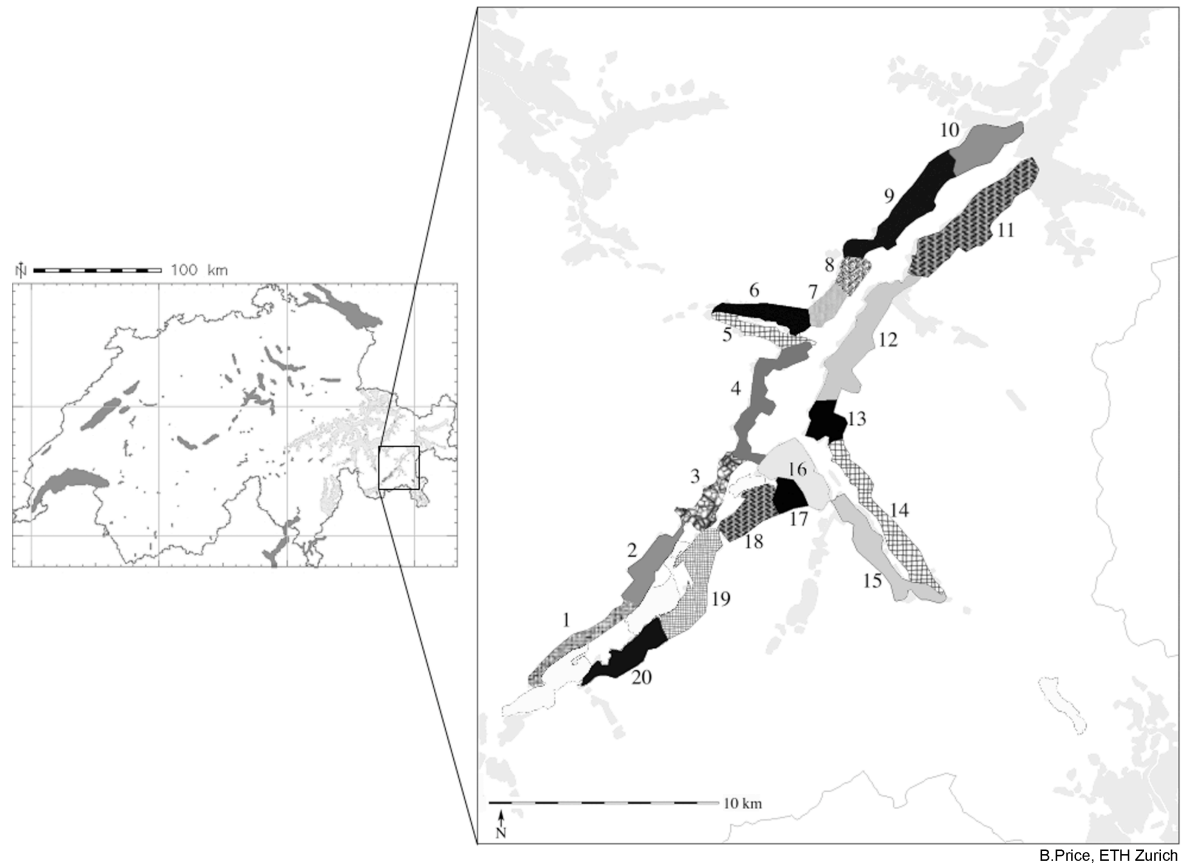


Figure 4.1: Location of the 20 sites within the Upper Engadine valley, Switzerland. Sites were delineated by Fischlin (1982) to be homogeneous with respect to exposure, altitude, aspect, and forest structure as well as to remain within a given upper size limit. Light grey coloured polygons depict forested areas.

From 1949-1979 detailed larval population surveys including recording of parasitism, tree species composition and other area specific data were conducted (e.g. Auer 1975) and have since been stored in a database. Larval densities, climate and other site-specific data for each of the 20 sites have been made available for 1949-1979 by going back to the original raw data with careful re-analysis techniques and using ecological dividing criteria (Fischlin 1982).

Elevation information covering the area of the Upper Engadine valley was taken from a Digital Elevation Model (DEM) with a spatial resolution of 50 m (DHM50 ©, Tydac AG). Slope and aspect information was then derived from this DEM using standard GIS techniques within the GRASS software environment.

4.2.2 LBM-M8 AND LBM-M9 MODELS

Fischlin (1982) developed a model of the local dynamics of the larch bud moth in the Upper Engadine valley based on the food quality hypothesis (LBM-M8 see also Fischlin and Baltensweiler 1979). The model considers the relationship between the larch bud moth and its host, the larch. Grazing by the larch bud moth causes an increase in raw fibre content of the larch needles, which has negative implications for larch bud moth fecundity and thus causes a decrease in the larch bud moth population. The model deals with local dynamics only, and treats an entire area such as a valley as a homogeneous area with no spatial structure (Fischlin and Baltensweiler 1979). The local dynamics model is a deterministic mathematical model, i.e. a second order, discrete time system of coupled, non-linear equations. The two state variables represent first the food quality, using the raw fibre content per needle fresh weight as an indicator, and second the population density given as the number of larch bud moth eggs per study area.

A spatially explicit Upper Engadine valley model also developed by Fischlin (1982), known as LBM-M9, incorporates the local dynamics model (as in LBM-M8) as a sub model and couples it with another sub-model for migration between the 20 sites within the Upper Engadine valley. The migration part of this model is also a deterministic mathematical model, and the behaviour of all female moths within a site is defined by a recursive formula relative to specific site conditions as determined by wind statistics and other site specific characteristics such as defoliation, forested area, or number of larch trees (Baltensweiler and Fischlin 1979, Fischlin 1982, in prep.). State variables are the number of flying females and the distance flown. Oviposition takes place as sites are visited. By the end of the flight season accumulated egg masses determine site-specific population sizes of the next generation (Baltensweiler and Fischlin 1979, Fischlin 1982).

Immigration and emigration determine the numbers of larvae in a given area, while wind speed and direction determine where and how far moths migrate. The spatial arrangement and distances between areas of forest (nearest neighbour) determine to which areas larch bud moth migrate. Once at a site, moths are assumed to continue dispersal from the centre of gravity (determined in planar projection) of the current site (Fischlin 1982).

Wind speed and direction for each site was derived from evening measurements taken at weather stations run by the Swiss Federal Office of Meteorology and Climatology between July and September (Bantle 1989). There are three wind speed categories: still ($<0.5\text{m/s}$), gentle ($0.5\text{-}2.8\text{m/s}$) and strong ($>2.8\text{m/s}$) in each of 8 compass directions. The wind parameters for LBM-M9 are then defined as a proportion of the total wind behaviour for each wind speed category as an average over time, and are considered constant over time (see also Baltensweiler and Fischlin 1979, Fischlin 1982).

Fischlin (1982) derived categories of larch bud moth flight behaviour: upwind flyers for moths that fly against gentle down slope winds (see above), calm flyers that fly in still wind conditions, downwind flyers that fly with strong winds. The proportion of moths in each behaviour category is equal to the average proportion of wind speeds in the corresponding wind speed category, see Table 4.1. Based on these data the LBM-M9 model calculates maximum flight distances from each 'site' in each of 16 compass directions for each type of moth flight behaviour. Further description of these models can be found in Fischlin (in prep.)

Table 4.1

Proportion (%) of moths in each behaviour category for each site within the Upper Engadine valley.

Site No.	Upwind flyers	Downwind flyers	Calm flyers
1	40	20	40
2	40	20	40
3	20	20	60
4	30	5	65
5	25	15	60
6	25	15	60
7	30	20	50
8	35	20	45
9	40	20	40
10	25	10	65
11	25	5	70
12	30	20	50
13	30	20	50
14	20	20	60
15	20	20	60
16	30	5	65
17	25	20	55
18	30	25	45
19	25	20	55
20	35	15	50

This amount is based on average wind conditions in each site and is assumed to be constant over time (Fischlin 1982)

LBM-M9 models migration based on average wind conditions at the centre of a site and does not take into account any topographical features nor any within site variations, such as within site varying wind conditions.

In this study we also used a variant of the LBM-M9 model, where migration was suppressed by forcing all females from a site to oviposit all eggs within their home site (LBM-M9a).

4.2.3 LBM-GIS

In this study we consider the influence of orography on larch bud moth flight and enhance the model LBM-M9 by developing a simplified migration model within the GRASS open source GIS environment (Neteler and Mitasova 2002) and designate the new model ‘LBM-GIS’. It simulates larch bud moth dispersal from individual sites with assumptions derived from Fischlin’s LBM-M9 (1982) according to the rules described below.

The mountainous topography of the Upper Engadine valley gives rise to a diurnal wind system, where cold air drains down slope during the evening and night, and during the day warm air flows upslope (Urfer-Henneberger 1964, Fischlin 1982, Baltensweiler and Rubli 1999). Upwind flyers fly against this down slope air drainage (in response to pheromones from the larch) and thus we can assume that upwind flyers fly uphill, or across flat areas but not downhill (we define here ‘flat’ areas as those with slopes between 0° and 5°). Downwind flyers fly with strong winds down slope and thus we can assume that downwind flyers fly downhill, or across flat areas (defined in the same way as above) but not uphill. These assumptions allow us to determine some simple rules for the influence of orography on larch bud moth flight.

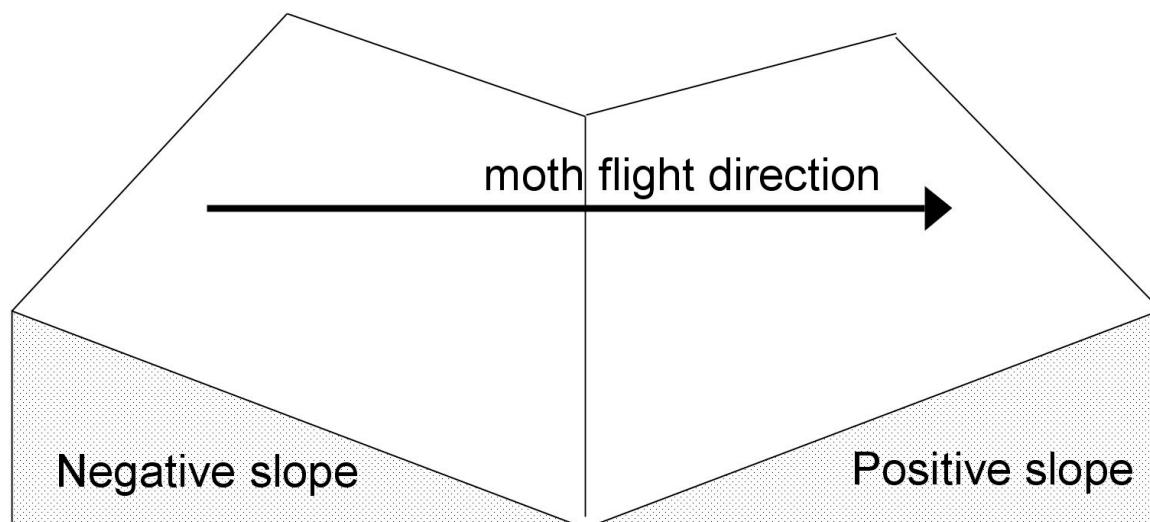
We assume that as calm flyers fly randomly in any still wind conditions they are not affected greatly by orography. The behaviour of downwind and upwind flyers allows for easy construction of a simple model describing the influence of landscape features. The LBM-M9 model simulates downwind flyers as migrating short distances only (0-5km), whereas upwind flyers fly distances up to 30km in response to pheromones. Thus the influence of an increase in spatial granularity is likely to be greater in the case of upwind flyers.

Possible flight direction is determined by average wind conditions measured in each site and maximum flight distance from each site for each year is simulated with the LBM-M9 model, dependant on the wind conditions. Starting from the centre of gravity of a site, the migration distances and directions given by LBM-M9 are applied to calculate a maximum migration area in LBM-GIS from the centre of each site.

Taking into consideration the behaviour of upwind and downwind flyers as described above, simple rules are used to calculate a possible migration area from the centre of each site in the direction(s) given by the LBM-M9 model.

LBM-GIS states that moths are able to fly in the 22.5° sector of their favoured direction (defined by average wind direction) to a maximum distance calculated by LBM-M9 from the centre of each site. Upwind flyers are able to traverse areas with a positive slope and flat areas, and downwind flyers were able to traverse areas with a negative slope and flat areas. Positive and negative slopes were determined dependant on aspect and the flight direction of larch bud moth. For example, for moths flying north, positive slopes are those with southern exposure and negative those with northern exposure (Figure 4.2).

Raster (or grid) layers of slope were constructed for each of the 16 flight directions and combined with raster layers of the maximum distance sector for each direction to determine possible flight areas for both upwind and downwind flyers.



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Figure 4.2: Definition of positive and negative slopes, depending on flight direction of larch bud moth. This scheme applies for all flight directions and aspects.

Maximum flight distance changes little from year to year, since it is dependant mostly on average wind conditions, which are assumed to remain constant over time. LBM-M9 gives two different sets of maximum flight distances due to increased flight occurring during population peak years, when high defoliation makes sites less attractive and causes more moths to emigrate in search of more attractive habitat. The first set of maximum distances are for the 1st- 4th and 7th- 9th years of a cycle and the second set for the 5th and 6th years of a cycle. Therefore only two sets of maximum distance raster layers were constructed.

The raster layers showing possible flight areas allowed us to determine to which sites moths migrated from each site. The numbers of migrating females in each direction was calculated with LBM-M9. We assumed that each target site could be reached with equal probability, thus the numbers of moth migrating to a site was calculated as the total number of moths flying in the given direction divided by the total number of possible target sites. We then added and subtracted emigrating and immigrating moths from each site to gain new population density values following dispersal as modelled by LBM-GIS.

4.2.4 COMPARISON OF RESULTS

In order to compare the outputs of LBM-GIS and LBM-M9 we calculated mean square errors of log transformed times series for each site between observed and modelled larval densities. We also compared observed densities with densities modelled with no dispersal process occurring (LBM-M9a). To determine how the models prediction ability changed with spatial location we calculated correlation coefficients for time series of each site separately. To compare the ability of the models to predict spatial patterns between the sites we calculated mean square errors between observed and modelled data at each site for each year of a single cycle (1949-1958).

To determine if modelling migration at a higher resolution gives us more insight into the behaviour of the larch bud moth in the Upper Engadine valley on average, we calculated the correlation coefficient between the modelled and observed values averaged over the entire valley and compared it to correlation coefficients between the observations and averaged LBM-M9 values and the results of LBM-M8, which simulates average values for the entire valley.

4.2.5 SENSITIVITY ANALYSIS

The sensitivity of the model to slope was tested by running the model with flat areas defined with cut-off at 1° and 15° instead of 5° . In addition, we tested the sensitivity of size of the flight sector by allowing moths to fly within a 45° sector of their favoured wind direction (LBM-GIS-45 in comparison to the 22.5° sector, and decreasing the sector size to 15° (LBM-GIS-15).

4.3 Results

Mean square error values for comparisons between observed and modelled time series of larval densities for the models LBM-GIS, LBM-M9 and LBM-M9a (no migration) are shown in Figure 4.3. There is no significant difference between the mean square error values although the larval densities simulated for the model with no migration (LBM-M9a) are lowest.

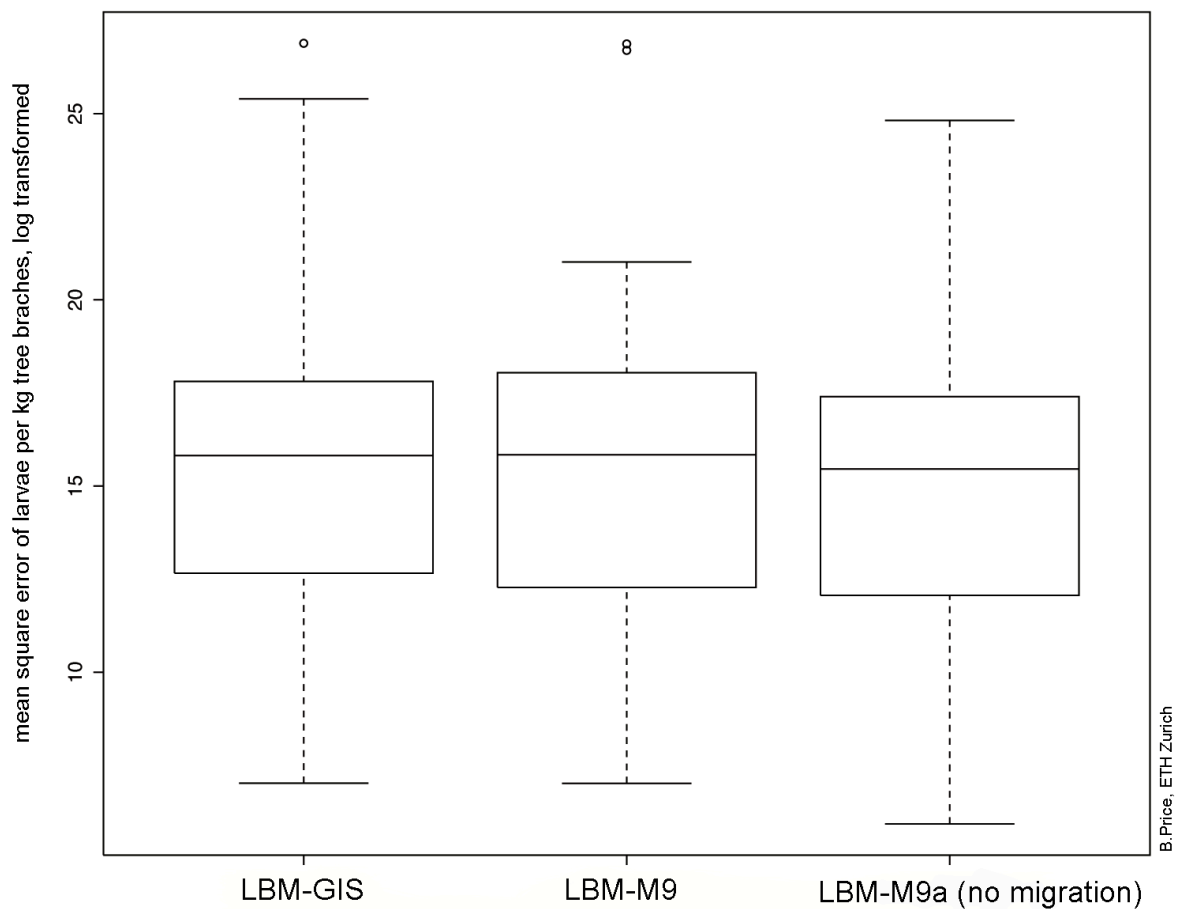


Figure 4.3: Box plot of mean square error values for log transformed times series of observed larval densities versus modelled densities for the models LBM-GIS, LBM-M9 and LBM-M9a (no migration).

Figure 4.4 shows a box plot of mean square error values between observed and modelled larval densities across space. Here we again observe no significant differences between the three models. However, for this comparison the model LBM-GIS produces the slightly lowest mean square error values suggesting this model might be best in reproducing the spatial pattern of larch bud moth across the Upper Engadine valley.

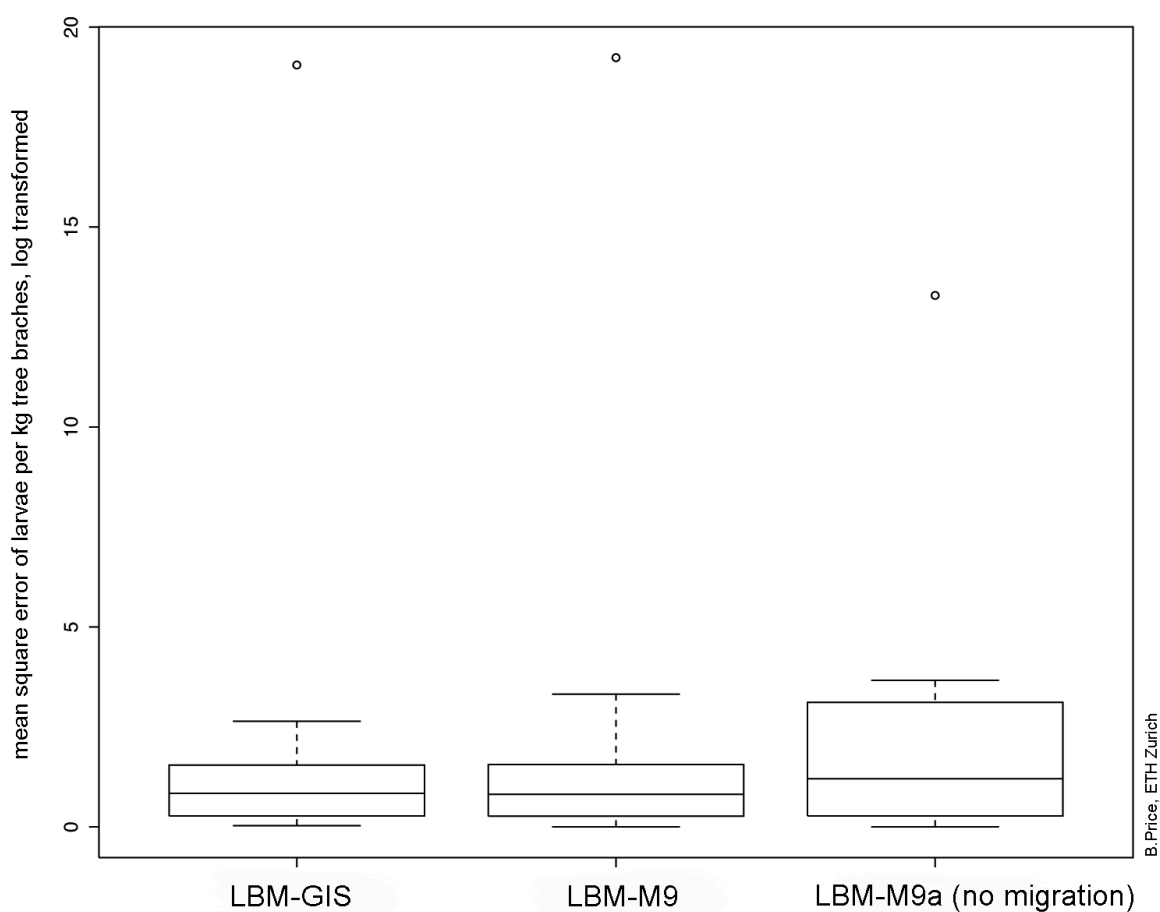


Figure 4.4: Box plot of mean square error values for observed larval densities versus modelled densities across space, i.e. for each year of an average cycle, for the models LBM-GIS, LBM-M9 and LBM-M9a (no migration).

Correlation coefficients between time series of observed and modelled time series for each site are displayed in Table 4.2. Correlation is significant at the $\alpha=0.05$ level in all cases. The model results with highest correlation to observed data vary depending on site, however, on average the results of LBM-GIS are best correlated with observed values.

Table 4.2

Correlation coefficients between observed and modelled time series (1949-1977) for each of the 20 sites (Fischlin 1982) for each of the models LBM-GIS, LBM-M9 and LBM-M9a (no migration)

site	LBM-GIS	LBM-M9	LBM-M9a (no migration)
1	0.7271	0.7719	0.7317
2	0.8225	0.6553	0.7219
3	0.7902	0.7464	0.7707
4	0.8083	0.5882	0.7313
5	0.7781	0.6130	0.7293
6	0.7120	0.5329	0.7075
7	0.7496	0.5828	0.7114
8	0.7356	0.7624	0.6067
9	0.5275	0.7504	0.6356
10	0.6395	0.7343	0.6130
11	0.5370	0.6328	0.6225
12	0.6062	0.6542	0.6303
13	0.7321	0.6066	0.6892
14	0.8665	0.7222	0.8040
15	0.7130	0.6795	0.7233
16	0.8160	0.6764	0.7749
17	0.9170	0.6938	0.7850
18	0.8547	0.6660	0.7509
19	0.8240	0.6605	0.7264
20	0.4529	0.6681	0.6156
mean	0.7305	0.6699	0.7041

All coefficients significant at the $\alpha=0.05$ level. Bold values represent maximum correlation for a given site.

The correlation analysis between modelled times series averaged over the entire Upper Engadine valley and the average observed values showed an increased correlation with incorporation of orography in the LBM-GIS model. The correlation coefficients were 0.843 for LBM-M8, 0.861 for LBM-M9 and 0.925 for LBM-GIS.

The LBM-GIS model was not sensitive to slope. Running the model with flat slope cut-off at 15° did not increase potential migration areas and thus did not change the number of sites that could be reached by migrating moths. To demonstrate this point, simulated potential migration areas for site 19 are shown as an example in Figure 4.5, where Figure 4.5a shows the potential migration area with flat area cut-off at 5° and Figure 4.5b for flat slope cut-off at 15° . There is no visible difference in the sites that can be reached. With flat area cut-off at 1° some migration was prevented, however only in very few cases and of small numbers of moths so as to cause no meaningful difference in results.

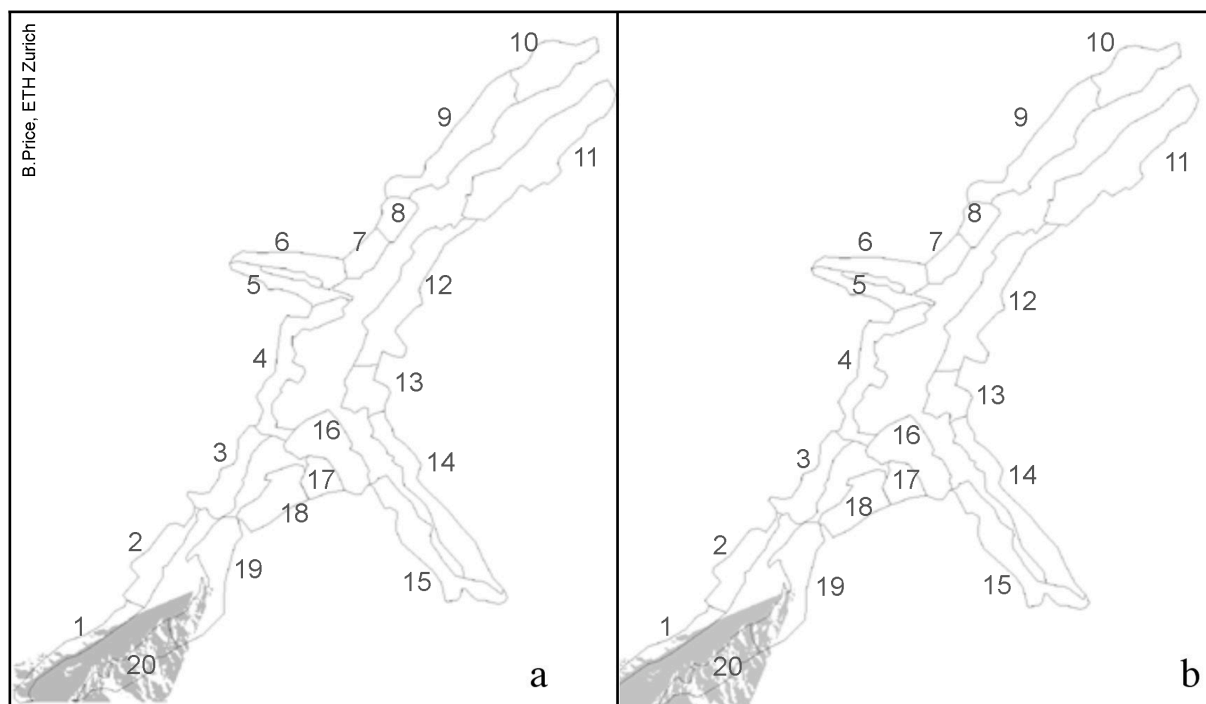


Figure 4.5: Potential migration areas from site 19 as modelled with LBM-GIS with a) flat-area cut-off at slope = 5° and b) flat-area cut-off at slope = 15° . We observe very little difference between potential migration areas with change in flat-area cut-off slope.

Enlarging the potential flight sector from 22.5° to 45° did not influence the ability of the LBM-GIS to predict observed densities overall (Figure 4.6) but did slightly decrease its ability to produce the observed spatial patterns as can be seen in the box plot of mean square errors for observed values compared to modelled values at each site across each year of a cycle (Figure 4.7). In addition, correlation coefficients between modelled and observed series were lower for the model with a larger potential flight sector (Table 4.3). A decrease in flight sector to 15°, restricted migration significantly giving results that were the same as, or very close to, the simulation results without migration (LBM-M9a).

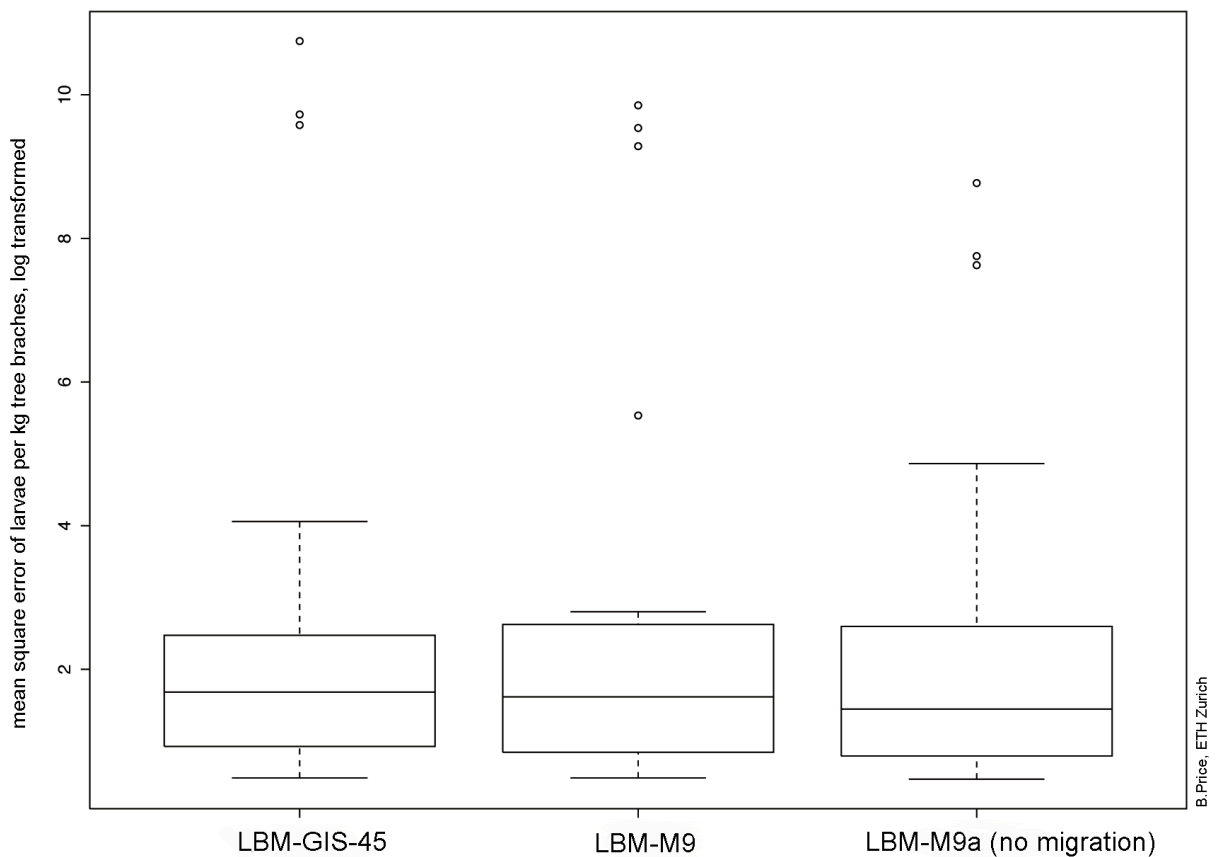


Figure 4.6: Sensitivity analysis: Box plot of mean square error values for log transformed times series of observed larval densities versus modelled densities for the following models: LBM-GIS-45 with a potential flight sector enlarged to 45°, LBM-M9 and LBM-M9a (no migration).

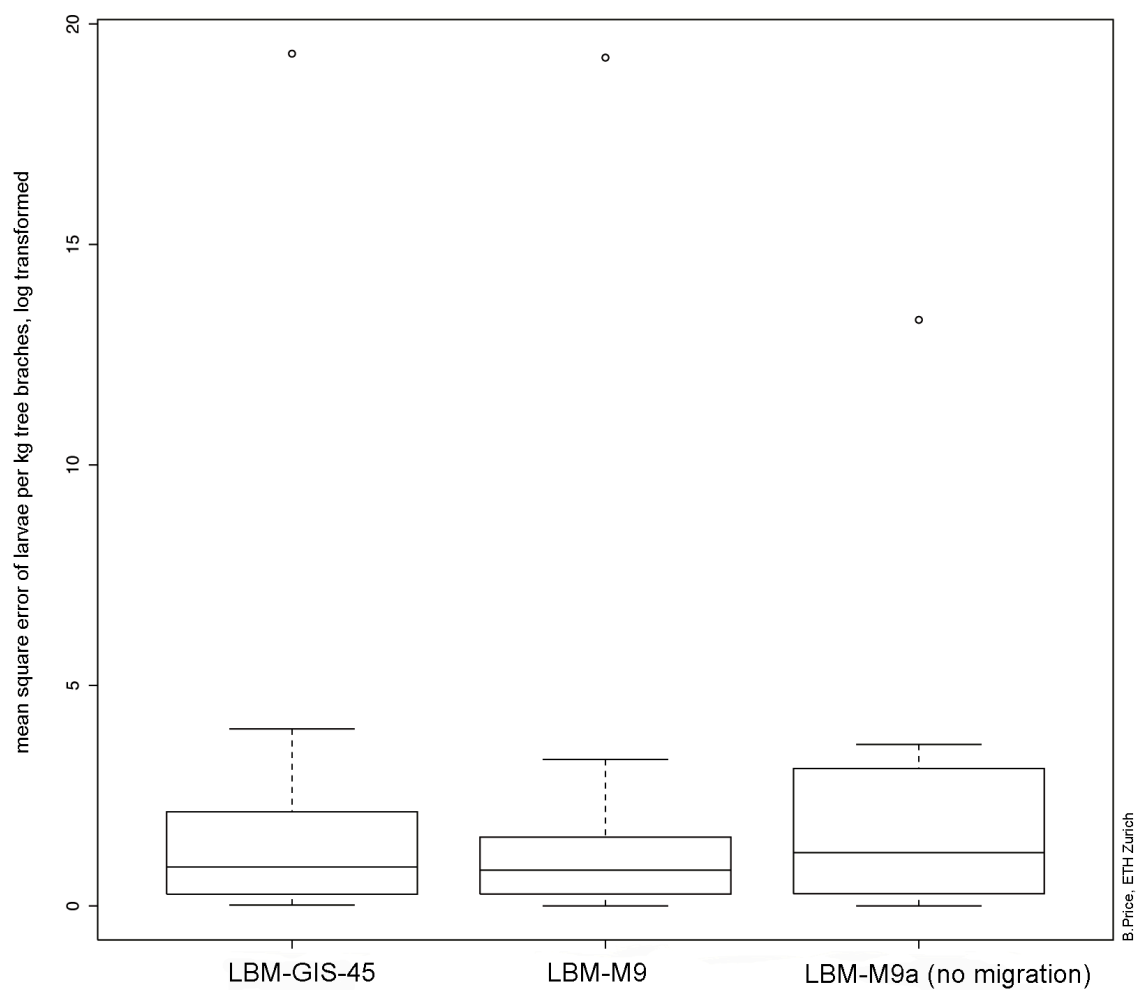


Figure 4.7: Sensitivity analysis: Box plot of mean square error values for observed larval densities versus modelled densities across space, i.e. for each year of an average cycle for the models LBM-GIS-45 with a potential flight sector enlarged to 45°, LBM-M9 and LBM-M9a (no migration).

Table 4.3

Sensitivity analysis: Correlation coefficients between observed and modelled time series (1949-1977) for each of the 20 sites (Fischlin 1982) for each of the models LBM-GIS-45 with 45° possible flight sector, LBM-M9 and LBM-M9a (no migration)

Site	LBM-GIS-45	LBM-M9	LBM-M9a (no migration)
1	0.7338	0.7719	0.7317
2	0.6590	0.6553	0.7219
3	0.7730	0.7464	0.7707
4	0.7436	0.5882	0.73127
5	0.7396	0.6129	0.7293
6	0.7075	0.5329	0.7075
7	0.7207	0.5828	0.7114
8	0.5759	0.7624	0.6067
9	0.6328	0.7504	0.6356
10	0.6130	0.7343	0.6130
11	0.6221	0.6328	0.6225
12	0.6310	0.6542	0.6303
13	0.6862	0.6066	0.6892
14	0.8057	0.7222	0.8040
15	0.7247	0.6795	0.7233
16	0.7695	0.6764	0.7750
17	0.7817	0.6938	0.7850
18	0.7496	0.6660	0.7509
19	0.7346	0.6605	0.7264
20	0.6179	0.6681	0.6156
Mean	0.7011	0.6699	0.7041

All coefficients significant at the $\alpha=0.05$ level. Bold values represent maximum correlation for a given site.

4.4 Discussion

Landscape features such as slope and altitude influenced simulated migration behaviour of upwind and downwind flyers, however the impact on resultant larval densities was not significant. Using LBM-GIS we were able to determine potential migration paths through the Upper Engadine valley at a high (50m) spatial resolution and consider the effect of orography on migration, which was not possible within the model LBM-M9 alone. Thus we could overcome at least partially the present limitations of the model resolving space coarsely, and were able to investigate the influence of topography on migration patterns of larch bud moth at a much higher spatial resolution than previously possible.

We learned from this study, simulating flight distances at a high spatial resolution within a GIS, how movement through the Upper Engadine valley is in some cases restricted. These constraints resulted from explicitly considering landscape features (i.e. topographical elements) at a higher spatial resolution, which prevented some migration from some sites in some directions that would have occurred if the model were used at a coarser spatial resolution. However, in other cases the finer spatial resolution of LBM-GIS enabled new migration paths. It allowed for more flexible movement of larch bud moth through the landscape where moths flying in a given direction from a given site could now deposit eggs in several sites that were otherwise not visited by moths in the coarser resolution model variant (LBM-M9). Since these effects may offset each other, on average, considering the influence of topographical features at a higher resolution on migration did not greatly impact the ability of the model to predict actual larch bud moth densities, either across space nor time (Figures 4.3 and 4.4).

However, some improvement in prediction of spatial and temporal patterns could be observed. In particular, correlation between modelled and observed time series was higher with the higher resolution migration model for many sites and also higher on average (Table 4.2 and 4.3).

Sites for which the LBM-GIS migration model was not able to better predict the observed patterns of larch bud moth densities are located at the ends of the

Upper Engadine valley: sites 8-12 at the north-eastern end and sites 1 and 20 at the south-western end (Figure 4.1). These sites would be more affected by immigration into the valley from outside the valley (sites 1 and 20 due to the predominant westerly winds entering the Upper Engadine valley via the Malojapass and travelling along the valley (Baltensweiler and Rubli 1999)) and emigration out of the valley (sites 8-12).

The LBM-GIS model does not take migration into and out of the valley into account, instead treating it as a closed system. However, this kind of migration is likely to be important in the Upper Engadine valley larch bud moth system, especially considering that local wind conditions within the Upper Engadine valley and the geographic location of these particular sites does not allow for much migration into and out of these areas. This observation also corroborates the hypothesis that aspects of orography are important in determining larch bud moth migration and associated population dynamics.

It has been qualitatively observed that populations of larch bud moth in areas on the right, northern-exposed sites of the Upper Engadine valley can experience a lag in density behind populations on the south-east exposed site (Baltensweiler and Rubli 1999). On the south-eastern side of the Upper Engadine valley (sites 1 to 4, 6 to 10), forests are pure larch whereas on the northern exposed side (sites 11 to 13, 16 to 20) forest coverage contains a large fraction (often > 50%) of Swiss stone pine. However, from current understanding of the ecology of larch bud moth, it is not plausible why these differences in species composition should cause the described lags. In a related study, cross-spectral analysis of larval census data (Price et al. in press) revealed a trailing phase lag in population densities between 2 and 4 months for sites 15, 16, 17 and 19 when compared to most other sites, whereas other northern exposed sites did not show such a lag. The time series of observed larval densities from these sites were better correlated with the LBM-GIS and LBM-M9a model than with the LBM-M9 simulating migration only at a coarse spatial resolution. This suggests that topographical features restricting migration may cause the phase lags observed in population cycles at these sites.

Comparison of the average observation values with the average modelled values over the entire valley showed that including the effect of orography on modelled migration as done in LBM-GIS allows us to improve our ability to predict the

temporal patterns of larch bud moth as observed at a relatively coarse spatial resolution of the valley (resolution of 20 sites, cf. Fischlin 1982). Moreover it increased our understanding of the spatial temporal dynamics within the valley.

The results of this study have general implications for modelling dispersal as a driver of spatial synchrony in populations at large scales. As orography at higher spatial resolution was shown to influence migration patterns, it is likely also to influence the synchrony of sub populations at large distances from each other inasmuch as it is caused by migration.

Our results suggest that a consideration of orography and topographical features at fine spatial resolution are important for migration patterns and resultant larch bud moth dynamics also at coarse spatial scales. In addition, the effects we found due to a change in spatial resolution and the inclusion of topographic features, provides further evidence for the basic hypothesis that migration is causing the observed synchrony within the Upper Engadine valley (e.g. Baltensweiler and Fischlin 1979, Fischlin 1982, Baltensweiler and Rubli 1999) and lags in synchrony for certain sites (Price et al. in press).

4.5 Conclusions and Outlook

The results show how an increase in spatial resolution impacted the behaviour of a set of dynamic larch bud moth models. Indeed, actual dispersal may be more sensitive to orography and topography than has been assumed previously. The ability to predict mean larval densities for large areas such as an entire valley did not improve through inclusion of topographical features at a finer spatial resolution. In fact this ability decreased, but not significantly. However, the ability to predict within valley spatio-temporal patterns was increased through inclusion of topographical features at a finer spatial resolution. This is in particular true with respect to observed lags in densities for some sites in the Upper Engadine valley.

This suggests that geographical features, in particular those related to orography, at a fine scale are important for larch bud moth migration. Our results are consistent with the basic hypothesis that migration is an important driver of spatio-temporal patterns in the Upper Engadine valley, but in no way conclusive as the Moran effect was not investigated here. Yet, to distinguish between the

two synchronizing mechanisms, explicit inclusion of migration at a fine spatial resolution may be relevant generally and in the case of the larch bud moth.

We can conclude that a fully integrative temporal-spatial modelling at a high spatial resolution will help to gain important new insights into the population dynamics of a key species such as larch bud moth. Only tighter coupling of temporal and spatial modelling, will enable further investigation of the implications of changes in spatial resolution for migration appropriately. This study demonstrated the sensitivity of dispersal to the degree in which additional landscape characteristics are incorporated. In the past, modelling efforts simulating larch bud moth dynamics, such as that with which LBM-M9 was developed (Fischlin 1982), were hampered by lack of availability of highly resolved spatio-temporal data. Linking temporally explicit simulation models to a GIS, reveals many new insights into the population dynamics of highly vagile species such as larch bud moth, particularly with respect to the influence of orography on dispersal.

4.6 Acknowledgments

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5 SPATIO-TEMPORAL MODELLING OF LARCH BUD MOTH DYNAMICS IN THE EUROPEAN ALPS: THE IMPORTANCE OF DATA RESOLUTION

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as submitted to *Landscape Ecology*

Abstract

Spatial scale and in particular grain (as an aspect of scale) of input data is likely to influence the behaviour of ecological models considerably. It is well known that coarse spatial resolution limits the usefulness of spatial models. However, that uncertainty increases with high resolution input data is often overlooked. Thus, there is likely an optimum spatial resolution, which depends on the nature of the input data and the ecological process being modelled. In this study we investigate how spatial grain of input data within the same spatial extent affects the ability of a model in predicting observed population dynamics of larch bud moth within the Upper Engadine valley in the Swiss Alps. Our results demonstrate that modelling larch bud moth at a higher resolution results in minor but insignificant improvements in the accuracy of predicting of observed larval densities. Increasing the input data resolution of the given model does not improve its ability to predict spatial patterns at the local scale and increases uncertainty. Observed spatial patterns could be predicted most accurately, and with minimised uncertainty with a model with a coarser spatial grain of input data, thereby confirming the postulated optimum spatial grain.

Key words: Upper Engadine valley, spatial grain, population dynamics, model prediction

5.1 Introduction

The larch bud moth, *Zeiraphera diniana* GN. (*Lep.*, *Tortricidae*), is a conspicuous forest defoliator that has caused large-scale defoliation of larch trees across the entire Alpine Arc approximately every 9 years, documented since at least 1854 (Auer 1969, 1977, Fischlin 1982, Baltensweiler and Fischlin 1988, Baltensweiler and Rubli 1999). Theory suggests that the cyclic population dynamics result from either an interaction between larch bud moth and its parasitoids (parasitoid-prey hypothesis) (Baltensweiler et al. 1977, Baltensweiler and Fischlin 1979, Fischlin 1982, Baltensweiler and Fischlin 1988), a feedback relationship between the larch bud moth and its host, the European Larch (*Larix decidua* MILLER) (food quality hypothesis), or a tri-trophic relationship combining the food quality hypothesis and the parasitoid-prey hypothesis (e.g. Turchin et al. 2003).

Models of larch bud moth dynamics have already been developed for a variety of spatial scales, ranging from local scales to that of the entire Alpine Arc (Fischlin 1982, 1983, Bjornstad et al. 2002, Turchin et al. 2003, Johnson et al. 2004). Many larch bud moth models focus on fluctuations over time, and those that do incorporate spatially varying properties have only been able to take advantage of spatial data at a very coarse spatial resolution, or have depended on subjective defoliation map data (Fischlin 1982, 1983, Bjornstad et al. 1999, Johnson et al. 2004).

Previous studies (e.g. Fischlin 1982, 1983, Bjornstad et al. 2002, Peltonen et al. 2002, Johnson et al. 2004, Price et al. in press) have described distinct spatio-temporal dynamics of larch bud moth, and these dynamics appear to change with spatial scale.

‘Scale is characterised by grain and extent. Grain is the finest possible spatial resolution within a given dataset. Extent refers to the size of the overall study area.’ (Turner et al. 2001). Most ecological studies are faced with a decrease in spatial grain as extent increases. However, it is in general unclear whether this can be justified or whether it occurs at the expense of relevant information. To study this question it would be of advantage to investigate the same population

system at several spatial scales. This study considers such a case of an increase in spatial grain within the same spatial extent.

Spatial scale and in particular the spatial grain (as an aspect of scale) of input data are likely to influence results produced by an ecological model considerably (Turner 1989, Wiens 1989, Levin 1992). While high resolution input data may be required to make predictions and model processes at high spatial grains, sampling and observational constraints, such as number of weather stations, tend to increase the uncertainty associated with these input data. Moreover, interpolation techniques, introduce further uncertainties through parameterisation and approximation of modelled processes. Such effects have been studied in many other contexts, such as climate modelling (e.g. Henderson-Sellers 1996, Gyalistras and Fischlin 1999, O'Neill and Steenman-Clark 2002), hydrology (Cotter et al. 2003), or geostatistics (Kyriakidis and Yoo 2005), but little in ecology (Landis 2003).

The required spatial resolution and accuracy of model results depend on the ecological processes being modelled (Levin 1992, Allen and Holling 2002). For certain ecological processes it may no longer make sense to use input data at a higher spatial grain as this may complicate computations with propagation of uncertainties or, at the worst, produce results that no longer make sense. However, using input data at low resolution only allows models to make broad predictions across large geographical areas. Moreover, small-scale processes of importance for understanding the ecological process at a large scale may become disregarded. Therefore, it is likely that for each ecological process being modelled there is a distinct optimum spatial grain for the input and model variables. That spatial grain should allow for highest accuracy in model predictions while being as coarse as possible to minimize uncertainty, yet still include any important small scale process. Beyond that spatial grain (at lower or higher spatial grains) accuracy of results may not improve or perhaps even decline (Mac Nally and Quinn 1998).

To investigate this idea we have studied larch bud moth population dynamics at the scale of the Upper Engadine valley, in particular looking at migration and local dynamics. This case study satisfied all requirements: (i) input data with differing spatial grains within the same extent, (ii) observed output data at a high spatial grain, and (iii) a family of validated models capable of generating spatio-

temporal patterns of population dynamics comparable to the patterns observed. We used Fischlin's (1982) spatially explicit model of larch bud moth migration throughout the Engadine with coarse spatial resolution coupled with a local dynamics model describing local population fluctuations. We combined this model with a GIS system (GRASS Neteler and Mitasova 2002) to allow integration of spatial data at several spatial resolutions. Using the GIS and a wind model (NUATMOS) (Ross et al. 1988), we generated the spatially explicit input data as required by the model and simulations were run at three different levels of spatial grain: the entire Upper Engadine valley, the 'site' ($\sim 3.5\text{km}^2$) and the forest compartment (~ 25 ha).

We determined how an increase in spatial resolution affects the migration patterns of the larch bud moth and the predicted population dynamics within the Upper Engadine. We address the following questions: Does an increase in spatial grain of model input data increase the accuracy of modelled larch bud moth dynamics? Can we better predict spatial patterns across a region by increasing the spatial grain of input data and model?

5.2 Material and Methods

5.2.1 STUDY AREA

The Upper Engadine valley is a sub alpine valley in the Swiss part of the European Alps (Figure 5.1) forested with mixed larch (*Larix decidua* MILLER) - Swiss stone pine (*Pinus cembra* L.) forests. Forests within the Upper Engadine valley were previously divided into 420 'Forst-Abteilungen' (forest compartments) designated according to the needs of forestry management. Thus their delineation is based on a mixture of political, practical, and ecological criteria. The forest compartments have an average area of 25 ha and an average forested area of 16.5 ha. From 1949 to 2005 larval surveys have been carried out within the Upper Engadine valley including recording of the forest compartment in which each surveyed tree was located (A. Fischlin in prep.).

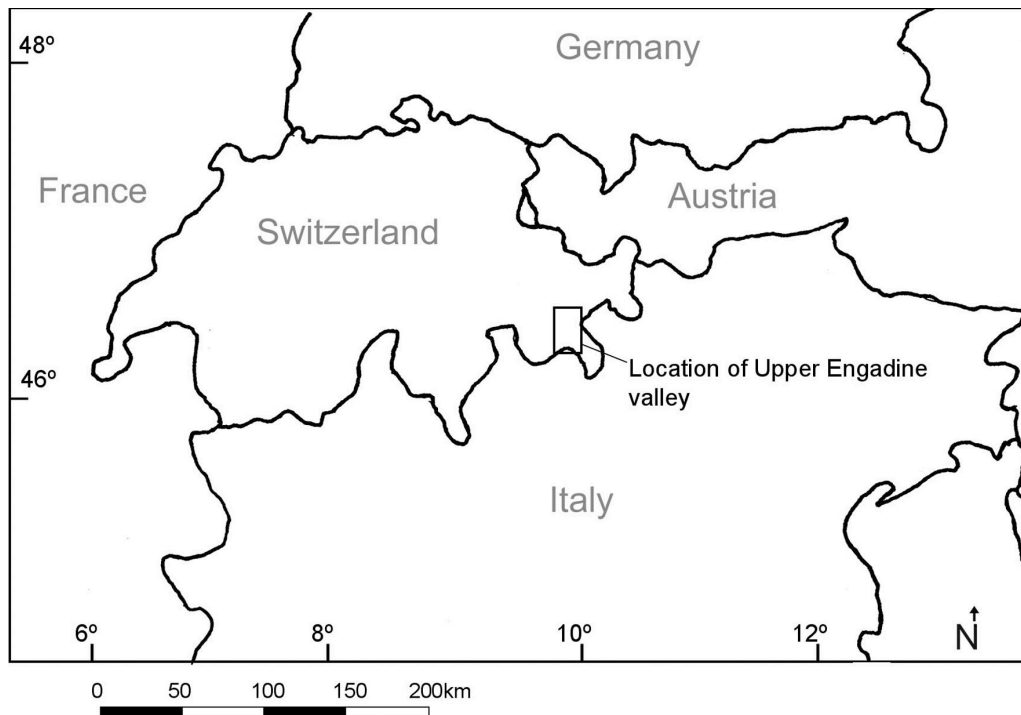


Figure 5.1: Location of the Upper Engadine Valley in Switzerland

5.2.2 MODELS

Fischlin (1982) developed a model of the local dynamics of the larch bud moth in the Upper Engadine valley based on the food quality hypothesis known as LBM-M8. The model considers the relationship between the larch bud moth and its host, the larch. Larch bud moth feeding causes an increase in raw fibre content of the larch needles, the chosen food quality indicator, which has negative implications for larch bud moth survival of larvae, pupal weight, and in turn determines female fecundity. Low food quality causes a decrease in the following year's larch bud moth population. The model deals with local dynamics only, and treats an entire valley as a homogeneous area with no spatial structure (Fischlin and Baltensweiler 1979). The local dynamics model is a deterministic mathematical model, i.e. a second order, discrete time system of coupled, non-linear equations.

We considered it reasonable to use our LBM-M8 larch-larch bud moth model in this study even though a recent study by Turchin et al. (2003) suggests that the parasitoid-larch bud moth interaction was the dominant factor driving the larch bud moth cycle (compared to the larch-larch bud moth interaction). Correlation analysis of the average observed larval densities for the Upper Engadine valley

and those predicted by our LBM-M8 model for the same time period as the data analysed by Turchin *et al.* (2003), resulted in a correlation coefficient of 0.840 (significant at the $\alpha = 0.05$ level). In addition, the formulation of the LBM-M8 model lends itself well to combination with a migration model, which would be more difficult with Turchin *et al.*'s (2003) model.

To model larch bud moth dynamics in a spatially explicit manner within the Upper Engadine valley, Fischlin (1982) divided the Upper Engadine into 20 spatially discrete regions, known as 'sites'. These sites are homogeneous with respect to aspect, elevation and forest type. The sites have an average area of 3.7km² and are between 2 and 30 km apart from site centre to site centre (Fischlin 1982). This model, known as LBM-M9, incorporates the local dynamics model (LBM-M8) as a sub-model and couples it with another sub-model for flight within the Engadine valley between the 20 sites (see also Baltensweiler *et al.* 1977, Baltensweiler and Fischlin 1979, Fischlin 1982). For a given flight season (autumn) the flight sub-model simulates the numbers of females emigrating from a given site and the numbers of eggs they oviposit in all the sites to which they immigrate. The flight part of LBM-M9 is also a deterministic mathematical model, and the behaviour of all female moths in a site is defined by a recursive formula involving the current site and all relevant neighbouring sites. Specific site conditions as determined by wind statistics and other site specific characteristics such as defoliation, forested area, and number of larch trees determine dispersal rules (Baltensweiler and Fischlin 1979, Fischlin 1982). The dispersal rules give the number of moths leaving the site in each flight direction. Moths leave their current site for the neighbouring sites where, on the next recursion level, the dispersal rules are again applied. The recursion continues until all flying moths are dispersed (Baltensweiler *et al.* 1977, Baltensweiler and Fischlin 1979, Fischlin 1982, Baltensweiler and Fischlin 1988). It is assumed that only mated females become airborne, and thus no interference between moths is considered. Therefore, this recursive formula may be repeatedly computed for the females of all sites in sequence. The abundance of larch bud moth larvae in each site for the next generation is determined by summing the number of eggs oviposited in each site by any female, multiplied by a winter egg survival ratio. Moths are assumed to migrate from the centre of each site (Fischlin 1982).

The spatially explicit input data required by LBM-M9 are listed in Table 5.1. Wind statistics (speed and direction) for the flight season July 15th - September 30th were derived for each site from records of the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) weather stations. Wind was recorded in three speed categories: still (<0.5m/s), gentle (0.5-2.8m/s) and strong (>2.8m/s) in each of eight compass directions. The wind parameters for LBM-M9 were then given as constants, i.e. the average proportion of the total wind behaviour for each wind speed category over time (Fischlin 1982). At the coarse resolution of the site, applying only eight wind directions yielded ambiguous neighbour relationships. Thus, each direction was further divided into two sub-directions within the LBM-M9 model (Fischlin 1982).

Table 5.1

Spatially explicit data required as input to model LBM-M9 and LBM-M11 with sources

Constant	Source (LBM-M9)	Source (LBM-M11)
Frequency of turbulence in site i	MeteoSwiss, 1901-1990 (Fischlin 1982)	MeteoSwiss, 1901-1990
Frequency of still winds (0-0.5m/s) in site i	MeteoSwiss, 1901-1990	NUATMOS (Ross et al. 1988)
Frequency of calm winds (0.5-2.8m/s) in site i	MeteoSwiss, 1901-1990	NUATMOS
Frequency of strong winds in site i	MeteoSwiss, 1901-1990	NUATMOS
Frequency of calm winds in site i in direction j	MeteoSwiss, 1901-1990	NUATMOS
Frequency of strong winds in site i in direction j	MeteoSwiss, 1901-1990	NUATMOS
Area of neighbouring site n in direction j in sub-sector A resp. B	MeteoSwiss, 1901-1990	n/a
Area of neighbouring site n in sector j	n/a	Calculated in GRASS (Neteler and Mitasova 2002)
Air distance from site i to neighbouring site n in sub-direction A resp. B	MeteoSwiss, 1901-1990	n/a
Air distance from site i to neighbouring site n in direction j	n/a	Calculated in GRASS

where: for LBM-M9 i = 1-20, n = 1 – 20, j = NE,E,SE,S,SW,W,NW, N
for LBM-M11 i = 1-420, n = 1-420, j = as above

We introduce in this paper a new higher resolution model known as LBM-M11 (LBM-M10 designates an even coarser spatial resolution, that of an entire Alpine valley. To explain cycle synchronization, the model simulates larch bud moth migration along the entire Alpine arc.). LBM-M11 has the same structure as LBM-M9 and requires the same type of input data, but at a finer spatial resolution as it models migration between the 420 forest compartments of the Upper Engadine valley. The mathematical equations are very similar, the only difference being that, due to the coarse spatial resolution of LBM-M9, migration is modelled in 16 directions from each site, whereas, at the higher resolution of LBM-M11 the sub division of wind directions was no longer necessary; shorter distances between forest compartments (as compared to distances between sites) meant there were no longer ambiguous relationships between neighbours. Therefore, migration in LBM-M11 is only modelled in eight directions from each forest compartment.

5.2.3 DATA

Larval census

Larval sampling is timed to take place when larch bud moth is predominately in the larval stages L3, L4 and L5. This timing depends on weather conditions and varies inter-annually (Fischlin 1993). Within the Upper Engadine valley, during the first phase of the larval survey (1949-1958: A. Fischlin in prep.) between 1000 and 2100 trees were sampled annually and the number of larvae per tree was determined (Auer 1961). From 1956-1979 the sampling method changed and approximately 400 larch trees were sampled annually according to a statistically sound random sampling scheme (Kälin and Auer 1954). Sample stratification was according to topographical features (altitude, exposure) and samples were weighted according to host-tree density per unit area (Baltensweiler and Fischlin 1988). During these annual population surveys approximately 3 kilograms of twigs and foliage (excluding cones) were taken from each tree; 1 kg from each of three levels within the crown. In 1956 and 1957 both sampling methods were employed to allow compatibility and comparison of the results. The larval censuses provide an average density estimate for the larval population (e.g. Auer 1969, 1978) and were converted to an annual absolute population estimate for the site and for the entire Engadine

Valley (Fischlin 1982). The census method within the Upper Engadine changed after 1977, meaning that annual data were no longer available for each of the 'sites' within the Upper Engadine valley (A. Fischlin in prep.). Instead, within three specific sample areas, three trees were randomly chosen. The sampled areas were chosen to be representative of the entire valley and were spread evenly along the length of the valley (Fischlin 1993). This allowed estimation of a mean population density for the entire valley. Larval census data with larval numbers recorded according to forest compartment ID is available in an electronic database for years 1957-1991 (LBM database: A. Fischlin in prep.). Earlier data were not digitised at the forest compartment level. Therefore, annual larval densities per forest compartment could be derived from the database. However, not all forest compartments have been surveyed and density values were not available for every year for every compartment.

Tree Data

The numbers of larch trees per forest compartment were recorded in management reports of the Upper Engadine Forestry division and prepared for LBM-M9 (Fischlin 1982). However, tree data was not available for every forest compartment. Therefore, an estimate of larch tree numbers was required for those forest compartments for which the data were missing. Grouping the forest compartments for which tree data were available according to exposure (northern and southern) and plotting forested area versus number of larch trees revealed a linear relationship (Figure 5.2) from which we estimated the number of larch trees in the remaining forest compartments.

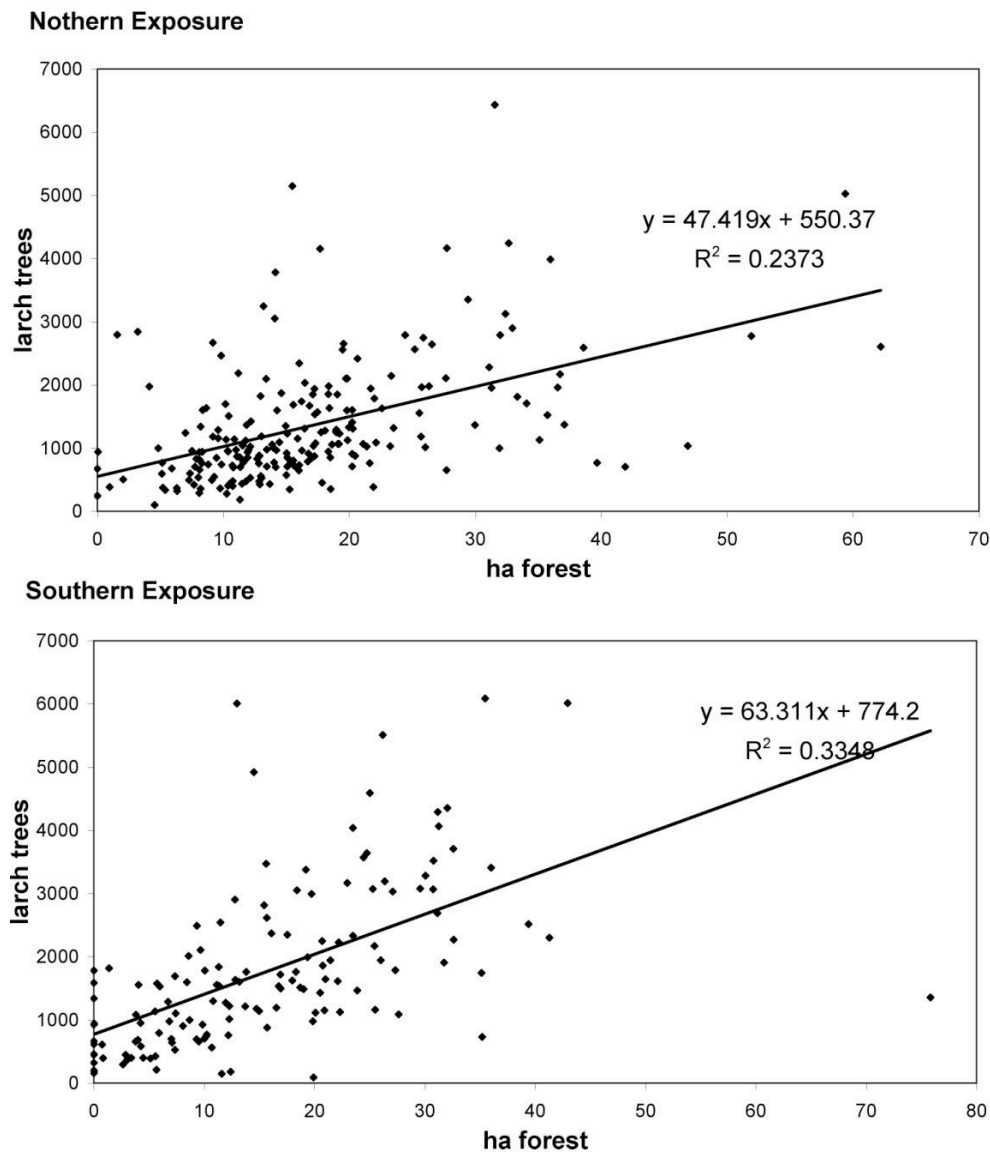


Figure 5.2: Number of larch trees per forest compartment plotted against forested area divided into forest compartments on northern and southern exposed slopes.

Wind Data

NUATMOS is a “physically consistent three dimensional diagnostic model designed to minimize the difference between the initial interpolated wind field and the final wind field subject to a mass-consistent constraint” (Ross et al. 1988). NUATMOS produces a “three dimensional mass-consistent windfield, which bases on arbitrarily located observations” (Ross et al. 1988). The input consists of parameters controlling NUATMOS, specification of the digital elevation model (DEM) on which NUATMOS is applied, and wind observations in the form of horizontal wind components. The wind direction and speed on the

surface is calculated from the three dimensional wind field NUATMOS generates (Bachmann 1998). In this study NUATMOS version 5N (07/31/91) (Ross et al. 1988) has been applied to a DEM with a spatial resolution of 50 m (DHM50 ©, Tydac AG).

The wind observation data used as input to NUATMOS was retrieved from the Swiss Federal Office of Meteorology and Climatology. The six meteorological observation stations chosen to provide initial conditions were within and around the Upper Engadine valley (Bever, Bivio, Corvatsch, Robbia/Poschiavo, Sils Maria, and St.Moritz). As topographical effects largely drive wind patterns within the Upper Engadine valley, average summer wind speed and direction values are considered constant through time by the LBM-M9 and LBM-M11 models (Fischlin 1982). Therefore, a period for which all of the relevant meteorological observation stations provide data, 1980 to 1982, was chosen from which to take data to drive NUATMOS. Since NUATMOS requires observations from at least one observation station not located on the surface, wind observations from the troposphere (ca. 5500 m.a.s.l.) were also taken.

The goal was to produce wind fields in the Upper Engadine required as input for the models LBM-M9 and LBM-M11, as described in section 2.2. Larch bud moth flight occurs only during a seasonal window of mid July to September in the early evening when temperatures are above 7°C (Fischlin 1982, Baltensweiler and Rubli 1999). Therefore only evening (19h30) wind measurements between July 15th and September 30th at temperatures above 7°C were retrieved.

This data was used to generate 200 wind observation input files for NUATMOS. Based on these wind observations, NUATMOS interpolated wind direction fields and wind speed fields for 200 points in time. These wind fields were then applied to generate the wind statistics for each cell as required by the larch bud moth models (see section 2.2).

The accuracy and the usefulness of the wind fields generated by NUATMOS were tested through evaluation of the generated wind fields against values from the meteorological observation station of Samedan, located in the centre of the Upper Engadine. The difference in average wind direction was 62.9 degrees and the observed average wind speed was 3.79 m/s compared to simulated average

wind speed of 1.63 m/s. An evaluation of NUATMOS by Connell (1989) has shown that the best agreement between modelled and observed values is achieved at mountain tops whereas poor agreement occurs at low wind speeds (i.e. 2m/s) and when re-circulating flow occurs on the lee side of mountains.

While the differences between modelled and observed wind speeds were considerable, the deviations in wind direction were less critical for modelling larch bud moth since the average difference of 62.9 degrees was less than the difference between major wind directions (north, south, east, west) of 90 degrees. Before the final decision on whether to use the NUATMOS results, we performed a sensitivity analysis of the LBM-M9 model to wind statistics. Simulating the model without wind, i.e. where all moths migrate randomly regardless of wind speed or direction, produced results with very little variation from the results simulated using MeteoSwiss wind data. Calculation of a

similarity index: $1 - \frac{\sum r1 - r2}{\sum r1 + r2}$ between the sets of results gave a mean similarity

index of 0.9729 (min: 0.9344, max: 0.9978, sd: 0.0025) suggesting the model is not sensitive to wind. Therefore, we decided it was reasonable to use the NUATMOS wind fields for the LBM-M11 model.

The models LBM-M9 and LBM-M11 require wind statistics representing the entire site, respectively forest compartment. Both models assume that female moths take-off from the centre of the site or forest compartment. Therefore, the wind statistics were computed from the values at the centre point (centre of gravity of planar projection) of each site or forest compartment.

Neighbourhood Data

To obtain the neighbourhood data for each forest compartment required as input to the LBM-M11 model, the forest compartments were first digitised and stored as a vector data layer within a GIS. The model requires knowledge of the nearest neighbours for each forest compartment in each of the eight compass directions. Therefore, forest compartments that are spatially separated and not sharing any borders are still neighbours as long as no other forest compartments are located between them. This meant that neighbours could not be determined by standard GIS neighbourhood analysis functions, which require adjoining borders. Based

on the centroid coordinates of each compartment, a list of closest neighbours was determined for each compartment. It was then necessary to manually determine which of those were or were not actual neighbours. Once the neighbours were assigned, a vector containing eight sectors, one for each of eight compass directions, was created for the centre of each compartment. By adding the vectors containing sectors with the forest compartment vector it was possible to determine (i) in which direction each neighbour is located, (ii) the area of each neighbour in the given compass sector and (iii) the distance to each neighbour centre.

5.2.4 COMPARISON OF MODELS PERFORMANCE

In order to compare the results of our higher resolution model LBM-M11 with the coarser spatial resolution models LBM-M9 and LBM-M8, mean square error (MSE) statistics were calculated for standardised modelled time series of larval density compared with standardised observed time series of larval density for each forest compartment (where observation data existed).

The forest compartment observation data was compared to the standard LBM-M11 model run data, LBM-M11 output with only random flight (not dependant on the wind field), the LBM-M9 output for the associated site and the LBM-M8 output (average of the entire Engadine valley). The series were standardised using a $\ln(x + 1)$ transformation, due to the presence of many zero observations.

In LBM-M11, the initial larval density in each forest compartment was determined from the mean larval density per tree over the entire Engadine valley and multiplied by the number of larch trees in each compartment. Thus the initial larval density per kg of tree branches is the same in each forest compartment (the model assumes that the number of kilograms of branches per larch tree is constant regardless of spatial location). However, when we examine field data (cf. Figures 5.3a and 5.4a) we see that observed larval density varies considerably from one forest compartment to another in some years. Thus we run the model over a long period (>80 years) so that the model approaches a steady state, where the relationship between the forest compartments remained similar and the initial conditions no longer influenced the modelled results. We considered this to be a steady state with respect to spatial variance. Thus we simulated larch bud moth densities for at least 100 years and compared

modelled densities at steady-state with an average cycle of observed densities to gain an understanding of the accuracy of the modelled results. The average cycle of observed larval densities is determined by averaging over all available, overlapped cycles (overlapping is obtained by temporal shift till peak years match Fischlin 1982)

We calculated the same MSE statistics as described above for standardised observed and steady state modelled time series.

While the MSE statistics inform us about how well our modelled data fits the observed data, they do not tell us much about how well the spatial patterns are modelled. In order to determine if our higher resolution model can predict observed spatial patterns we performed linear regression for each year of an average observed cycle versus each year of a steady state modelled cycle, for modelled and observed values at the 'site' resolution and at the forest compartment resolution. Finally we categorised both observed and modelled larval densities from one cycle into 4 groups: 0-1, 1-10, 10-100 and 100-1000 larvae/kg tree branches. We then mapped these values for each year in one cycle and compared maps by calculating coincidences between the maps.

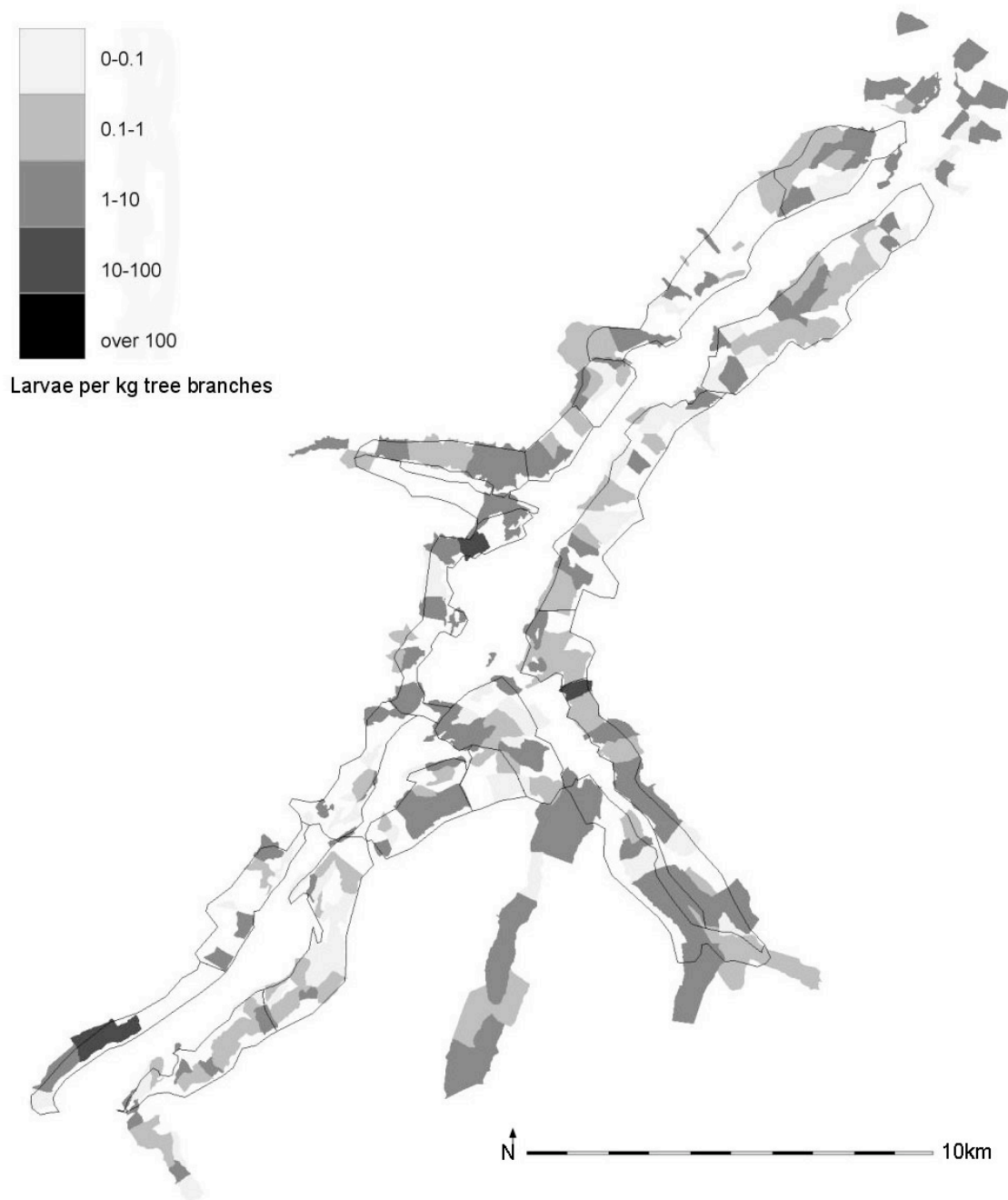


Figure 5.3a: Observed larval densities (larvae/kilogram tree branches, retrieved from LBM database: A. Fischlin in prep.) for 1960 (trough year of the larch bud moth cycle) per forest compartment. The darker the colour, the greater the larval density. Lines indicate 'site' borders.

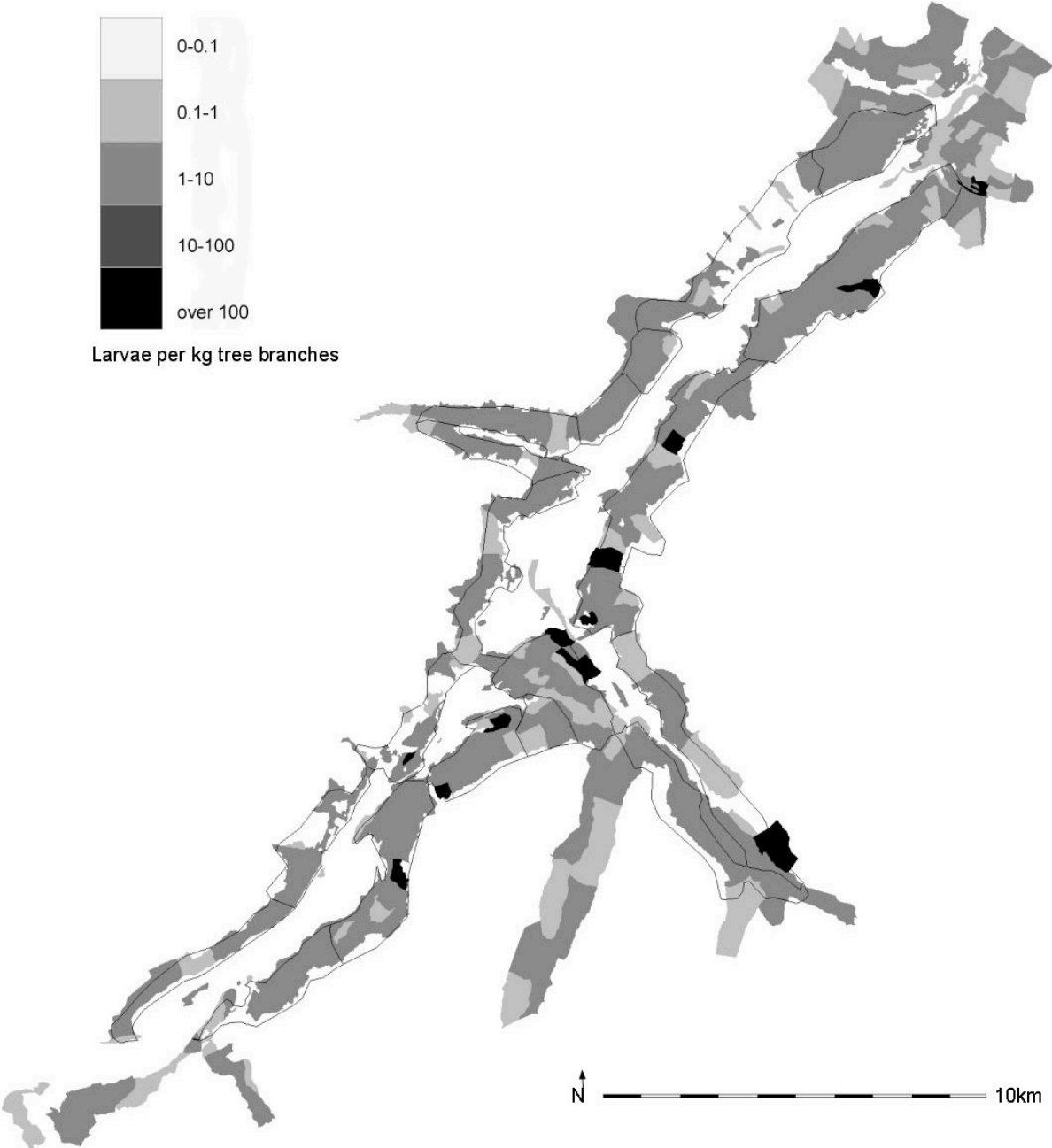


Figure 5.3b: Simulated larval densities (larvae/kilogram tree branches retrieved from LBM database: A. Fischlin in prep.) for 1960 (trough year of the larch bud moth cycle) per forest compartment. Simulated with model LBM-M11. The darker the colour, the greater the density. Lines indicate ‘site’ borders.

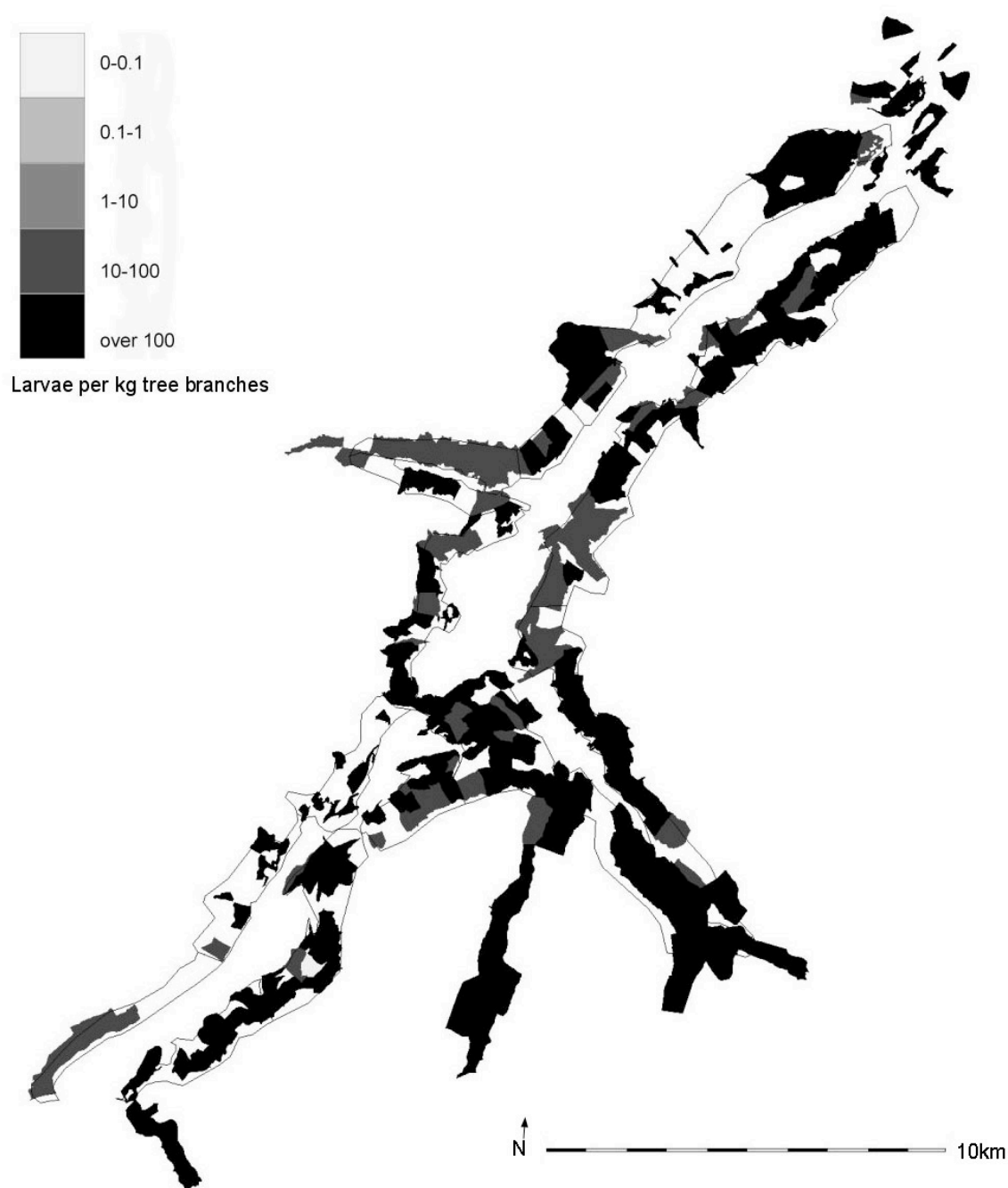


Figure 5.4a: Observed larval densities (larvae/kilogram tree branches retrieved from LBM database: A. Fischlin in prep.) for 1963 (peak year of the larch bud moth cycle) per forest compartment. The darker the colour, the greater the larval density. Lines indicate 'site' borders.

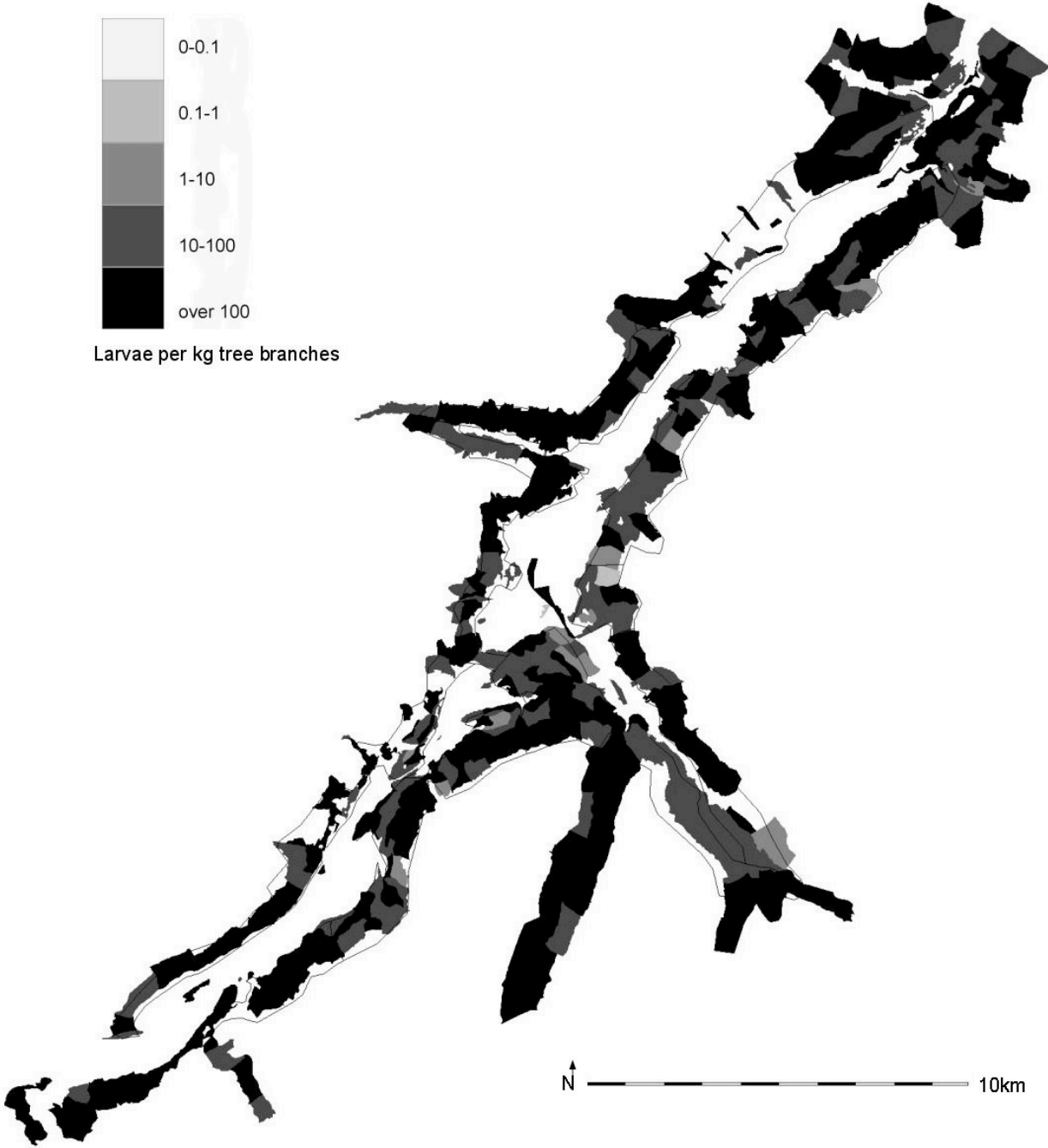


Figure 5.4b: Simulated larval densities (larvae/kilogram tree branches retrieved from LBM database: A. Fischlin in prep.) for 1963 (peak year of the larch bud moth cycle) per forest compartment. Simulated with model LBM-M11. The darker the colour, the greater the density. Lines indicate ‘site’ borders.

Another measure of whether a higher spatial grain model is needed to define spatial patterns would be to determine if larval density values are highly variable over space. Once we have classified the densities as described above we can measure landscape pattern through calculation of landscape metrics. Contagion enables us to distinguish whether area with the same category value are clumped together across the landscape or dissected (O'Neill et al. 1988, Li and Reynolds 1993, Turner et al. 2001). A measure of contagion for modelled and observed density maps will also give us an indication of whether the model predicts more or less spatial variability than is observed. We calculated a contagion index for modelled and observed density maps for each year of a single cycle using the contagion metric as described by Li and Reynolds (1993) (adapted from O'Neill et al. (1988)):

$$C = \frac{1 + \sum_{i=1}^n \sum_{j=1}^n (P_{ij}) \ln(P_{ij})}{2 \ln(n)}$$

where P_{ij} = the probability that patch type i is adjacent to patch type j , and n is the number of patch types on the landscape.

5.3 Results

Comparison of the modelled time series with the observed time series for each forest compartment for the LBM-M8 model run, the LBM-M9 model run, the steady-state LBM-M11 run and the LBM-M11 model run with uniform wind conditions, reveal that the average value of MSE for the steady state cycle of LBM-M11 is the lowest by a small margin (Figure 5.5). This result suggests that LBM-M11 has the best fit to the observed data although the range of values suggests there is no significant ($\alpha=0.05$) difference between the fit of LBM-M11 compared to all other model runs.

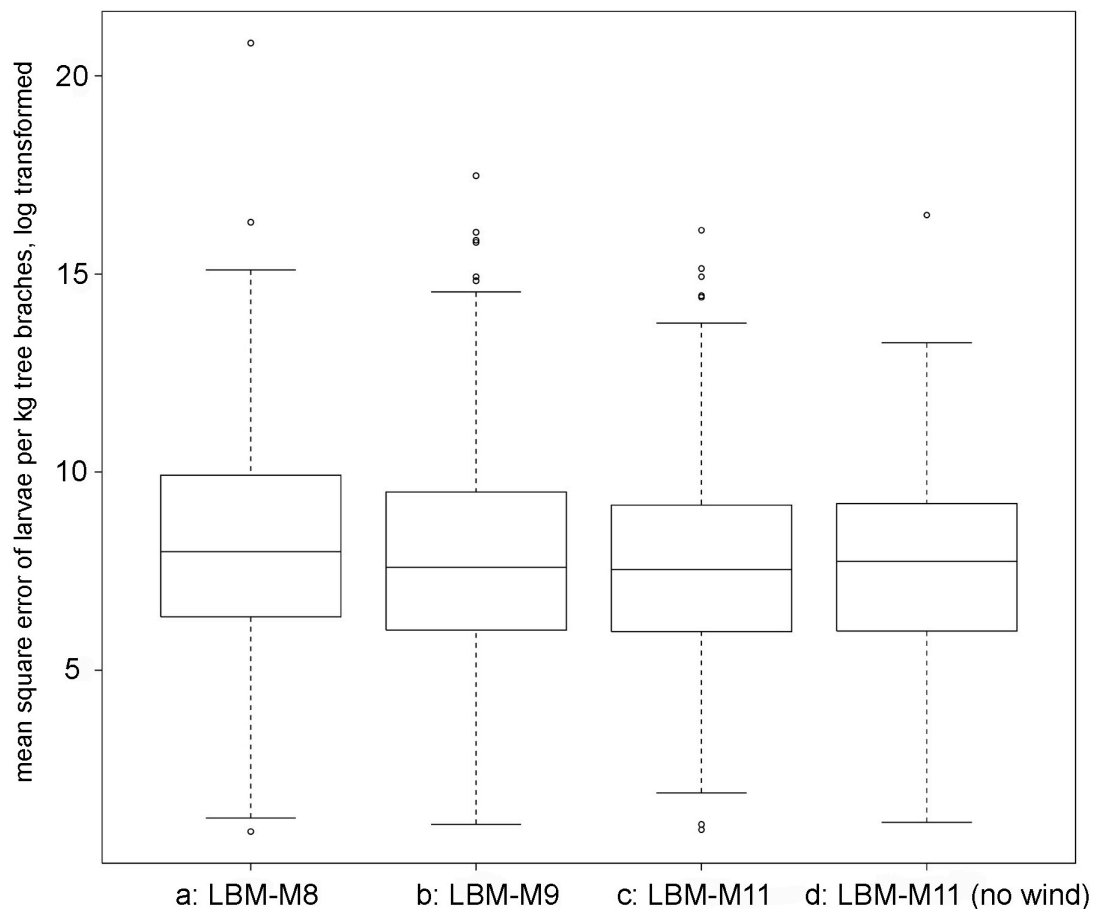


Figure 5.5: Boxplot of mean square errors for comparisons between log-transformed time series of observed larval densities per forest compartment (larvae/kilogram tree branches, retrieved from LBM database: A. Fischlin in prep.) and log-transformed time series of larval densities simulated by a: LBM-M8 model at the entire valley spatial grain, b: LBM-M9 model at the ‘site’ spatial grain, c: LBM-M11 model at a steady state with respect to spatial variance and d: LBM-M11 model with uniform calm wind conditions (flight occurring randomly, i.e. any wind effects ignored).

The results of linear regression at the spatial grain of the ‘site’ show a linear relationship between observed and modelled values, except for trough years (1, 8 and 9) where R^2 values are low due to zero values in the observations which can not be predicted by the model (Table 5.2). This suggests that the LBM-M9 model is actually capable of predicting the observed spatial pattern of larch bud moth larval densities. At the spatial grain of the forest compartment, R^2 values are very low and slopes close to zero across all comparisons (Table 5.3). This result suggests that the LBM-M11 model is not able to accurately predict the spatial pattern observed in larval densities at the forest compartment resolution.

The intercept values increase as larval densities increase, with the highest values at peak years and very small values for trough years.

Table 5.2

Linear regression results between modelled (LBM-M9) and observed larval densities at the 'site' spatial grain across space for each year of a single cycle

Cycle year	Regression equation	R-squared
1	$x = 0.17142 - 0.1157y$	0.0082
2	$x = -0.014 + 1.466y$	0.6783
3	$x = 0.03913 + 0.6953y$	0.3147
4	$x = 1.2795 + 0.4075y$	0.3591
5	$x = 42.7218 + 0.3204y$	0.2
6	$x = -22.464 + 1.523y$	0.1479
7	$x = 64.057 + 1.124y$	0.63
8	$x = 27.264 - 1.967y$	0.06882
9	$x = 3.2745 - 0.8120y$	0.0428

where x is observed larval density, and y is modelled larval density. Year 1 is a trough year and years 5 and 6 peak years.

Table 5.3

Linear regression results between modelled (LBM-M11) and observed larval densities at the forest compartment spatial grain across space for each year of a single cycle

Cycle year	Regression equation	R-squared
1	$x = 22.205 + 0.0316y$	0.0006
2	$x = 41.129 + 0.06428y$	0.0009
3	$x = 58.8813 - 0.1483y$	0.0013
4	$x = 50.458 - 0.0165y$	0.0003
5	$x = 99.157 - 1.027y$	0.006
6	$x = 55.267 - 0.063y$	0.0034
7	$x = 43.867 - 0.0091y$	0.0043
8	$x = 47.3624 - 0.591y$	0.0001
9	$x = 49.8715 - 0.4717y$	0.0011

where x is observed larval density, and y is modelled larval density. Year 1 is a trough year and years 5 and 6 peak years.

As we know that there is little difference between the overall predictive ability of the coarse resolution model and the fine resolution model, we are now interested in how well the spatial pattern at the forest compartment spatial grain is modelled: whether high and low values are correctly predicted as high or low values. Given the results of our MSE calculations we surmise that actual larval densities are not better predicted than by a coarser resolution model. One problem is that the observed data shows many instances of zero larch bud moth/kg tree branches, while the model does not predict zero values at cycle troughs (local population extinction).

Calculation of coincidences between the maps of observed and modelled (LBM-M11) larval densities over one cycle suggests that the LBM-M11 model is not capable of predicting spatial pattern well, with only one category predicted well in each year of a cycle (Table 5.4).

Table 5.4

Coincidence between observed and modelled larval density maps over one cycle (1958-1967)

Larval density (/kg branches)	1958	1959	1960	1961	1962	1963	1964	1965	1966
0-1	87.8	25.51	0	NA	NA	NA	2.33	0	69.1
1-10	0	77.32	65.57	6.95	0	NA	79.08	57.76	0
10-100	NA	NA	0	61.88	25.89	32.81	32.12	NA	NA
> 100	NA	NA	NA	33.75	60.5	64.52	NA	NA	NA

Numbers denote the percentage of cells in the observed map that were correctly categorised by the model for each of 4 categories of larval density

There is no pattern between the contagion values for observed maps and those for modelled (LBM-M11) maps, i.e. contagion indices for the observed density maps are neither consistently greater nor smaller than those for modelled density maps over time (Table 5.5). Very high contagion values occur in trough years (i.e. 8 and 9) because a majority of forest compartments have recordings of zero larvae per kilogram tree branches.

Table 5.5

Contagion value for modelled (with LBM-M11) and observed maps of larval densities for each year of an average cycle.

Year	Observed	Modelled
1	0.7966	0.7815
2	0.5126	0.5845
3	0.6184	0.6641
4	0.6166	0.4878
5	0.6047	0.6620
6	0.6054	0.6620
7	0.6123	0.5890
8	0.9430	0.6314
9	0.9632	0.4878

Larval densities were categorised as 0-1, 1-10, 10-100 and over 100 larvae per kilogram of tree branches

5.4 Discussion

Calculation of mean square error values between times series of observed larch bud moth densities at the forest compartment level and modelled larch bud moth densities at three different spatial grains revealed that, on average, a higher resolution model achieves a slightly greater accuracy in prediction. However, the improvement in accuracy is not significantly ($\alpha=0.05$) better than that of the coarser resolution models (Figure 5.5).

Results of linear regression reveal that the LBM-M9 model predicts spatial pattern at the ‘site’ spatial grain rather well (Table 5.2). However, low R^2 values and linear regression slopes close to zero at the forest compartment spatial grain (Table 5.3) suggest a poor relationship between the observed and the predicted values across space.

When we examine the time series produced by the model in comparison with the observed densities we find that in general the LBM-M11 model over estimates densities at cycle troughs (particularly with respect to zero value observations) and otherwise under-estimates densities. This under-estimation is also revealed through examination of the regression equations (Table 5.3). These inaccuracies of the modelled densities also bias our correlation and regression analyses, making it unlikely that significant relationships could be detected.

Calculating the coincidence between two maps of larval densities categorised into 4 categories showed that in any given year more than 50 % of the observed values were predicted to be in the correct category for the most commonly occurring category (Table 5.4). However, other categories were poorly predicted. This result suggests again that the LBM-M11 model does not predict observed spatial pattern well.

However, the high spatial resolution model, LBM-M11, reproduced some spatial patterns that by eye can be seen to match some of the patterns observed from field data (Figures 5.3 and 5.4). Visual examination of maps of observed larval densities across the Upper Engadine valley (Figures 5.3a and 5.4a) and calculation of contagion indices reveals that larval densities are not heterogeneous across space. However, considerable clumping of values occurs (Table 5.5), and can be seen to correspond well to the extent of the ‘sites’ defined in LBM-M9 (Figures 5.3a and 5.4a), particularly during peak years (Figure 5.4a). Then we find clumping of compartments with similar larval densities to match closely to the site definitions. While a uniform pattern of densities across sites or across the Upper Engadine valley as predicted by LBM-M8 is unrealistic and obviously not applicable for the purposes of determining spatial pattern, the pattern predicted by LBM-M9 fits the observed data well (Table 5.2, Figures 5.3a and 5.4a).

As the local cyclic dynamics for each forest compartment depend on the mechanism driving the model, discrepancies between observed and modelled densities could be caused by an inappropriate choice of local dynamics model. In this study we used the food quality hypothesis model to describe local dynamics (Fischlin 1982). Turchin et al. (2003) have found that a food-quality hypothesis based model explains the observed larch bud moth cycles less well than a model based on the parasitoid hypothesis or a tri-trophic model

combining interaction between the larch bud moth and both parasitoids and the host larch. While the food quality hypothesis fits our data well at the grain and extent of the Upper Engadine valley treated as a single spatial unit (LBM-M8), this may be the case because an averaging out of the local heterogeneity improves the predictability of the patterns (Wiens 1989).

The inability of the LBM-M11 model to predict spatial variability at forest compartment spatial grain also suggests that this migration model is not particularly suitable at that resolution. A different migration model may be needed in order to predict spatial patterns given at that or similar spatial resolutions. In addition, it is also possible that larch bud moth populations should no longer be considered as distinct populations which consist of individuals with common properties, in contrast to other populations distinguished at that level. Instead the animals living within any given forest compartment may merely form an arbitrarily designated group of individuals, which all share characteristics with the individuals from neighbouring groups, thus not forming a true population.

Visual analysis of the maps of observed larval densities (Figure 5.3 and 5.4) and the contagion indices (Table 5.5) show considerable clumping across several forest compartments, suggesting that in many cases larch bud moth populations should not be considered to be separate from each other at the forest compartment level. Since forest compartments are not defined only by ecological criteria, let alone criteria that govern the population dynamics of larch bud moth, this result appears plausible.

The variance of any given variable changes in measurement scale. Moreover, the manner in which it changes will depend on whether the grain or extent is altered (Wiens 1989). In estimating larch bud moth densities from tree based samples (Auer 1969), the extent of the sample size is effectively reduced by averaging measurements per forest compartment as compared to a measurement for the entire Engadine valley. This effect actually causes a change in measurement extent. With fewer observations per sample extent, our values for each forest compartment have a higher probability of differing from the actual density level than those averaged from observations over the entire Upper Engadine valley, increasing the uncertainty in our modelled results. In addition, the fewer observations per spatial extent also means greater likelihood of zero

density values in low density years, although the larch bud moth is not always likely to actually be totally absent from any given area. This makes it difficult to compare observations with modelled predictions.

Due to the relatively small numbers of trees sampled within each forest compartment sample, 95% confidence intervals around the mean observed larval density values are often larger than the difference between modelled and observed values. Some examples of 95% confidence intervals are given in Table 5.6. This suggests that in many cases modelled values may not deviate as far from the actual values as our MSE results suggest, as the observation data is also uncertain due to very small sample sizes.

Table 5.6

95% confidence intervals for observed mean larval densities per forest compartment

Compartment I.D.	Sample size	Year	Larval density (/kg tree branches)	95% confidence interval
167	2	1960	1.3542	±0.6125
292	2	1960	1.3334	±2.6133
342	13	1963	117.675	±43.857
132	2	1963	375.261	±257.036

5.5 Conclusion

Our results show that while a higher resolution model of larch bud moth dynamics across the Alpine Arc predict larch bud moth densities slightly but not significantly better than a coarse spatial resolution model, it is not capable of reproducing well a spatial pattern similar to that observed.

We find that the inaccuracies in the model predictions are likely due to joint effects of increased variance in the observed data, due to smaller sample sizes per extent, and the inappropriateness of defining distinct larch bud moth populations and thus use of the spatial dynamics flight sub model at a higher resolution. These effects increase the uncertainty in the input data as well as the observational data.

In order to determine spatial patterns of larch bud moth, our results suggest that a coarser spatial grain such as that of the ‘site’ ($\sim 3.7\text{km}^2$) appears to be optimum with minimum uncertainty given the available data and the characteristics of the modelled processes. Incorporating greater spatial detail into existing models did not produce spurious results or unexplainable behaviour, but also did not enhance our ability to predict larch bud moth dynamics and introduced uncertainties.

Further comparisons using a similar method but incorporating a parasitoid hypothesis as the local dynamics sub-model and/or a different migration model would likely glean more insights into the causal mechanisms of larch bud moth dynamics and help distinguish the parasitoid hypothesis and food quality hypothesis as appropriate candidates.

5.6 Acknowledgments

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6 DISCUSSION

One of the key advantages of this study is the use of larval census data at a variety of spatial extents and resolutions to both quantify spatio-temporal patterns of larch bud moth population dynamics and compare the predictive ability of models at different spatial grains. Recently published studies on larch bud moth, which have modelled large scale synchrony and hypothesised on causal mechanisms (e.g. Bjornstad et al., 2002; Peltonen et al., 2002; Johnson et al., 2004) have based their conclusions on the use of defoliation map data. Degree of defoliation was and remains of prime interest in the analysis of the larch bud moth system, particularly in the past when larch bud moth was considered a pest or when tree mortality occurs, and is an excellent indicator of larval population densities. However, degree of defoliation has only been recorded in a qualitative manner, where three categories of defoliation were defined (light:1-33%, medium:34-66% and heavy:67-100%) and a variety of foresters recorded defoliation through on-ground assessment (Baltensweiler & Rubli, 1999). Although the assessment process was carefully coordinated, any such field method will likely result in subjectively biased measurements. The larval census methods however, record actual numbers of larvae found per kilogram of sampled tree branches (Auer, 1969, 1978; Baltensweiler & Rubli, 1999) and thus provide little opportunity for subjective bias.

6.1 The role of IPODLAS

This research formed part of the project ‘Knowledge Based Dynamic Landscape Analysis and Simulation for Alpine Environments’, which developed methodologies and tools for the integration of spatial (GIS and VISu) and temporal (Systems Modelling) modelling systems, resulting in an integrated system/tool: IPODLAS (Interactive, Process Orientated, Dynamic Landscape Analysis and Simulation). The use of the spatio-temporal dynamics of the larch bud moth as a case study for the development of IPODLAS, also provided the framework for integrated use of the GIS and visualisation systems with a temporal modelling system. This integration made spatio-temporal analysis and modelling of the larch bud moth system possible and allowed for conclusions to

be reached regarding the spatio-temporal dynamics of larch bud moth and the influence of migration, which would otherwise have not been possible. The four-dimensional visualisation of larch bud moth migration and resultant defoliation within the Upper Engadine valley provided through the IPODLAS system (Wu et al., submitted), allowed simulation results to be seen in an intuitive manner, which also highlighted certain results and made spatial-temporal patterns more obvious. This in turn led to a better understanding of the system and pointed to issues relating to the influence of topography of larch bud moth dispersal that could then be more thoroughly investigated via quantitative methods. The visualisation also allowed for easier explanation of simulation results to others.

6.2 Spatio-temporal dynamics of larch bud moth at differing scales

Cross-spectral and cross-correlation analysis based on this larval census data allowed us to demonstrate that larch bud moth does exhibit travelling waves from west to east across the Alpine arc (Tables 3.1 and 3.2) as hypothesised by Bjornstad (2002). Our results suggest that the epicentre hypothesis as proposed by Johnson et al. (2004) is plausible in the case of one epicentre only at the western end of the Alps, and not two epicentres, as he suggested. However a travelling waves is more credible.

We were also able to confirm the previously hypothesised synchronous fluctuation of larch bud moth populations across the Upper Engadine valley (Fischlin & Baltensweiler, 1979; Fischlin, 1982; Baltensweiler & Rubli, 1999). However, our analysis revealed some discrepancies in synchrony at the valley scale. Certain sites trailed or lead most other sites despite having similar characteristics (such as forest type and aspect) to their neighbouring sites. This phenomenon could be related to local scale dispersal patterns as influenced by local-scale wind patterns.

6.3 Influence of data resolution of modelling larch bud moth dynamics

The results of the time series analysis could be compared with a modelling analysis of larch bud moth dynamics within the Upper Engadine valley, modelling migration as affected by orography at a high spatial resolution. Thus

we were able to demonstrate that orography may have a more significant effect on larch bud moth migration than has previously been considered. The discrepancies in synchrony we observed through time series analysis could be explained by the influence of orography on local wind patterns on which migration is dependant, causing some cyclic populations to lag behind others within the extent of the Upper Engadine valley. The results of these two studies also suggest that dispersal is likely the dominant process explaining synchrony and changes in synchrony at the valley scale.

While the consideration of geographical features at a higher spatial grain proved important for migration processes, and gave us more accurate predictions of larch bud moth population dynamics, modelling the entire system at the higher spatial grain of the forest compartment (~25 ha) did not allow us to significantly better predict temporal patterns of larch bud moth dynamics, than models at coarser grain - the 'site' grain (~3.7km²), or the entire Engadine valley, (Figure 5.5). The higher resolution model was also unable to predict the spatial pattern at the forest compartment spatial grain (Table 5.3 and 5.4).

As the number of important variables in ecological modelling studies tend to decrease at coarse scales (Meentemeyer & Box, 1987), conducting a modelling analysis at a higher spatial grain requires significant time and effort in determining values of input parameters at the higher spatial grain and an increase in cost in terms of simulation time, as well as the introduction of uncertainties. Thus knowledge of an optimum spatial grain for modelling forest insect systems such as the larch bud moth is of importance and interest.

Observed and modelled data from the spatial resolution of the forest compartment shows significant clumping beyond the spatial grain of the forest compartment (Figures 5.3 and 5.4). This suggests that larch bud moth populations are in fact not distinct populations at the forest compartment grain. In fact, clumping often occurs over areas similar to the 'site' areas. Forest compartments are human divisions based on forest management practices and not natural boundaries, unlike the 'sites', which were devised based on ecological dividing criteria (Fischlin, 1982). Therefore, it also makes more ecological sense that populations should be considered distinct at the 'site' spatial grain but not at the forest compartment spatial grain.

Our results suggest that models at the site spatial grain provide the optimum prediction of spatial and temporal patterns of larch bud moth dynamics with minimal uncertainty from the models available. However, it is also plausible that a spatial grain in-between the site and the forest compartment maybe be more appropriate. If regions for local dynamics could be redefined based on ecological criteria relevant to the larch bud moth at a finer spatial grain than that of the site and then modelled, we may achieve better prediction of spatio-temporal larch bud moth dynamics. However, making observation data available for these new regions would be an arduous and time consuming task, thus validation of the model would be difficult.

Geographical Information Systems typically define spatial grain based on pixel size or grid spacing of digital elevation models, which are often 25m or 50m grids (Turner et al., 2001). For the study of many ecological systems, such as larch bud moth population dynamics, this spatial grain is well beyond the level where we can obtain field data and therefore understand the system (Levin, 1992; Turner et al., 2001). Indeed, as we found in this research, modelling population dynamics at such a fine resolution often no longer makes sense, and results are difficult to validate due to the lack of availability of sufficient field data. However, when combining temporal and spatial modelling systems, as required for development of IPODLAS, such problems must be considered and thus optimum spatial resolution determined.

Our results suggested that the LBM-M9 models at the ‘site’ spatial grain provide the optimum results when considering prediction of both spatial and temporal patterns. However, coupling this model with a migration model considering orography at a higher resolution results in an even better correlation with observed time series (Table 4.2). This suggests that while modelling the entire system at a higher spatial grain does not provide a significant improvement in predictive ability, the incorporation of some parameters at a higher spatial grain to the migration sub model, particular those relating to orography, would be of value. These findings have implications for the study of other migratory insect systems particularly those in mountainous areas where wind systems and thus migration are likely also influenced by orography at a fine resolution.

6.4 References

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7 CONCLUSIONS

The main aims of this research were to I) to determine the spatio-temporal dynamics of larch bud moth populations at differing scales and II) To investigate the influence of data resolution on modelling larch bud moth dynamics and determine an optimum resolution for modelling larch bud moth dynamics in the Upper Engadine valley allowing for a balance between model complexity, output accuracy, minimal uncertainty and simulation time.

7.1 Spatio-temporal dynamics of larch bud moth at differing scales

Through time series analysis we were able to confirm that patterns of synchrony at the valley scale and travelling waves at the Alpine arc scale in population cycles of larch bud moth are present but they are not consistent, particularly not across all sites in the Upper Engadine valley.

At the Alpine arc scale waves of larch bud moth travel from west to east across the Alpine arc. Wind-driven dispersal mechanisms in conjunction with a gradient in habitat quality (possibly habitat connectivity) provide a feasible explanation for this phenomenon, whereas the Moran effect does not. Time series analysis suggests that larch bud moth are unlikely to spread from epicentres within the Alps, unless only one epicentre exists at the western end of the Alps.

At the scale of the Upper Engadine valley populations of larch bud moth are in close synchrony with one another with the exception of populations in areas to which migration is restricted due to the influence of orography on wind patterns. This finding also confirms the hypothesis that migration is driving synchrony at the valley extent rather than the Moran effect.

7.2 Influence of data resolution of modelling larch bud moth dynamics

Modelling larch bud moth population dynamics and migration processes at a variety of spatial grains within the same spatial extent with under the same process models revealed that for the larch bud moth, optimum modelling spatial

grain with minimum uncertainty is that of the 'site' with an average area of 3.7km². Increasing the detail, or resolution, of input data and modelling the whole system at the 25 hectare spatial grain does not provide an improvement in the ability to predict spatial or temporal patterns of larch bud moth dynamics, and introduces uncertainty. However, dispersal appears to be more sensitive to wind conditions as influenced by orography and topography at a higher spatial resolution than has been assumed previously. Observed larval census data shows significant clumping at extents similar to those of the 'sites'. Thus, while larch bud moth populations should only be considered distinct at the 'site' level and therefore local dynamics modelled at this spatial grain, modelling of migration processes between the sites taking into account orography at a higher resolution would result in better predictive ability of the model.

Comparison of our time series analysis and modelling results revealed that migration is an important causal mechanism for observed patterns of synchrony at the valley scale.

APPENDIX

I Mathematical model LBM-M8

The condensed mathematical formulation of the model is as follows:

$$r_{t+1} = g_{recr}(def, r_t) * r_t;$$

$$e_{t+1} = (1.0 - gm_{starv}(p1 * r_t + p2, p3 * r_t * e_t + p4 * e_t)) * (p5 * r_t^3 + p6 * r_t^2 + p7 * r_k + p8) * e_t;$$

$$def = (1.0 - gm_{starv}(p1 * r_t + p2, p3 * r_t * e_t + p4 * e_t)) * \frac{p3 * r_t * e_t + p4 * e_t}{p1 * r_t + p2};$$

where:

r = raw fibre content, % fresh weight

e = larch bud moth eggs

def = defoliation %

$$g_{mstarv}(p1 * r_t + p2, p3 * r_t * e_t + p4 * e_t) = \begin{cases} 0 & \text{a} \\ \exp \frac{p1 * r_t + p2}{p3 * r_t * e_t + p4 * e_t} & \text{b} \end{cases}$$

$$g_{recr}(def, r_t) = \begin{cases} 1 & \text{c} \\ p9/r_t & \text{d} \\ 1 - (p10 + abs((p11 - r_t)/(r_t - p9)))/r_t & \text{e} \\ 1 + (def - p12) * (p11 - r_t)/(p13 - p12)/r_t & \text{f} \\ p11/r_t & \text{g} \end{cases}$$

terms :

$$a \quad p3 * r_t * e_t + p4 * e_t = 0$$

$$b \quad p3 * r_t * e_t + p4 * e_t > 0$$

$$c \quad (def < p12) \wedge (r_t = p9)$$

$$d \quad (def < p12) \wedge (r_t > p9) \wedge (z * r_t > r_t - p9)$$

$$e \quad (def < p12) \wedge (r_t > p9) \wedge (z * r_t \leq r_t - p9)$$

$$f \quad (def \geq p12) \wedge (def < p13)$$

$$g \quad (def > p12) \wedge (def \geq p13)$$

$$\text{where: } z * r_t = p10 + \text{abs}((p11 - r_t) / (r_t - p9))$$

$$p1 = c1;$$

$$p2 = c5;$$

$$p3 = -c2 * c6 * (1 - c1);$$

$$p4 = c6 * (1 - c1) * (1 - c3);$$

$$p5 = c2 * c7 * c9 * c10 * (1 - c1);$$

$$p6 = c9 * (1 - c1) * (c2 * c7 * c11 - c10 * (c2 * (1 - c8) + c7 * (1 - c3)));$$

$$p7 = c9 * (1 - c1) * (c10 * (1 - c3) * (1 - c8) - c11 * (c2 * (1 - c8) + c7 * (1 - c3)));$$

$$p8 = c9 * c11 * (1 - c1) * (1 - c3) * (1 - c8);$$

$c1$ = egg winter mortality

$c2$ = slope of small larve mortality vs. raw fibre

$c3$ = y - intercept of small larvae mortality vs. raw fibre

$c4$ = slope of needle biomass vs. raw fibre

$c5$ = y - intercept of needle biomass vs. raw fibre

$c6$ = food demand of large larvae, kg/larvae

$c7$ = slope of large larvae mortality vs. raw fibre

$c8$ = y - intercept of large larvae mortality vs. raw fibre

$c9$ = sex ratio

c_{10} = slope of fecundity vs. raw fibre

c_{11} = y - intercept of fecundity vs, raw fibre

c_{12} = minimum raw fibre, %

c_{13} = minimum decrement of raw fibre, %

c_{14} = maximum raw fibre, %

c_{15} = defoliation threshold

c_{16} = defoliation threshold of maximum stress

c_{17} = branches per tree, kg

II Mathematical model migration sub model LBM-M9

The equation system for the migration model is as follows:

IF $d(k) < \delta(\sigma)$ THEN

$$l_i = l_i + fec_{\sigma} \cdot \eta(\sigma \rightarrow i) \cdot f(k);$$

$\forall j_A = N \dots NW$

$$f_A(k+1) = \phi_A(i \rightarrow j_A) \cdot \eta(\sigma \rightarrow i) \cdot f(k);$$

$$d_A(k+1) = d(k) + \theta_A(i \rightarrow j_A);$$

$f_A(k+1) > 0 \Rightarrow$ RECURSION continues if $\exists j_A$

$\forall j_B = N \dots NW$

$$f_B(k+1) = \phi_B(i \rightarrow j_B) \cdot \eta(\sigma \rightarrow i) \cdot f(k);$$

$$d_B(k+1) = d(k) + \theta_B(i \rightarrow j_B);$$

$f_B(k+1) > 0 \Rightarrow$ RECURSION continues if $\exists j_B$

ELSIF $d(k) \geq \delta(\sigma)$ THEN

$$l_i = l_i + fec_{\sigma} \cdot f(k);$$

$f_A(k+1) = f_B(k+1) = 0 \Rightarrow$ RECURSION ends

END IF

where:

i = current site

j = target site

σ = original site

k = recursion level

l_i = eggs laid in site i

f_A = females leaving the site in sub - direction A

d = distance flown

fec = fecundity

$$\phi A(i \rightarrow jA) = \frac{c12_{i \rightarrow jA}}{c12_{i \rightarrow jA} + c12_{i \rightarrow jB}} w;$$

$$\phi B(i \rightarrow jB) = \frac{c12_{i \rightarrow jB}}{c12_{i \rightarrow jA} + c12_{i \rightarrow jB}} w;$$

$$\theta A(i \rightarrow jA) = c15_{i \rightarrow jA} \frac{v}{w};$$

$$\theta B(i \rightarrow jB) = c15_{i \rightarrow jB} \frac{v}{w};$$

$$\delta(\sigma) = \frac{1}{c1 + c2 * def_{\sigma}};$$

$$\eta(\sigma \rightarrow i) = 1 - \Omega(\sigma \rightarrow i) \cdot d(k) + c6_i;$$

$$w = \left(\frac{1}{8} c5(1 - c6_i) + (1 - c5) \left(\frac{1}{8} c7_i + c10_{i \rightarrow j} c8_i + c11_{i \rightarrow m} c9_i\right)\right);$$

$$v = \left(\frac{1}{8} (c5(1 - c6_i) + c7_i(1 - c5)) + c13 c10_{i \rightarrow j} c8_i(1 - c5) + c17 c11_{im} c9_i(1 - c5)\right);$$

$$\Omega(\sigma \rightarrow i) = c3 + c4 * def_i + (c1 + c2 * def_{\sigma})(1 - c3 - c4 * def_i);$$

m = direction from source site to target site

c1 = minimal number of exhausted females per flown kilometre

c2 = increase in exhausted females from defoliation

c3 = y-intercept of maximum attractivity for egg deposition

c4 = regression coefficient of decrease in attractivity by defoliation

c5 = fraction of females not transported by wind

c6i = frequency of turbulence in site i

c7i = frequency of still wind (0-0.5m/s) in site i

c8i = frequency of calm wind (0.5-2.8m/s) in site i

-
- $c9_i$ = frequency of strong winds in site i
- $c10_{i \rightarrow j}$ = frequency of calm wind in site i in direction j
- $c11_{i \rightarrow m}$ = frequency of strong wind in site i in direction j
- $c12_{i \rightarrow jA}$ = Area of site i in direction j in sub-sectors A
- $c12_{i \rightarrow jB}$ = Area of site i in direction j in sub-sectors B
- $c13$ = Proportion of zigzag flight distance of air distance for wind speed of 1.93m/s
- $c14$ = fraction of air speed from overall speed by flight in strong winds
- $c15_{i \rightarrow jA}$ = Air distance from site i to site j in sub-directions A
- $c15_{i \rightarrow jB}$ = Air distance from site i to site j in sub-directions B

III Modula-2 code LBM-M11

LBMMASTER

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MODULE LBM;

(*
  Module      LBM  (Larch Bud Moth)

  Purpose     Master module of the Model Defintion Program (MDP)
              of the larch bud moth system according to Fischlin
              (1982) including local as well as spatial
              dynamics.

              This implementation simulates the system
              behavior for the Upper Engadine Valley at the
              forest compartment (abteilung) resolution - ie a
              local dynamics model running for each abteilung
              and migration modelled between these forest
              compartments.

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              Systems: Der subalpine Lärchen-Arvenwald und der
              graue Lärchenwickler Zeiraphera diniana Gn. (Lep.,
              Tortricidae). Diss. ETH Nr 6977. Swiss Federal
              Institute of Technology Zürich, Switzerland,
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              analysis of the larch bud moth system. Part I: the
              larch-larch bud moth relationship. Mitt. Schweiz.
              Ent. Ges., 52: 273-289.

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              of migration for the population dynamics of the
              larch bud moth, Zeiraphera diniana Gn. (Lep.
              Tortricidae).
              Mitt. Schweiz. Ent. Ges., 52: 259-271.

  Implementation and Revisions:
  =====

  Author   Date       Description of change
  -----   ----       -
  af       21/1/89    First implementation (DM 1.0,
                    ModelWorks ≈1.0, MacMETH 2.x)
  af       03/04/90  Update for newest DM, MW etc.
                    MacMETH 2.6+, DM 2.0, ModelWorks 1.3a
  af       04/04/90  Adding a menu for model management
  af       02/11/91  LBMIdentify added
  af       03/11/91  Fixing of model activation scheme
  af       19/05/97  Uses now StructModAux
  af       17/05/99  Lotka-Volterra Controller added
  af       05/06/02  Aux modules (SubmodelSet, IdentParMod, and

```

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                DrawParSpace now in AuxLib (RAMSES >=
                3.0.2fc12)
af    09/06/02    SetMyGlobPreferences supports SASystem
brp   24/03/04    adjusted for use in LBM M9
brp   09/09/05    adjusted for use in LBM M11
*)

(* DM core *)
FROM DMMessages IMPORT Inform;
FROM DMMenus IMPORT InstallCommand, RemoveCommand, Command,
  AccessStatus, Marking, InstallAliasChar, InstallMenu,
  Separator, InstallSeparator;

(* MW *)
FROM SimBase IMPORT SetDefltGlobSimPars, SetGlobSimPars,
  MWWindowArrangement, SetDefltProjDescrs, SetSimTime,
  SetMonInterval,
  InstallClientMonitoring;
FROM SimMaster IMPORT RunSimEnvironment, InstallDefSimEnv;
FROM SimGraphUtils IMPORT PlaceGraphOnSuperScreen;

(* Aux *)
FROM StructModAux IMPORT customM, chooseCmd, InstallCustomMenu,
  ChooseModel, SetSimEnv, GetSysConfig, BooleanFct,
  AssignSubModel, InstallMyGlobPreferences;
FROM SubmodelSet IMPORT StructModelSet, SetSubmodelName,
  LearnAboutOldSysConfiguration, InformAboutNewSysConfiguration;
FROM IdentParMod IMPORT identifyParModDescr,
  ActivateIdentifyParMod, DeactivateIdentifyParMod,
  IdentifyParModIsActive;

(* LBM *)
FROM LBMObsLbm IMPORT lbmObsUEDescr, lbmObsSADescr,
  UseObservationsSA, ObservationsSAIsInUse, UnuseObservationsSA,
  UseObservationsUE, ObservationsUEIsInUse, UnuseObservationsUE,
  kMin, kMax, kMinSA, kMaxSA;

FROM LBModel IMPORT larchLbmModDescr,
  UseLarchLBMod, LarchLBModIsInUse, UnuseLarchLBMod,
  lbmFlightDescr,
  UseLBMFlight, LBMFlightIsInUse, UnuseLBMFlight;

VAR
  obsUE, obsSA, model, flightMod: INTEGER;

  remAllCmd, helpCmd: Command;

PROCEDURE SetMyGlobPreferences;
  CONST dummy = 0.1;
  wtitle = TRUE; wremark = TRUE; autofooter = TRUE;
  recM = TRUE; recSV = TRUE; recP = TRUE; recMV = TRUE; recG =
  TRUE;
BEGIN
  SetDefltGlobSimPars(1949.0, 1977.0, 0.1, 0.1, 1.0, 1.0);
  IF ObservationsSAIsInUse() THEN
    SetDefltGlobSimPars(FLOAT(kMinSA), FLOAT(kMaxSA), dummy,

```

```
dummy, 1.0, 1.0);
END(*IF*);
SetDeflProjDescrs("Larch Bud Moth at abteilung resolution in
the Upper Engadine","LBM M11", "brp ETHZ/Sept 2005",
wtitle,wremark,autofooter, recM, recSV, recP, recMV, recG);
PlaceGraphOnSuperScreen(tiled);
END SetMyGlobPreferences;

PROCEDURE ConfigureSystem;
VAR sms: StructModelSet; i: INTEGER;
BEGIN (* ConfigureSystem *)
  GetSysConfig(sms);
  LearnAboutOldSysConfiguration(sms);
  ChooseModel;
  GetSysConfig(sms);
  InformAboutNewSysConfiguration(sms);
END ConfigureSystem;

PROCEDURE GiveHelp;
BEGIN (* GiveHelp *)
  Inform("Sorry, no help on this system available","","")
END GiveHelp;

PROCEDURE AssignSubmodel(VAR which: INTEGER; descr: ARRAY OF
CHAR;
act,deact: PROC; isact: BooleanFct);
BEGIN (* AssignSubmodel *)
  AssignSubModel(which, descr, act, deact, isact);
  SetSubmodelName(which, descr);
END AssignSubmodel;

PROCEDURE RemoveAllMods;
BEGIN
  UnuseObservationsUE;
  UnuseObservationsSA;
  UnuseLarchLBMod;
  UnuseLBMFlight;
END RemoveAllMods;

PROCEDURE SetupSimEnvironment;
CONST configureAlwaysAtBegin = FALSE;
VAR sms: StructModelSet;
PROCEDURE InstallLBMConfigMenu;
BEGIN (* InstallLBMConfigMenu *)
  InstallMenu(customM, "Models", enabled);
  RemoveCommand(customM,chooseCmd);
  InstallCommand(customM,chooseCmd,"Activation...",
ConfigureSystem, enabled, unchecked);
  InstallAliasChar(customM,chooseCmd,"L");
  InstallCommand(customM, remAllCmd,"Unload all",
RemoveAllMods,enabled, unchecked);
  InstallAliasChar(customM,remAllCmd,"U");
```

```
    InstallSeparator(customM,line);
    InstallCommand(customM,helpCmd, "On the system...",
                  GiveHelp, enabled,unchecked);
END InstallLBMConfigMenu;

BEGIN
  InstallLBMConfigMenu;
  (* default configuration: *)
  sms := {obsUE,model,flightMod}; SetSimEnv(sms);
  IF configureAlwaysAtBegin THEN
    InstallDefSimEnv(ConfigureSystem) END(*IF*);
END SetupSimEnvironment;

BEGIN
  InstallMyGlobPreferences(SetMyGlobPreferences);
  AssignSubmodel(obsUE,lbmObsUEDescr,
                UseObservationsUE, UnuseObservationsUE,
                ObservationsUEIsInUse);
  AssignSubmodel(obsSA,lbmObsSADescr,
                UseObservationsSA, UnuseObservationsSA,
                ObservationsSAIsInUse);
  AssignSubmodel(model,larchLbmModDescr,
                UseLarchLBMod, UnuseLarchLBMod,
                LarchLBModIsInUse);
  AssignSubmodel(flightMod,lbmFlightDescr,
                UseLBMFlight, UnuseLBMFlight,
                LBMFlightIsInUse);
  RunSimEnvironment( SetupSimEnvironment );
END LBM.
```

LBMMODEL

```
DEFINITION MODULE LBMMODEL;
```

```
(*****
```

```
Module LBMMODEL      (Version 2.0)
```

```
Copyright (c) 2005 by Andreas Fischlin  
and Swiss Federal Institute of Technology Zurich ETHZ
```

```
Purpose      Simulates Larch Bud Moth, Zeiraphera diniana Gn.  
            (Lep., Tortricidae), population dynamics for the  
            Upper Engadine valley from 1949 till 2002. The  
            model is from Fischlin & Baltensweiler (1979)  
            respectively Fischlin (1982) and models local as  
            well as spatial population dynamics according to  
            Fischlin (1982), but for forest compartments  
            rather than the 20 'sites'. Local dynamics model  
            the larch - larch bud moth relationship (food  
            quality hypothesis).
```

```
Remark     The model is implemented as a ModelWorks model to  
            be simulated and compared with observations  
            during a RAMSES session (Fischlin, 1991).
```

```
References
```

```
Fischlin, A. & Baltensweiler, W., 1979. Systems analysis  
of the larch bud moth system. Part I: the larch-larch  
bud moth relationship. Mitt. Schweiz. Ent. Ges.,  
52: 273-289.
```

```
Fischlin, A., 1982. Analyse eines Wald-Insekten-Systems:  
Der subalpine Lärchen-Arvenwald und der graue  
Lärchenwickler Zeiraphera diniana Gn. (Lep.,  
Tortricidae). Diss. ETH No. 6977, Swiss Federal  
Institute of Technology: Zürich,  
Switzerland, pp. 294.
```

```
Fischlin, A., 1991. Interactive modeling and simulation  
Of environmental systems on workstations. In: Möller,  
D.P.F. (ed.), Analysis of Dynamic Systems in Medicine,  
Biology, and Ecology. Springer, Berlin a.o., pp. 131-  
145.
```

```
Programming
```

- o Design
Andreas Fischlin 08/02/2005
- o Implementation
Bronwyn Price 13/09/2005

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 <http://www.sysecol.ethz.ch/SysEcol>

Last revision of definition: 14/11/2005 BRP

*****)

CONST

larchLbmModDescr = "Larch - Larch Bud Moth Model (forest
 compartment spatial grain)";
 lbmFlightDescr = "Larch Bud Moth Flight with Upper Engadine
 valley model";

PROCEDURE UseLarchLBMod;
 PROCEDURE LarchLBModIsInUse(): BOOLEAN;
 PROCEDURE UnuseLarchLBMod;
 PROCEDURE UseLBMFlight;
 PROCEDURE LBMFlightIsInUse(): BOOLEAN;
 PROCEDURE UnuseLBMFlight;

END LBModel.

IMPLEMENTATION MODULE LBModel;

(*

Implementation and Revisions:

=====

Author	Date	Description of change
-----	----	-----
AF	08/02/2005	First implementation
BRP	13/09/2005	Adapted for use in M11 Addition of LBM Flight as a submodel Describing migration between forest compartments (abteilungen). Addition of procedures for Initialisation, Model Objects, Dynamics, Activation ,Deactivation and Use.

*)

(* DM core *)

FROM DMWindIO IMPORT WriteString, WriteLn,
 SetWindowFont, FontStyle, WindowFont, GetPen,
 DisplayPredefinedPicture,
 SetPen, MaxCol, CellWidth;
 FROM DMWindows IMPORT RectArea, UpdateAllWindows;


```

(* DM optional *)
FROM DMMathLib IMPORT Exp, Ln, Entier;

(* MW *)
FROM SimBase IMPORT Model, DeclM, IntegrationMethod, DeclSV,
  Parameter, StateVar, Derivative, NewState, AuxVar,
  StashFiling, Tabulation, Graphing, DeclMV, DeclP, RTCType,
  SetDefltCurveAttrForMV, Stain, LineStyle,
  StashFileName, SetSimTime, SetMonInterval,
  SetProjDescrs, GetMV, SetMV, RemoveM, MDeclared,
  notDeclaredModel,
  NoInput, NoOutput, NoTerminate;
FROM SimMaster IMPORT
  SimRun, CurrentTime, InstallExperiment;

(* LBM *)
FROM LBMValley IMPORT
  SiteIndex, UE, maxSiteIndex,
  Site, DoForAllSites,
  Valley, UpperEngadine, PrepareValley, ValleyExists;
FROM LBMLifeCycle IMPORT
  InitializeLBMLifeCycle, ComputeLifeCycle, EggsFromDensity,
  ActivateLBMLifeCycle, IsLBMLifeCycleActive,
  DeactivateLBMLifeCycle;
FROM LBMObsLbm IMPORT yLL, yUL,
  yMeanDash, YMeanDash, kMin, kMax, kMinSA, kMaxSA,
  AssignDataUE, AssignDataSA;
FROM LBMFlyPars IMPORT fstSite;
FROM LBMFlight IMPORT InitialiseLBMFlight,
  DistributeFemaleMoths,
  ActivateLBMFlight, IsLBMFlightActive, DeactivateLBMFlight;

PROCEDURE AboutLBMod;
  CONST mothID = 1001; heliID = 1008; rawFibID = 1009; picH =
    133; picW = 247; VAR r: RectArea;
  PROCEDURE AllowForColorDrawing; BEGIN UpdateAllWindows END
    AllowForColorDrawing; (* Fixes a ModelWorks 3 problem *)
  PROCEDURE DrawToTheRight (picID,picW,picH: INTEGER; or: REAL);
    VAR xs,ys,offset: INTEGER;
  BEGIN (* DrawToTheRight *)
    GetPen(xs,ys);
    WriteString(" ");
    GetPen(r.x,r.y);
    offset := MaxCol(); offset := offset*CellWidth();
    offset := TRUNC(or*FLOAT(offset));
    INC(r.x,offset); r.w := picW; r.h := picH; DEC(r.y,r.h);
    AllowForColorDrawing;
    DisplayPredefinedPicture("",picID,r);
    SetPen(xs,ys);
  END DrawToTheRight;
BEGIN
  SetWindowFont(Monaco, 9, FontStyle{});
  WriteString(""); WriteLn;
  SetWindowFont(Chicago, 12, FontStyle{});

```

```

WriteString("Model of the Larch - Larch Bud Moth Relationship
");WriteLn;
WriteString("coupled with a flight model for migration between
Forest compartments (abteilungen) "); WriteLn;
WriteString("Local dynamics modelled under food quality
Hypothesis according to Fischlin (1982)"); WriteLn;
SetWindowFont(Monaco, 9, FontStyle{});
WriteString(""); WriteLn;
DrawToTheRight(mothID,picW,picH,0.6);
WriteString("Purpose Simulates Larch Bud Moth, Zeiraphera
diniana Gn. "); WriteLn;
WriteString("(Lep., Tortricidae), population dynamics for the
Upper"); WriteLn;
WriteString("Engadine valley from 1949 till the present. The
model"); WriteLn;
WriteString("is from Fischlin & Baltensweiler (1979)
respectively"); WriteLn;
WriteString("Fischlin (1982) and models local population
dynamics"); WriteLn;
WriteString("according to the larch - larch bud moth
relationship"); WriteLn;
WriteString("(food quality hypothesis). Also simulated are
Spatial dynamics:"); WriteLn;
WriteString("LBM flight according to equations in Fischlin
(1982)"); WriteLn;
WriteString("between forest compartments (Abteilungen)");
WriteLn;
WriteString(""); WriteLn;
WriteString("Remark The model is implemented as a ModelWorks
model to"); WriteLn;
WriteString("be simulated and compared with observations ");
WriteLn;
WriteString("during a RAMSES session (Fischlin, 1991).");
WriteLn;
DrawToTheRight(rawFibID,picW,picH,0.6);
WriteString(""); WriteLn;
WriteString("References"); WriteLn;
WriteString(" "); WriteLn;
WriteString("Fischlin, A. & Baltensweiler, W., 1979. Systems
analysis of ");
WriteLn;
WriteString("the larch bud moth system. Part I: the larch-
larch bud moth");
WriteLn;
WriteString("relationship. Mitt. Schweiz. Ent. Ges., 52:
273-289.");
WriteLn;
WriteString(""); WriteLn;
WriteString("Fischlin, A., 1982. Analyse eines Wald-Insekten-
Systems: Der");
WriteLn;
WriteString("subalpine Lärchen-Arvenwald und der graue
Lärchenwickler");
WriteLn;
WriteString("Zeiraphera diniana Gn. (Lep., Tortricidae).
Diss. ETH No. ");
WriteLn;

```

```

WriteString("6977, Swiss Federal Institute of Technology:
           Zürich,"); WriteLn;
WriteString("Switzerland, pp. 294."); WriteLn;
WriteString(""); WriteLn;
WriteString("Fischlin, A., 1991. Interactive modeling and
           simulation of ");
WriteLn;
WriteString("environmental systems on workstations. In:
           Möller, D.P.F.");
WriteLn;
WriteString(" (ed.), Analysis of Dynamic Systems in Medicine,
           Biology, and");
WriteLn;
WriteString("Ecology. Springer, Berlin a.o., pp. 131-145.");
WriteLn;
WriteString(""); WriteLn;
WriteString("           Programming"); WriteLn;
DrawToTheRight(heliID,picW,picH,0.6);
WriteString(""); WriteLn;
WriteString("o Design & Implementation"); WriteLn;
WriteString("Andreas Fischlin & Bronwyn Price 01/05/87 &
           13/09/2005");
WriteLn;
WriteString("           "); WriteLn;
WriteString("           "); WriteLn;
WriteString("Swiss Federal Institute of Technology Zurich ETHZ
           "); WriteLn;
WriteString("Terrestrial Systems Ecology "); WriteLn;
WriteString("Universitätstrasse 16 "); WriteLn;
WriteString("CH-8092 Zurich "); WriteLn;
WriteString("SWITZERLAND "); WriteLn;
WriteString(""); WriteLn;
WriteString("URLs: "); WriteLn;
WriteString("<mailto:RAMSES@env.ethz.ch> "); WriteLn;
WriteString("<http://www.sysecol.ethz.ch> "); WriteLn;
WriteString("<http://www.sysecol.ethz.ch/SimSoftware/RAMSES/>
           "); WriteLn;
END AboutLBMod;

```

```
VAR
```

```

m3, flight: Model;
firstSite, lastSite: Parameter;
sno: INTEGER;

```

```
PROCEDURE InitializeStateVectorFromObs (VAR site: Site);
```

```
VAR k: INTEGER;
```

```
BEGIN (* InitializeStateVectorFromObs *)
```

```
WITH site.x DO WITH site.p DO
```

```
CASE sno OF
```

```
1 :
```

```
k:= Entier(CurrentTime());
```

```
IF (kMin<=k) AND (k<=kMax) THEN
```

```
AssignDataUE;
```

```
rt := 15.0; et:= EggsFromDensity(yMeanDash,site);
```

```
ELSIF (kMinSA<=k) AND (k<=kMaxSA) THEN
```

```

        AssignDataSA;
        rt := 15.0; et:= EggsFromDensity(YMeanDash,site);
        END(*IF*);
| 2   : rt:= 16.0;
        et:= EggsFromDensity(160.0,site);
| 3   : rt:= 15.0;
        et:= EggsFromDensity(140.0,site);
| 4   : rt:= 12.0 (*=p9*);
        et:= EggsFromDensity(400.0,site);
| 5   : rt:= 18.0 (*=p11*);
        et:= EggsFromDensity(0.018,site);
        END(*CASE*);
    END(*WITH*); END(*WITH*);
END InitializeStateVectorFromObs;

PROCEDURE InitializeM3;
BEGIN (* InitializeM3 *)
    PrepareValley(UpperEngadine,TRUNC(firstSite),TRUNC(lastSite));
    ActivateLBMLifeCycle(m3);
    InitializeLBMLifeCycle;
    sno := 1;
    DoForAllSites(UpperEngadine,InitializeStateVectorFromObs);
END InitializeM3;

PROCEDURE InitializeFlight;
BEGIN (* InitializeFlight *)
    ActivateLBMFlight(flight);
    InitialiseLBMFlight;
END InitializeFlight;

PROCEDURE DynamicLC;
BEGIN (* DynamicLC *)
    DoForAllSites(UpperEngadine,ComputeLifeCycle);
END DynamicLC;

PROCEDURE DynamicFlight;
BEGIN (* DynamicFlight *)
    DistributeFemaleMoths;
END DynamicFlight;

PROCEDURE InitializePhasePortrait (VAR(*speed-up*) site: Site);
    VAR curScMin,curScMax: REAL;
        curSf: StashFiling; curT: Tabulation; curG: Graphing;
BEGIN (* InitializePhasePortrait *)
    WITH site.x DO
        (* put rt on abscissa *)
        GetMV(m3,rt,curScMin,curScMax,curSf,curT,curG);
        SetMV(m3,rt,curScMin,curScMax,notOnFile,writeInTable,isX);
    END(*WITH*);
END InitializePhasePortrait;

PROCEDURE PhasePortrait;
    CONST maxsno = 5;
BEGIN
    DoForAllSites(UpperEngadine,InitializePhasePortrait);
    FOR sno := 1 TO maxsno DO SimRun END; sno:= 1;
END PhasePortrait;

```

```
PROCEDURE ModelObjectsM3;
BEGIN (* ModelObjectsM3 *)
  DeclP(firstSite, FLOAT(fstSite), FLOAT(UE),
        FLOAT(maxSiteIndex), noRtc, "Index of first site",
        "firstSite", "#");
  DeclP(lastSite, FLOAT(maxSiteIndex), FLOAT(UE),
        FLOAT(maxSiteIndex), noRtc,
        "Index of last site", "lstSite", "#");
  PrepareValley(UpperEngadine, TRUNC(firstSite), TRUNC(lastSite));
  ActivateLBMLifeCycle(m3);
END ModelObjectsM3;

PROCEDURE ModelObjectsF;
BEGIN (* ModelObjectsF *)
  IF NOT ValleyExists(UpperEngadine) THEN
    DeclP(firstSite, FLOAT(fstSite), FLOAT(UE),
          FLOAT(maxSiteIndex), noRtc,
          "Index of first site", "firstSite", "#");
    DeclP(lastSite, FLOAT(maxSiteIndex), FLOAT(UE),
          FLOAT(maxSiteIndex), noRtc,
          "Index of last site", "lstSite", "#");
    PrepareValley(UpperEngadine, TRUNC(firstSite), TRUNC(lastSite));
  END (*IF*);
  ActivateLBMFlight(flight);
END ModelObjectsF;

PROCEDURE ActivateLBMCModel;
BEGIN
  DeclM(m3, discreteTime, InitializeM3, NoInput, NoOutput,
        DynamicLC, NoTerminate, ModelObjectsM3,
        larchLbmModDescr, "m3", AboutLBMod);
END ActivateLBMCModel;

PROCEDURE DeactivateLBMCModel;
BEGIN
  IF IsLBMLifeCycleActive() THEN DeactivateLBMLifeCycle END;
  RemoveM(m3); m3 := notDeclaredModel;
END DeactivateLBMCModel;

PROCEDURE ActivateLBMFModel;
BEGIN
  DeclM(flight, discreteTime, InitializeFlight, NoInput,
        NoOutput,
        DynamicFlight, NoTerminate, ModelObjectsF,
        lbmFlightDescr, "flight", AboutLBMod);
END ActivateLBMFModel;

PROCEDURE DeactivateLBMFModel;
BEGIN
  IF IsLBMFlightActive() THEN DeactivateLBMFlight END;
  RemoveM(flight); flight := notDeclaredModel;
END DeactivateLBMFModel;

PROCEDURE UseLarchLBMod;
BEGIN (* UseLarchLBMod *)
```

```
    IF NOT MDeclared(m3) THEN ActivateLBMCMModel END(*IF*);
END UseLarchLBMod;

PROCEDURE LarchLBModIsInUse(): BOOLEAN;
BEGIN (* LarchLBModIsInUse *)
    RETURN MDeclared(m3)
END LarchLBModIsInUse;

PROCEDURE UnuseLarchLBMod;
BEGIN (* UnuseLarchLBMod *)
    IF MDeclared(m3) THEN DeactivateLBMCMModel END;
END UnuseLarchLBMod;

PROCEDURE UseLBMFlight;
BEGIN
    IF NOT MDeclared(flight) THEN ActivateLBMFModel END (*IF*);
END UseLBMFlight;

PROCEDURE LBMFlightIsInUse(): BOOLEAN;
BEGIN
    RETURN MDeclared(flight)
END LBMFlightIsInUse;

PROCEDURE UnuseLBMFlight;
BEGIN
    IF MDeclared(flight) THEN DeactivateLBMFModel END;
END UnuseLBMFlight;

(*****
*#####  Module Management  #####*
*****)

PROCEDURE InitLBModel;
BEGIN (*InitLBModel*)
    m3 := notDeclaredModel;
    flight := notDeclaredModel;
END InitLBModel;

BEGIN (* LBModel *)
    InitLBModel;
END LBModel.
```

LBMLIFE CYCLE

```

DEFINITION MODULE LBMLifeCycle;

(*****

Module LBMLifeCycle      (Version 1.0)

  Copyright (c) 2005 by Andreas Fischlin
  and Swiss Federal Institute of Technology Zurich ETHZ

Purpose      Simulates Larch Bud Moth life cycle, i.e. the
              local population dynamics for any given
              site for one generation Model b: local
              dynamics: larch - larch bud moth
              interaction (food quality hypothesis)

References   Fischlin 1982, "Analyse eines Wald-Insekten
              Systemes:
              Der subalpine Lärchen-Arvenwald und der Graue
              Lärchenwickler Zeiraphera diniana Gn. (Lep.,
              Tortricidae)", Diss ETHZ No. 6977.

Remark      This module requires several other modules
              to actually become an operative submodel

Programming

  o Design
    Andreas Fischlin      08/02/2005

  o Implementation
    Andreas Fischlin      08/02/2005

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Last revision of definition: 08/02/2005 AF

*****
)

FROM SimBase IMPORT Model, StateVar, OutVar, AuxVar;
FROM LBMValley IMPORT Site;

```

```
PROCEDURE InitializeLBMLifeCycle; (* each time at begin of a
                                simulation run *)
PROCEDURE ComputeLifeCycle(VAR site: Site); (* dynamic part *)
PROCEDURE EggsFromDensity(yt: OutVar; VAR(*speed-up*) site: Site):
    StateVar;

PROCEDURE ActivateLBMLifeCycle(m: Model);
PROCEDURE IsLBMLifeCycleActive(): BOOLEAN;
PROCEDURE DeactivateLBMLifeCycle;

END LBMLifeCycle.
```



```

IMPLEMENTATION MODULE LBMLifeCycle;

(*

Purpose      Simulates Larch Bud Moth life cycle, i.e. the
              local population dynamics for any given
              forest compartment for one generation. Local
              dynamics: larch - larch bud moth
              interaction (food quality hypothesis)

Reference     Fischlin 1982, "Analyse eines Wald-Insekten
              Systemes:
              Der subalpine Lärchen-Arvenwald und der Graue
              Lärchenwickler Zeiraphera diniana Gn. (Lep.,
              Tortricidae)", Diss ETHZ No. 6977.

Remark       This module requires several other modules
              to actually become an operative submodel

Programming

  o Design
    Andreas Fischlin          08/02/2005

  o Implementation
    Andreas Fischlin          08/02/2005

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  <http://www.sysecol.ethz.ch>

Implementation and Revisions:
=====

Author   Date       Description
-----  -
af       08/01/05   First implementation (derived from
                    earlier implementations, cf. LBM M8)
brp      13/09/05   adaptation for use in M11.
                    et no longer declared as state variable,
                    as this caused its value to be over
                    written, instead it is AuxVar,
                    initialised based on tree data. Updated
                    each year based
                    on value calculated by LBMFlight.

*)

```

```

(* DM core *)
FROM DMConversions IMPORT UndefREAL;
FROM DMWindIO IMPORT WriteString, WriteLn,
  SetWindowFont, FontStyle, WindowFont, GetPen,
  DisplayPredefinedPicture,
  SetPen, MaxCol, CellWidth;
FROM DMWindows IMPORT RectArea, UpdateAllWindows;

(* DM optional *)
FROM DMMathLib IMPORT Exp, Ln, Entier;
FROM DMKeyChars IMPORT BestCH;

(* MW *)
FROM SimBase IMPORT Model, DeclM, IntegrationMethod, DeclSV,
  Parameter, StateVar, Derivative, NewState, AuxVar, OutVar,
  StashFiling, Tabulation, Graphing, DeclMV,
  SetDefltCurveAttrForMV, Stain, LineStyle,
  StashFileName, SetSimTime, SetMonInterval,
  SetProjDescrs, GetMV, SetMV, MVDeclared,
  RemoveM, MDeclared, SVDeclared, notDeclaredModel,
  PDeclared, DeclP, RemoveP, RTCType,
  NoInput, NoOutput, NoTerminate;
FROM SimMaster IMPORT
  SimRun, CurrentTime, InstallExperiment;
FROM SimGraphUtils IMPORT PlotSym;

(* AuxLib *)
FROM TabFunc IMPORT TabFUNC, DeclTabF, RemoveTabF, Yie;
FROM RandGen IMPORT U, SetSeeds;
FROM ReadData IMPORT negLogDelta;

(* LBM *)
FROM LBMObsLbm IMPORT yLL, yUL,
  yMeanDash, YMeanDash, kMin, kMax, kMinSA, kMaxSA,
  AssignDataUE, AssignDataSA;
FROM LBMObsLarch IMPORT nLL, nUL, nDLLTol, nDULTol;

FROM LBMValley IMPORT
  Valley, UpperEngadine, Site, DoForAllSites, AppendSiteIndex;

FROM LBModMonit IMPORT StartMonitorObj, StopMonitorObj;

VAR
  ownerM: Model;
  (* model parameters: *)
  c1,c2,c3,c4Dash,c5Dash,
  c6,c7,c8,c9,c10,c11,c12,c13,c14,c15,c16,c17:
    Parameter;
  p3,p4,p5,p6,p7,p8,p9,p10,p11,p12,p13: Parameter;
  (* aux vars: *)
  springEggs, sl, ll, gmsl, gmsta, gmlp, fol, nl,
  dem, eaten, ut: AuxVar;

  (* parameters used for insecticide treatments *)
  yTh, alfa: Parameter;
  (* parameters used for pheromone treatments *)

```

```

phi: Parameter;
(* parameters used to control controller's behavior *)
strictly, regularly: Parameter;
seed0, seed1, seed3: INTEGER;

(* parameters used for immigration *)
conglobation: Parameter;
immig: Parameter;
(* optional parameters, required to compute monitorable vars: *)
lmin,lmax: Parameter;

(* simulation management: *)
vtTF: TabFUNC; yr,vt: ARRAY [kMin..kMax] OF REAL;
parSetVari: REAL;

PROCEDURE AssignSiteSpecParams1(VAR site: Site);
BEGIN (* AssignSiteSpecParams1 *)
  WITH site.p DO
    c4:= c4Dash*nrt;
    c5:= c5Dash*nrt;
    p1:=c4;
    p2:=c5;
  END(*WITH*);
END AssignSiteSpecParams1;

PROCEDURE AssignSiteSpecParams2(VAR site: Site);
BEGIN (* AssignSiteSpecParams2 *)
  WITH site.p DO
    p14:=c6*c17*nrt;
  END(*WITH*);
END AssignSiteSpecParams2;

PROCEDURE InitializeLBMLifeCycle;

  PROCEDURE SetParameters;
  BEGIN
    DoForAllSites(UpperEngadine,AssignSiteSpecParams1);
    p3:=-c2*c6*(1.0-c1);
    p4:=c6*(1.0-c1)*(1.0 -c3);
    p5:=c2*c7*c9*c10*(1.0-c1);
    p6:=c9*(1.0-c1)*(c2*c7*c11-c10*(c2*(1.0-c8)+c7*(1.0-c3)));
    p7:=c9*(1.0-c1)*(c10*(1.0-c3)*(1.0-c8)-c11*(c2*(1.0-
      c8)+c7*(1.0-c3)));
    p8:=c9*c11*(1.0-c1)*(1.0-c3)*(1.0-c8);
    p9:=c12;
    p10:=c13;
    p11:=c14;
    p12:=c15;
    p13:=c16;
    DoForAllSites(UpperEngadine,AssignSiteSpecParams2);
  END SetParameters;

  PROCEDURE SetProjDescriptor;
  BEGIN (* SetProjDescriptor *)
    IF alfa=0.0 THEN

```

```

    SetProjDescrs("LBM dynamics, Upper Engadine","", "",
    TRUE(*wtitle*), TRUE(*wremark*), TRUE(*autofooter*),
    TRUE(*recM*), TRUE(*recSV*), TRUE(*recP*), FALSE
    (*recMV*), FALSE(*recG*));
ELSE
    SetProjDescrs("Bttreatment","", "", TRUE(*wtitle*),
    TRUE(*wremark*), TRUE(*autofooter*), TRUE(*recM*),
    TRUE(*recSV*), TRUE(*recP*), FALSE(*recMV*), FALSE(*recG*));
END(*IF*);
END SetProjDescriptor;

PROCEDURE SetMonitoring;
VAR
    curScMin, curScMax: REAL;
    curSf: StashFiling; curT: Tabulation; curG: Graphing;
BEGIN (* SetMonitoring *)
    IF IsLBMLifeCycleActive() AND (parSetVari>0.0) THEN
        (* p[i] parameter set => certain monitoring vars are not
        defined, exclude them from monitoring *)
        GetMV(ownerM, sl, curScMin, curScMax, curSf, curT, curG);
        SetMV(ownerM, sl, curScMin, curScMax, notOnFile, notInTable,
            notInGraph);
        GetMV(ownerM, gmsl, curScMin, curScMax, curSf, curT, curG);
        SetMV(ownerM, gmsl, curScMin, curScMax, notOnFile, notInTable,
            notInGraph);
        GetMV(ownerM, fol, curScMin, curScMax, curSf, curT, curG);
        SetMV(ownerM, fol, curScMin, curScMax, notOnFile, notInTable,
            notInGraph);
        GetMV(ownerM, gmsta, curScMin, curScMax, curSf, curT, curG);
        SetMV(ownerM, gmsta, curScMin, curScMax, notOnFile, notInTable,
            notInGraph);
        GetMV(ownerM, ll, curScMin, curScMax, curSf, curT, curG);
        SetMV(ownerM, ll, curScMin, curScMax, notOnFile, notInTable,
            notInGraph);
        GetMV(ownerM, gmllp, curScMin, curScMax, curSf, curT, curG);
        SetMV(ownerM, gmllp, curScMin, curScMax, notOnFile, notInTable,
            notInGraph);
    END(*IF*);
END SetMonitoring;

BEGIN (*InitializeLBMLifeCycle*)
    SetParameters;
    SetProjDescriptor;
    SetMonitoring;
    SetSeeds(seed0, seed1, seed3);
END InitializeLBMLifeCycle;

PROCEDURE EggsFromDensity(yt: OutVar; VAR(*speed-up*) site:
    Site): StateVar;
VAR k: INTEGER;
BEGIN (* EggsFromDensity *)
    IF NOT IsLBMLifeCycleActive() THEN RETURN UndefREAL() END;
    WITH site.p DO WITH site.x DO
        k:= Entier(CurrentTime());
        IF (kMin<=k) AND (k<=kMax) THEN
            RETURN yMeanDash*p14/(p3*rt+p4);

```

```

    ELSIF (kMinSA<=k) AND (k<=kMaxSA) THEN
        RETURN YMeanDash*p14/(p3*rt+p4);
    END(*IF*);
END(*WITH*); END(*WITH*);
END EggsFromDensity;

PROCEDURE ComputeLifeCycle(VAR site: Site);
PROCEDURE gmstarv(fol,dem: REAL): REAL;
BEGIN
    IF dem>0.0 THEN RETURN Exp(-fol/dem)
    ELSIF dem=0.0 THEN RETURN 0.0 END;
END gmstarv;

PROCEDURE grecr(def,rt: REAL): REAL;
CONST eps = 0.00001;
VAR
    zrt: REAL;
BEGIN (*grecr*)
    IF (def < p12) THEN
        IF (rt >= p9-eps) AND (rt <= p9) (* rt = p9 *) THEN
            RETURN 1.0
        ELSIF rt > p9 THEN
            zrt:= p10+ABS((p11-rt)/(rt-p9));
            IF zrt > rt-p9 THEN
                RETURN p9/rt
            ELSE (*zrt <= rt-p9*)
                RETURN 1.0-zrt/rt
            END(*IF*);
        ELSE
            (* " --- warning: rt < p9" *)
            HALT (* should never occur *)
            END(*IF*);
        ELSE (*def >= p12*)
            IF def < p13 THEN
                RETURN 1.0+(def-p12)*(p11-rt)/(p13-p12)/rt
            ELSIF (def > p12) (*AND (def >= p13)*) THEN
                RETURN p11/rt
            ELSE (*(def = p12) AND (def >= p13)*)
                HALT (* should never occur *)
            END(*IF*);
        END(*IF*);
    END grecr;

PROCEDURE ControllerActive (): BOOLEAN;
BEGIN (* ControllerActive *)
    RETURN ((TRUNC(CurrentTime())MOD TRUNC(regularly)) = 0) AND
        (U())<=strictly)
END ControllerActive;

PROCEDURE ShowTreatment(trf: REAL);
CONST atY = 0.95;
BEGIN (* ShowTreatment *)
    IF trf=0.0 THEN RETURN END(*IF*);
    PlotSym(CurrentTime(),atY,"v");
    PlotSym(CurrentTime(),atY+0.02,"|");
END ShowTreatment;

```

```

BEGIN (*ComputeLifeCycle*)
  WITH site DO WITH site.x DO WITH site.p DO WITH site.o DO
    IF parSetVari=0.0 THEN (* implemented with c[i] parameter
      set *)
      springEggs := (1.0 - c1) * et;
      gmsl := c2*rt+c3;
      sl := (1.0 - gmsl)*springEggs;
      ll := sl;
      nl:= (p9*lmin-p11*lmax)/(p9-p11)+(lmax-lmin)/(p9-p11)*rt;
      IF (ll/nrt/c17>=yTh) AND ControllerActive() THEN
        ll := (1.0-alfa)*ll; ShowTreatment(alfa);
      END(*IF*);
      yt := ll/nrt/c17; ytLn:= Ln(negLogDelta+yt);
      fol := c4*rt + c5;
      dem := c6*ll;
      gmsta := gmstarv(fol,dem);
      ll := (1.0 - gmsta)*ll;
      eaten := c6*ll;
      def := eaten/fol;
      rtl:=greocr(def,rt)*rt;
      fol := fol-eaten;
      gmllp := c7*rt+c8;
      f := (1.0-gmllp)*ll*c9;
      gfec := c10*rt+c11;
      IF (ll/nrt/c17<yTh) AND ControllerActive() THEN
        et := (1.0-phi)*gfec*f;
        ShowTreatment(phi);
      ELSE
        et := gfec*f;
      END(*IF*);
    ELSE (* implemented with p[i] parameter set *)
      springEggs:= (1.0 - c1) * et;
      IF (p3*rt+p4)*et/p14>=yTh THEN
        ShowTreatment(alfa);
        et := (1.0-alfa)*et
      END(*IF*);
      yt:= (p3*rt+p4)*et/p14; ytLn:= Ln(negLogDelta+yt);
      nl:= (p9*lmin-p11*lmax)/(p9-p11)+(lmax-lmin)/(p9-p11)*rt;
      def:= (1.0-gmstarv(p1*rt+p2,p3*rt*et+p4*et))*
        (p3*rt*et+p4*et)/(p1*rt+p2);
      rtl:=greocr(def,rt)*rt;
      IF (p3*rt+p4)*et/p14<yTh THEN
        et:=(1.0-phi)*(1.0-gmstarv(p1*rt+p2,p3*rt*et+p4*et))*
          (p5*rt*rt*rt+p6*rt*rt+p7*rt+p8)*et;
        ShowTreatment(phi);
      ELSE
        et:=(1.0-gmstarv(p1*rt+p2,p3*rt*et+p4*et))*
          (p5*rt*rt*rt+p6*rt*rt+p7*rt+p8)*et;
      END(*IF*);
    END(*IF*);
    IF conglobation > 0.0 THEN
      ut := immig*nrt; (* konglobation *)
    ELSE
      ut := Yie(vtTF,CurrentTime())*immig*nrt;
      (* translocation *)
    END
  END

```

```

    END(*IF*);
    et := et + ut;
  END(*WITH*); END(*WITH*); END(*WITH*); END(*WITH*);
END ComputeLifeCycle;

PROCEDURE MonitorEt(VAR(*speed-up*) site: Site): AuxVar;
BEGIN (* MonitorEt *)
  RETURN site.x.et
END MonitorEt;

PROCEDURE DeclareStateVars(VAR site: Site);
  CONST rawFibreSimResultsFileName = "M11SimRawFibre.DAT";
  VAR ident: ARRAY [0..31] OF CHAR;
BEGIN (* DeclareStateVars *)
  WITH site.x DO
    IF NOT SVDeclared(ownerM,rt) THEN
      AppendSiteIndex("rt",site.six,ident);
      DeclSV(rt, rt1, 15.0, 11.99, 18.5,
        "Raw fiber content (% fresh weight)", ident, "%");
    END(*IF*);

    IF NOT MVDeclared(ownerM,rt) THEN
      AppendSiteIndex("rt",site.six,ident);
      DeclMV(rt, 10.0, 20.0, "Raw fiber content
        (% fresh weight)", ident,
        "%", notOnFile, writeInTable, notInGraph);
    END(*IF*);
    IF NOT MVDeclared(ownerM,et) THEN
      AppendSiteIndex("et",site.six,ident);
      DeclMV(et, 0.0, 1.0E12, "Larch bud moth eggs
        (individuals in fall)",
        ident, "#", notOnFile, writeInTable, notInGraph);
      StartMonitorObj(MonitorEt,rawFibreSimResultsFileName);
    END(*IF*);
    IF NOT MVDeclared(ownerM,def) THEN
      AppendSiteIndex("def",site.six,ident);
      DeclMV(def, 0.0, 1.0,"Defoliation",
        "d", "", notOnFile, writeInTable, notInGraph);
    END (*IF*);
    IF NOT MVDeclared(ownerM,gfec) THEN
      AppendSiteIndex("gfec",site.six,ident);
      DeclMV(gfec, 0.0, 150.0,
        "Fecundity of larch bud moth females",
        "gfec", "", notOnFile, writeInTable, notInGraph);
    END(*IF*);
    IF NOT MVDeclared(ownerM,f) THEN
      AppendSiteIndex("f",site.six,ident);
      DeclMV(f, 0.0, 1.0E12,
        "Larch bud moth females (individuals)",
        "f", "lbm", notOnFile, writeInTable, notInGraph);
    END(*IF*);
  END(*WITH*);
END DeclareStateVars;

PROCEDURE DeclareOutputs(VAR site: Site);

```

```

CONST bullet = '.'; VAR ident: ARRAY [0..31] OF CHAR;
BEGIN (* DeclareOutputs *)
  WITH site.o DO
    AppendSiteIndex("Y",site.six,ident);
    IF NOT MVDeclared(ownerM,yt) THEN
      DeclMV(yt, yLL, yUL,"Larval density (larvae/kg branches)",
        ident, "lbm/kg", writeOnFile, writeInTable, notInGraph);
      SetDefltCurveAttrForMV
        (ownerM, yt,ruby,unbroken,BestCH(bullet));
    END (*IF*);
    AppendSiteIndex("Ln(Y)",site.six,ident);
    IF NOT MVDeclared(ownerM,ytLn) THEN
      DeclMV(ytLn, Ln(negLogDelta), Ln(negLogDelta+yUL),
        "Ln of larval density (larvae/kg branches)",
        ident, "lbm/kg", notOnFile, notInTable, isY);
      SetDefltCurveAttrForMV
        (ownerM, ytLn,ruby,unbroken,BestCH(bullet));
    END (*IF*);
  END(*WITH*);
END DeclareOutputs;

PROCEDURE DeclareModelObjects;
  PROCEDURE FillUpVtTF;
    CONST v0 = 889.970; v1 = 288.630; v2 = 39.174; v3 = 4.239;
          v4 = 1.0;
    VAR i: INTEGER; peaks: ARRAY [1..5] OF INTEGER;
    PROCEDURE FillFromPeak(peak,delta: INTEGER; val: REAL);
      BEGIN
        vt[peak+delta] := val; vt[peak-delta] := val;
      END FillFromPeak;
    BEGIN
      FOR i := kMin TO kMax DO
        yr[i] := FLOAT(i); vt[i] := v4;
      END(*FOR*);
      peaks[1] := 1954; peaks[2] := 1963; peaks[3] := 1973;
      peaks[4] := 1981;
      peaks[5] := 1990;
      FOR i := 1 TO 5 DO
        FillFromPeak(peaks[i],0,v0); FillFromPeak(peaks[i],1,v1);
        FillFromPeak(peaks[i],2,v2); FillFromPeak(peaks[i],3,v3);
      END(*FOR*);
    END FillUpVtTF;
  BEGIN (* DeclareModelObjects *)
    DoForAllSites(UpperEngadine,DeclareStateVars);

    DeclMV(springEggs, 0.0, 1.0E12,"Larch bud moth eggs in spring
      (individuals)",
      "springEggs", "lbm", notOnFile, writeInTable, notInGraph);
    DeclMV(sl, 0.0, 1.0E12,
      "Larch bud moth small larvae (individuals)",
      "sl", "lbm", notOnFile, writeInTable, notInGraph);
    DeclMV(gmsl, 0.0, 1.0,
      "Mortality of small larvae",
      "gmsl", "", notOnFile, writeInTable, notInGraph);

    DoForAllSites(UpperEngadine,DeclareOutputs);
  
```



```

DeclMV(fol, 0.0, 25.0E6, "Foliage",
  "fol", "kg", notOnFile, writeInTable, notInGraph);
DeclMV(gmsta, 0.0, 1.0,
  "Starvation mortality of large larvae",
  "gmsta", "", notOnFile, writeInTable, notInGraph);
DeclMV(l1, 0.0, 1.0E12,
  "Larch bud moth large larvae (individuals)",
  "l1", "lbm", notOnFile, writeInTable, notInGraph);
DeclMV(gml1p, 0.0, 1.0,
  "Mortality of large larvae and pupae",
  "gml1p", "", notOnFile, writeInTable, notInGraph);

DeclMV(nl, nLL, nUL, "Length of larch needles",
  "n", "mm", notOnFile, notInTable, notInGraph);

DeclP(c1, 0.5728, 0.4841, 0.6538, noRtc,
  "c1 (egg winter mortality)", "c1", "");
DeclP(c2, 0.05112, 0.016, 0.087, noRtc,
  "c2 (slope of small larvae mortality vs. rf)", "c2", "%");
DeclP(c3, -0.17932, -0.565, 0.206, noRtc,
  "c3 (y-intercept of small larvae mortality vs. rf)",
  "c3", "");
DeclP(c4Dash, -2.25933, -2.4129, -2.1057, noRtc,
  "c4 (slope of needle biomass vs. rf)", "c4", "%");
DeclP(c5Dash, 67.38939, 62.8076, 71.9712, noRtc,
  "c5 (y-intercept of needle biomass vs. rf)", "c5", "");
DeclP(c6, 0.005472, 0.0027, 0.0106, noRtc,
  "c6 (food demand of a large larvae)", "c6", "kg/lbm");
DeclP(c7, 0.124017, 0.1070, 0.1410, noRtc,
  "c7 (slope of large larvae mortality vs. rf)", "c7", "%");
DeclP(c8, -1.435284, -1.685, -1.1855, noRtc,
  "c8 (y-intercept of large larvae mortality vs. rf)",
  "c8", "");
DeclP(c9, 0.44, 0.363, 0.517, noRtc,
  "c9 (sex ratio)", "c9", "");
DeclP(c10, -18.475457, -24.7217, -12.2294, noRtc,
  "c10 (slope of fecundity vs. rf)", "c10", "lbm/%");
DeclP(c11, 356.72636, 264.9847, 448.4680, noRtc,
  "c11 (y-intercept of fecundity vs. rf)", "c11", "lbm");
DeclP(c12, 11.99, 11.79, 12.19, noRtc,
  "c12 (minimum rf)", "c12", "%");
DeclP(c13, 0.425, 0.4, 0.5, noRtc,
  "c13 (minimum decrement of rf)", "c13", "%");
DeclP(c14, 18.0, 17.5, 18.5, noRtc,
  "c14 (maximum rf)", "c14", "%");
DeclP(c15, 0.4, 0.35, 0.6, noRtc,
  "c15 (defoliation threshold)", "c15", "");
DeclP(c16, 0.8, 0.7, 1.0, noRtc,
  "c16 (defoliation threshold of maximum stress)",
  "c16", "");
DeclP(c17, 91.3, 91.3, 91.3, noRtc,
  "c17 (branches per tree)", "c17", "kg");
DeclP(lmin, 19.01, nDLLTol, nDULTol, noRtc,
  "Mean minimum needle length", "lmin", "mm");
DeclP(lmax, 28.67, nDLLTol, nDULTol, noRtc,
  "Mean maximum needle length", "lmax", "mm");

```

```

(* controller: insecticide or parafferomone treatments *)
DeclP(yTh, 50.0, yLL, yUL, noRtc,
      "Threshold density for treatment",
      "yTh", "lbm/kg");
DeclP(alfa, 0.00, 0.0, 1.0, noRtc,
      "Insecticide caused mortality of large larvae (BTmort)",
      "alfa", "");
DeclP(phi, 0.00, 0.0, 1.0, noRtc,
      "Pheromone caused reduction in fecundity",
      "phi", "");
DeclP(strictly, 1.0, 0.0, 1.0, noRtc,
      "Probability that controller functions",
      "strictly", "");
DeclP(regularly, 1.0, 1.0, FLOAT(MAX(INTEGER)), noRtc,
      "Regularity of controller functioning",
      "regularly", "");
seed0 := 1; seed1 := 1000; seed3 := 31700;

(* immigration scenarios *)
DeclP(immig, 0.00, 0.0, 1.0, noRtc,
      "Immigration caused absolute population growth",
      "immig", "eggs/year/tree");
DeclP(conglobation, 1.0, 0.0, 1.0, noRtc,
      "Conglobation (1) vs. translocation (0) switch",
      "conglobation", "1/0");
FillUpVtTF;
DeclTabF(vtTF, yr, vt, kMax-kMin+1, TRUE,
        "Immigration according translocation hypothesis",
        "year", "vt", "year", "%",
        FLOAT(kMin), FLOAT(kMax), 0.0, 1000.0);
(* parameter variant set control *)
DeclP(parSetVari, 0.0, 0.0, 1.0, noRtc,
      "Parameter set variant flag (=0: use ci, =1:
      use pi parameters)",
      "parSetVari", "");
END DeclareModelObjects;

PROCEDURE UpdateModelObjects;
BEGIN (* UpdateModelObjects *)
  (* only site specific objects need updating *)
  DoForAllSites(UpperEngadine, DeclareStateVars);
  DoForAllSites(UpperEngadine, DeclareOutputs);
END UpdateModelObjects;

PROCEDURE UndeclareModelObjects;
BEGIN (* UndeclareModelObjects *)

END UndeclareModelObjects;

PROCEDURE ActivateLBMLifeCycle(m: Model);
BEGIN (* ActivateLBMLifeCycle *)
  IF NOT IsLBMLifeCycleActive() THEN
    ownerM := m;

```

```
    DeclareModelObjects;
ELSE
    UpdateModelObjects;
END(*IF*);
END ActivateLBMLifeCycle;

PROCEDURE IsLBMLifeCycleActive(): BOOLEAN;
BEGIN (* IsLBMLifeCycleActive *)
    RETURN MDeclared(ownerM) AND PDeclared(ownerM,c1) (* assume c1
        existence implies existence of all other objects *)
END IsLBMLifeCycleActive;

PROCEDURE DeactivateLBMLifeCycle;
BEGIN (* DeactivateLBMLifeCycle *)
    IF NOT IsLBMLifeCycleActive() THEN
        UndeclareModelObjects;
        ownerM := notDeclaredModel;
    END(*IF*);
END DeactivateLBMLifeCycle;

(*****
(*#####  Module Management  #####*)
(*****

PROCEDURE InitLBMLifeCycle;
BEGIN (*InitLBMLifeCycle*)
    ownerM := notDeclaredModel;
END InitLBMLifeCycle;

BEGIN (* LBMLifeCycle *)
    InitLBMLifeCycle;
END LBMLifeCycle.
```

LBMFLIGHT

```

DEFINITION MODULE LBMFlight;

(*****

Module LBMFLight      (Version 2.0)

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  and Swiss Federal Institute of Technology Zurich ETHZ

Purpose  Simulates all spatial dynamics, i.e. flight
         activities, of larch bud moth between forest
         compartments (abteilungen)

Remarks This module may be coupled with a local dynamics
         model. It provides an interface between local and
         spatial dynamics according to equation (64) on p.
         162 (Fischlin, 1982).

Refs    Fischlin, A. 1982. Analyse eines Wald-
         Insekten-Systems: Der subalpine Lärchen-Arvenwald
         und der graue Lärchenwickler Zeiraphera diniana Gn.
         (Lep., Tortricidae). Diss. ETH Nr. 6977. Swiss
         Federal Institute of Technology Zürich, Switzerland,
         294pp, page 90, Table 10

         Baltensweiler, W. and Fischlin, A. 1979. The rôle
         of migration for the population dynamics of the
         larch bud moth, Zeiraphera diniana Gn. (Lep.
         Tortricidae). Mitt. Schweiz. Ent. Ges. 52: 259-271.

         Baltensweiler, W. and Fischlin, A. 1988. The larch
         bud moth in the European Alps. In: Berryman, A.A.
         (ed.), Dynamics of Forest- Insect Populations,
         Plenum Publishing Corporation, 331-351.

Programming

  o Design
    Bronwyn Price          25/03/2004

  o Implementation
    Bronwyn Price          25/03/2004

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URLs:
  <mailto:RAMSES@env.ethz.ch>
  <http://www.sysecol.ethz.ch>

Last revision of definition: 13/09/2005 BRP

*****
)

```

```

FROM SimBase IMPORT Model;
FROM LBMValley IMPORT Site;

PROCEDURE OpenMigFile;
PROCEDURE WriteMigResults;
PROCEDURE CloseMigFile;

PROCEDURE InitialiseLBMFlight;
PROCEDURE DistributeFemaleMoths;

PROCEDURE ActivateLBMFlight(m: Model);(* activates the flight
model for the
Upper Engadine *)
PROCEDURE IsLBMFlightActive(): BOOLEAN;
PROCEDURE DeactivateLBMFlight; (* deactivates the flight model
for the Upper
Engadine *)

END LBMFlight.

```

```

IMPLEMENTATION MODULE LBMFlight;

(*
REVISION LIST:
DATE      AUTHOR  MAJOR CHANGES MADE:
-----
24.03.04  brp      First implementation
13.09.05  brp      Adjustment and update for use in model
structure of M11
calculated flight between abteilungen.
Parameters and variables are now in
LongMatrices and records rather than
arrays.
*)

(* DM core *)
FROM DMWindowIO IMPORT WriteString, WriteLn,
SetWindowFont, FontStyle, WindowFont, GetPen,
DisplayPredefinedPicture;
FROM DMWindows IMPORT RectArea, UpdateAllWindows;

(* DM optional *)
FROM DMPortab IMPORT LongFLOAT, LR, SR, LongTRUNC, LCTRUNC,
LCFLOAT;
FROM DMMathLib IMPORT Exp, Ln, Entier;
FROM DMLongMathLib IMPORT LongEntier;

FROM DMFiles IMPORT TextFile, neverOpenedFile, Lookup, PutReal,
WriteChars, WriteChar, WriteEOL, Close,
PutInteger, PutLongReal, PutLongInt, PutLongCard;
FROM DMStrings IMPORT AssignString;
FROM DMMessages IMPORT DoInform, Inform;
FROM DMLanguage IMPORT fileResBase, allOk;

(* MW *)
FROM SimBase IMPORT Model, DeclM, IntegrationMethod, DeclSV,

```

```

Parameter, StateVar, Derivative, NewState, AuxVar,
StashFiling, Tabulation, Graphing, DeclMV, DeclP, RTCType,
SetDefltCurveAttrForMV, Stain, LineStyle,
StashFileName, SetSimTime, SetMonInterval,
SetProjDescrs, GetMV, SetMV, RemoveM, MDeclared,
notDeclaredModel, PDeclared,
NoInput, NoOutput, NoTerminate, InstallClientMonitoring,
DoNothing,
NoModelObjects, NoAbout;

FROM SimMaster IMPORT
  SimRun, CurrentTime, InstallExperiment;
FROM SimGraphUtils IMPORT PlotSym;

(* LBM *)
FROM LBMObsLbm IMPORT yLL, yUL,
  yMeanDash, YMeanDash, kMinSA, kMaxSA,
  AssignDataUE, AssignDataSA;
FROM LBMMathLib IMPORT LRTRUNC;

FROM LBMValley IMPORT
  Valley, UpperEngadine, Site, DoForAllSites, AppendSiteIndex,
  Neighbourhood, nbr;

FROM LBMFlyPars IMPORT LoadParameters, NeighbourDirection,
  nilSiteIndex, UE,
  maxSiteIndex, fstDirection, lastDirection, fstSite,
  SiteAttribute, DirectionParameter, AdjacentSite, sp ;

CONST
  migSimResultsFileName = "females_migrating.txt";
  uWdistSimResultsFileName = "Upwind_distance_flown.txt";
  dWdistSimResultsFileName = "Downwind_distance_flown.txt";
  cFdistSimResultsFileName = "CalmFlyer_distance_flown.txt";

TYPE
  SiteStateVar = ARRAY [UE..maxSiteIndex] OF LONGCARD;
  SiteAuxVar = ARRAY [UE..maxSiteIndex] OF LONGREAL;

VAR
  iStr: ARRAY [0..7] OF CHAR;
  msg: ARRAY [1..255] OF CHAR;

  ownerMF: Model;
  eggs: SiteAuxVar;
  defol, fec: ARRAY [UE..maxSiteIndex] OF Parameter;
  cf1, cf2, cf3, cf4, cf5, cf6, cf13, cf14: Parameter;
  dist, distU, distC, distD, delta: ARRAY [fstSite..maxSiteIndex]
    OF AuxVar;
  n, dw, cf, uw, fools, fem: ARRAY [UE..maxSiteIndex] OF
    LONGREAL;

  as: INTEGER;
  migSimResF, uWdistSimResF, dWdistSimResF, cFdistSimResF:
    TextFile;

```

```

PROCEDURE AssignSiteSpecParams1(VAR site: Site);
  VAR i: INTEGER;
BEGIN (* AssignSiteSpecParams1 *)
  WITH site.p DO
    FOR i := fstSite TO maxSiteIndex DO
      cf7:= sp.c7[i];
      cf8:= sp.c8[i];
      cf9:= sp.c9[i];
    END(*FOR*);
  END(*WITH*);
END AssignSiteSpecParams1;

PROCEDURE DefineModelParameters(VAR site: Site);
  VAR
    i,j,m: INTEGER;
    vow, dvow,cvow,uvow: LONGREAL;
BEGIN (* DefineModelParameters *)
  DoForAllSites(UpperEngadine,AssignSiteSpecParams1);
  WITH site DO WITH site.x DO WITH site.p DO WITH nbr DO
    FOR i := fstSite TO maxSiteIndex DO
      FOR j := fstDirection TO lastDirection DO
        IF j > 3 THEN m := j - 4
        ELSE
          m := j + 4
        END(*IF*);
        w^[i]^[j+1]:= (((1.0/8.0)*cf5*(1.0-cf6)) + (1.0-
          cf5)*((1.0/8.0)*cf7 + SR(c10^[i]^[j+1])*
          cf8 + SR(c11^[i]^[m+1])*cf9));
        v^[i]^[j+1]:= (((1.0/8.0)*(cf5*(1.0-cf6)) + cf7*(1.0-
          cf5)) + cf13*SR(c10^[i]^[j+1])*cf8*(1.0-
          cf5) + cf14*SR(c11^[i]^[m+1])*cf9*
          (1.0-cf5));
        IF c10^[i]^[j+1] > 0.0D THEN
          uww^[i]^[j+1]:=(((1.0/8.0)*cf5*(1.0-cf6)) +
            (1.0-cf5)*(SR(c10^[i]^[j+1])*cf8));
          uwv^[i]^[j+1]:= (((1.0/8.0)*(cf5*(1.0-cf6))) +
            cf13*SR(c10^[i]^[j+1])*cf8*(1.0-cf5));
        ELSE
          uww^[i]^[j+1]:=0.0D;
          uwv^[i]^[j+1]:= 0.0D;
        END(*IF*);
        IF c11^[i]^[m+1] > 0.0D THEN
          dwv^[i]^[j+1]:= (((1.0/8.0)*cf5*(1.0-cf6)) +
            (1.0-cf5)*(SR(c11^[i]^[m+1])*cf9));
          dwv^[i]^[j+1]:= (((1.0/8.0)*(cf5*(1.0-cf6))) +
            cf14*SR(c11^[i]^[m+1])*cf9*(1.0-cf5));
        ELSE
          dwv^[i]^[j+1]:= 0.0D;
          dwv^[i]^[j+1]:= 0.0D;
        END(*IF*);
        cfw^[i]^[j+1]:= (((1.0/8.0)*cf5*(1.0-cf6)) +
          (1.0-cf5)*((1.0/8.0)*cf7));
        cfv^[i]^[j+1]:= (((1.0/8.0)*(cf5*(1.0-cf6)) +
          cf7*(1.0-cf5));
        IF c12^[i]^[j+1] > 0.0D THEN
          phi^[i]^[j+1] := w^[i]^[j+1];

```

```

ELSE
  phi^[i]^[j+1]:= 0.0D;
END(*IF*);
vow:= v^[i]^[j+1]/w^[i]^[j+1];
the^[i]^[j+1] := c15^[i]^[j+1]*vow;
IF dwv^[i]^[j+1] = 0.0D THEN
  theD^[i]^[j+1]:= 0.0D;
ELSE
  dvow:= dwv^[i]^[j+1]/dww^[i]^[j+1];
  theD^[i]^[j+1] := c15^[i]^[j+1]*dvow;
END(*IF*);
cvow:= cfv^[i]^[j+1]/cfw^[i]^[j+1];
theC^[i]^[j+1] := c15^[i]^[j+1]*cvow;
IF uwv^[i]^[j+1] = 0.0D THEN
  theU^[i]^[j+1]:= 0.0D;
ELSE
  uvow:= uwv^[i]^[j+1]/uww^[i]^[j+1];
  theU^[i]^[j+1] := c15^[i]^[j+1]*uvow;
END(*IF*);
as:= LongEntier(adjSite^[i]^[j+1]);
END(*FOR*);
END(*FOR*);
END (*WITH*); END (*WITH*); END (*WITH*); END (*WITH*);
END DefineModelParameters;

PROCEDURE InitialiseLBMFlight;
  VAR i: INTEGER;
BEGIN (* Initialise *)
  FOR i := UE TO maxSiteIndex DO
    fem[i]:= 0.0D;
  END(*FOR*);
  LoadParameters;
  DoForAllSites(UpperEngadine,DefineModelParameters);
END InitialiseLBMFlight;

PROCEDURE UpdateAuxVars (VAR v:Valley);
  VAR i: INTEGER;
BEGIN (* UpdateAuxVars *)
  FOR i := fstSite TO maxSiteIndex DO
    fem[i]:= v^.site[i].x.f;
    defol[i]:= v^.site[i].x.def;
    fec[i]:= v^.site[i].x.gfec;
    eggs[i]:= 0.0;
  END(*FOR*);
END UpdateAuxVars;

PROCEDURE ComputeTimeDependantAuxVars;
  VAR
    i,io: INTEGER;
BEGIN (* ComputeTimeDependantAuxVars *)
  FOR io := fstSite TO maxSiteIndex DO
    FOR i := fstSite TO maxSiteIndex DO
      delta[io]:= 1.0/(cf1+(cf2*defol[io]));
      nbr.w1^[io]^[i]:= cf3+cf4*defol[i];
      nbr.w2^[io]^[i]:= (cf1+(cf2*defol[io]))*(1.0-cf3-

```



```

        cf4*defol[i]);
    nbr.a1^[io]^[i]:= nbr.w1^[io]^[i] + nbr.w2^[io]^[i];
    nbr.s1^[io]^[i]:= fec[io]*((1.0-cf6)*
        SR(nbr.a1^[io]^[i])+cf6);
    END(*FOR*);
END(*FOR*);
END ComputeTimeDependantAuxVars;

PROCEDURE NewEggs (VAR v:Valley);
    VAR i: INTEGER;
BEGIN (* NewEggs *)
FOR i := fstSite TO maxSiteIndex DO
    v^.site[i].x.et:= eggs[i];
    END(*FOR*);
END NewEggs;

PROCEDURE DistributeFemaleMoths;
    VAR
        s2byd,nd: REAL;
        i,ci,j: INTEGER;
        femEm :ARRAY [fstSite..maxSiteIndex] OF ARRAY
            [fstDirection..lastDirection] OF LONGREAL;
        fecModif, egg, dfems, alm1: LONGREAL;
    PROCEDURE Fly(fems:LONGREAL; d,cd,ud,dd: AuxVar; ci:INTEGER);
    BEGIN (* Fly *)
        IF d < delta[i]THEN
            egg:= nbr.s1^[i]^[ci]*fems;
            eggs[i]:= egg + eggs[i];
            dfems:= LR(d)*fems;
            nd:= SR(nbr.a1^[i]^[ci])*d;
            n[ci]:= 1.0-nd+cf6;
            FOR j := fstDirection TO lastDirection DO
                nbr.distAdj^[i]^[j+1]:= d+SR(nbr.the^[ci]^[j+1]);
                nbr.distAdjC^[i]^[j+1]:= cd+SR(nbr.theC^[ci]^[j+1]);
                IF nbr.c10^[i]^[j+1] = 0.0D THEN
                    nbr.distAdjU^[i]^[j+1]:= nbr.distAdjU^[i]^[j+1];
                ELSE
                    nbr.distAdjU^[i]^[j+1]:= ud+SR(nbr.theU^[ci]^[j+1]);
                END(*IF*);
                IF nbr.c11^[i]^[j+1] = 0.0D THEN
                    nbr.distAdjD^[i]^[j+1]:= nbr.distAdjD^[i]^[j+1];
                ELSE
                    nbr.distAdjD^[i]^[j+1]:= dd +
                        SR(nbr.theD^[ci]^[j+1]);
                END(*IF*);
                as:= LongEntier(nbr.adjSite^[ci]^[j+1]);
                femEm[ci,j]:= nbr.phi^[ci]^[j+1]*n[ci]*fems;
                IF femEm[ci,j] >= 1.0D THEN
                    nbr.femfly^[i]^[as]:= nbr.femfly^[i]^[as] +
                        femEm[ci,j];
                    Fly (femEm[ci,j],nbr.distAdj^[i]^[j+1],
                        nbr.distAdjC^[i]^[j+1],nbr.distAdjU^[i]^[j+1],
                        nbr.distAdjD^[i]^[j+1],as)
                ELSE
                    END(*IF*);
            END(*FOR*);
END(*FOR*);

```

```

        ELSIF d >= delta[i] THEN
            egg:= LR(fec[i])*fems;
            eggs[ci]:= eggs[ci] + egg;
            FOR j := fstDirection TO lastDirection DO
                femEm[ci,j]:= 0.0D;
            END(*FOR*);
        ELSE
            END(*IF*);
        END Fly;
BEGIN (* DistributeFemaleMoths *)
    FOR i := fstSite TO maxSiteIndex DO
        n[i]:= 0.0D;
        eggs[i]:= 0.0;
        dist[i]:= 0.0;
        distU[i]:= 0.0;
        distD[i]:= 0.0;
        distC[i]:= 0.0;
        s2byd:= 0.0;
        nd:= 0.0;
        dfems:= 0.0D;
        alm1:= 0.0D;
        fecModif:= 0.0;
        egg:= 0.0;
        FOR j := fstDirection TO lastDirection DO
            as:= LongEntier(nbr.adjSite^[i]^[j+1]);
            femEm[i,j]:= 0.0D;
            nbr.distAdj^[i]^[j+1]:= 0.0D;
            nbr.distAdjU^[i]^[j+1]:= 0.0D;
            nbr.distAdjD^[i]^[j+1]:= 0.0D;
            nbr.distAdjC^[i]^[j+1]:= 0.0D;
        END(*FOR*);
        FOR ci := fstSite TO maxSiteIndex DO
            nbr.femfly^[i]^[ci]:= 0.0D;
        END(*FOR*);
    END(*FOR*);
    UpdateAuxVars(UpperEngadine);
    ComputeTimeDependantAuxVars;
    FOR i := fstSite TO maxSiteIndex DO
        Fly(fem[i],dist[i],distC[i],distU[i],distD[i],i);
    END(*FOR*);
    NewEggs(UpperEngadine);
END DistributeFemaleMoths;

PROCEDURE OpenMigFile;
    CONST TAB = 11C;
    VAR resCode, ci: INTEGER;
BEGIN (* OpenFile *)
    migSimResF := neverOpenedFile;
    AssignString(migSimResultsFileName,migSimResF.filename);
    Lookup(migSimResF,migSimResF.filename,TRUE(*new*));
    PutInteger(migSimResF, TRUNC(1949.0),15);
    WriteChar(migSimResF,TAB);
    PutInteger(migSimResF, TRUNC(1977.0),15);
    WriteChar(migSimResF,TAB);
    PutInteger(migSimResF, maxSiteIndex,15);
    WriteChar(migSimResF,TAB);
    WriteEOL(migSimResF);

```

```

WriteChars(migSimResF, "Year"); WriteChar(migSimResF, TAB);
WriteChars(migSimResF, "Site Number"); WriteChar(migSimResF,
    TAB);
    FOR ci := fstSite TO maxSiteIndex DO
        PutInteger(migSimResF, ci, 15); WriteChar(migSimResF, TAB);
    END(*FOR*);
WriteChars(migSimResF, "Def"); WriteChar(migSimResF, TAB);
WriteEOL(migSimResF);
END OpenMigFile;

PROCEDURE WriteMigResults;
    CONST TAB = 11C;
    VAR i, ci: INTEGER;
BEGIN (* WriteResults *)
    FOR i := fstSite TO maxSiteIndex DO
        PutInteger(migSimResF, TRUNC(CurrentTime()), 15);
        WriteChar(migSimResF, TAB);
        PutInteger(migSimResF, i, 15);
        WriteChar(migSimResF, TAB);
        FOR ci := fstSite TO maxSiteIndex DO
            PutLongReal(migSimResF, (nbr.femfly^[i]^[ci]), 15, 7);
            WriteChar(migSimResF, TAB);
        END(*FOR*);
        PutReal(migSimResF, defol[i], 15, 7);
        WriteChar(migSimResF, TAB);
        WriteEOL(migSimResF);
    END(*FOR*);
END WriteMigResults;

PROCEDURE CloseMigFile;
BEGIN (* CloseFile *)
    Close(migSimResF);
END CloseMigFile;

PROCEDURE OpenUWDistFile;
    CONST TAB = 11C;
    VAR resCode: INTEGER;
        ci: INTEGER;
BEGIN (* OpenFile *)
    uWdistSimResF := neverOpenedFile;
    AssignString(uWdistSimResultsFileName, uWdistSimResF.filename);
    Lookup(uWdistSimResF, uWdistSimResF.filename, TRUE(*new*));
    WriteChars(uWdistSimResF, "Year"); WriteChar(uWdistSimResF,
        TAB);
    WriteChars(uWdistSimResF, "Site Nr"); WriteChar(uWdistSimResF,
        TAB);
    WriteChars(uWdistSimResF, "NE"); WriteChar(uWdistSimResF,
        TAB);
    WriteChars(uWdistSimResF, "ENE"); WriteChar(uWdistSimResF,
        TAB);
    WriteChars(uWdistSimResF, "E"); WriteChar(uWdistSimResF, TAB);
    WriteChars(uWdistSimResF, "ESE"); WriteChar(uWdistSimResF,
        TAB);
    WriteChars(uWdistSimResF, "SE"); WriteChar(uWdistSimResF,
        TAB);
    WriteChars(uWdistSimResF, "SSE"); WriteChar(uWdistSimResF,

```

```

        TAB);
WriteChars(uWdistSimResF, "S"); WriteChar(uWdistSimResF, TAB);
WriteChars(uWdistSimResF, "SSW"); WriteChar(uWdistSimResF,
        TAB);
WriteChars(uWdistSimResF, "SW"); WriteChar(uWdistSimResF,
        TAB);
WriteChars(uWdistSimResF, "WSW"); WriteChar(uWdistSimResF,
        TAB);
WriteChars(uWdistSimResF, "W"); WriteChar(uWdistSimResF, TAB);
WriteChars(uWdistSimResF, "WNW"); WriteChar(uWdistSimResF,
        TAB);
WriteChars(uWdistSimResF, "NW"); WriteChar(uWdistSimResF,
        TAB);
WriteChars(uWdistSimResF, "NNW"); WriteChar(uWdistSimResF,
        TAB);
WriteChars(uWdistSimResF, "N"); WriteChar(uWdistSimResF, TAB);
WriteChars(uWdistSimResF, "NNE"); WriteChar(uWdistSimResF,
        TAB);
WriteEOL(uWdistSimResF);
END OpenUWDistFile;

PROCEDURE WriteUWDistResults;
CONST TAB = 11C;
VAR i,ci,j: INTEGER;
BEGIN (* WriteResults *)
FOR i := fstSite TO maxSiteIndex DO
PutReal(uWdistSimResF, CurrentTime(),15,7);
WriteChar(uWdistSimResF,TAB);
PutInteger(uWdistSimResF,i,15); WriteChar(uWdistSimResF,
        TAB);
FOR j := fstDirection TO lastDirection DO
PutLongReal(uWdistSimResF, nbr.distAdjU^[i]^[j+1],15,7);
WriteChar(uWdistSimResF, TAB);
END(*FOR*);
WriteEOL(uWdistSimResF);
END(*FOR*);
END WriteUWDistResults;

PROCEDURE CloseUWDistFile;
BEGIN (* CloseFile *)
Close(uWdistSimResF);
END CloseUWDistFile;

PROCEDURE OpenDWDistFile;
CONST TAB = 11C;
VAR resCode, ci: INTEGER;
BEGIN (* OpenFile *)
dWdistSimResF := neverOpenedFile;
AssignString(dWdistSimResultsFileName,dWdistSimResF.filename);
Lookup(dWdistSimResF,dWdistSimResF.filename,TRUE(*new*));
WriteChars(dWdistSimResF, "Year"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "Site Nr"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "NE"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "ENE"); WriteChar(dWdistSimResF,

```

```

        TAB);
WriteChars(dWdistSimResF, "E"); WriteChar(dWdistSimResF, TAB);
WriteChars(dWdistSimResF, "ESE"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "SE"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "SSE"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "S"); WriteChar(dWdistSimResF, TAB);
WriteChars(dWdistSimResF, "SSW"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "SW"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "WSW"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "W"); WriteChar(dWdistSimResF, TAB);
WriteChars(dWdistSimResF, "WNW"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "NW"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "NNW"); WriteChar(dWdistSimResF,
        TAB);
WriteChars(dWdistSimResF, "N"); WriteChar(dWdistSimResF, TAB);
WriteChars(dWdistSimResF, "NNE"); WriteChar(dWdistSimResF,
        TAB);
WriteEOL(dWdistSimResF);
END OpenDWDistFile;

PROCEDURE WriteDWDistResults;
  CONST TAB = 11C;
  VAR i,ci,j: INTEGER;
BEGIN (* WriteResults *)
  FOR i := fstSite TO maxSiteIndex DO
    PutReal(dWdistSimResF, CurrentTime(),15,7);
    WriteChar(dWdistSimResF,TAB);
    PutInteger(dWdistSimResF,i,15); WriteChar(dWdistSimResF,
      TAB);
    FOR j := fstDirection TO lastDirection DO
      PutLongReal(dWdistSimResF, nbr.distAdjD^[i]^[j+1],15,7);
      WriteChar(dWdistSimResF, TAB);
    END(*FOR*);
    WriteEOL(dWdistSimResF);
  END(*FOR*);
END WriteDWDistResults;

PROCEDURE CloseDWDistFile;
BEGIN (* CloseFile *)
  Close(dWdistSimResF);
END CloseDWDistFile;

PROCEDURE OpenCFDistFile;
  CONST TAB = 11C;
  VAR resCode: INTEGER;
      ci: INTEGER;
BEGIN (* OpenFile *)
  cFdistSimResF := neverOpenedFile;
  AssignString(cFdistSimResultsFileName,cFdistSimResF.filename);

```

```

Lookup(cFdistSimResF,cFdistSimResF.filename,TRUE(*new*));
WriteChars(cFdistSimResF, "Year"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "Site Nr"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "NE"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "ENE"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "E"); WriteChar(cFdistSimResF, TAB);
WriteChars(cFdistSimResF, "ESE"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "SE"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "SSE"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "S"); WriteChar(cFdistSimResF, TAB);
WriteChars(cFdistSimResF, "SSW"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "SW"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "WSW"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "W"); WriteChar(cFdistSimResF, TAB);
WriteChars(cFdistSimResF, "WNW"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "NW"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "NNW"); WriteChar(cFdistSimResF,
      TAB);
WriteChars(cFdistSimResF, "N"); WriteChar(cFdistSimResF, TAB);
WriteChars(cFdistSimResF, "NNE"); WriteChar(cFdistSimResF,
      TAB);
WriteEOL(cFdistSimResF);
END OpenCFDistFile;

PROCEDURE WriteCFDistResults;
  CONST TAB = 11C;
  VAR i,ci,j: INTEGER;
BEGIN (* WriteResults *)
  FOR i := fstSite TO maxSiteIndex DO
    PutReal(cFdistSimResF, CurrentTime(),15,7);
    WriteChar(cFdistSimResF,TAB);
    PutInteger(cFdistSimResF,i,15); WriteChar(cFdistSimResF,
      TAB);
    FOR j := fstDirection TO lastDirection DO
      PutLongReal(cFdistSimResF, nbr.distAdjC^[i]^[j+1],15,7);
      WriteChar(cFdistSimResF, TAB);
    END(*FOR*);
    WriteEOL(cFdistSimResF);
  END(*FOR*);
END WriteCFDistResults;

PROCEDURE CloseCFDistFile;
BEGIN (* CloseFile *)
  Close(cFdistSimResF);
END CloseCFDistFile;

```

```
PROCEDURE OpenFiles;
BEGIN (* OpenFiles *)
  OpenMigFile;
  OpenUWDistFile;
  OpenDWDistFile;
  OpenCFDistFile;
END OpenFiles;

PROCEDURE WriteResults;
BEGIN (* WriteResults *)
  WriteMigResults;
  WriteUWDistResults;
  WriteDWDistResults;
  WriteCFDistResults;
END WriteResults;

PROCEDURE CloseFiles;
BEGIN (* CloseFiles *)
  CloseMigFile;
  CloseUWDistFile;
  CloseDWDistFile;
  CloseCFDistFile;
END CloseFiles;

PROCEDURE DeclareModelObjects;
BEGIN
  DeclP(cf1, 0.0068, 0.004, 0.009, noRtc,
    "cf1 (min exhausted females)", "cf1", "/km");
  DeclP(cf2, 0.042, 0.016, 0.087, noRtc,
    "cf2 (increase in exhausted females with defoliation)",
    "cf2", "/km");
  DeclP(cf3, 0.95, 0.85, 1.0, noRtc,
    "cf3 (y-intercept of maximum attractivity for egg
    deposition)", "cf3", "");
  DeclP(cf4, -0.72, -0.92, -0.52, noRtc,
    "cf4 (regression coef. of decrease in attractivity with
    defoliation)", "cf4", "");
  DeclP(cf5, 0.0, 0.0, 0.5, noRtc,
    "cf5 (fraction of females not transported by wind)",
    "cf5", "%");
  DeclP(cf6, 0.00, 0.00, 1.0, noRtc,
    "cf6 (frequency of turbulence)", "cf6", "%");
  DeclP(cf13, 2.0, 0.0, 2.5, noRtc,
    "cf13 (proportion of flight distance in zigzag for windspeed
    1.93m/s)", "cf13", "%");
  DeclP(cf14, 0.261, 0.1, 0.35, noRtc,
    "cf14 (fraction of air speed from flight in strong winds",
    "cf14", "%");
END DeclareModelObjects;

PROCEDURE ActivateLBMFlight(m: Model);
BEGIN (* ActivateLBMFlight *)
  IF NOT IsLBMFlightActive() THEN
    ownerMF := m;
    DeclareModelObjects;
```

```
    END(*IF*);
END ActivateLBMFlight;

PROCEDURE IsLBMFlightActive(): BOOLEAN;
BEGIN (* IsLBMFlightActive *)
    RETURN MDeclared(ownerMF) AND PDeclared(ownerMF,cfl)
    (* assume c1 existence implies existence of all other objects *)
END IsLBMFlightActive;

PROCEDURE DeactivateLBMFlight;
BEGIN (* DeactivateLBMFlight *)
    IF NOT IsLBMFlightActive() THEN
        ownerMF := notDeclaredModel;
    END(*IF*);
END DeactivateLBMFlight;

(*****
(*#####  Module Management  #####*)
(*****

PROCEDURE InitLBMFlight;
BEGIN (*InitLBMLifeCycle*)
    ownerMF := notDeclaredModel;
END InitLBMFlight

BEGIN
    InitLBMFlight;
END LBMFlight.
```


LBMFLYPARS

```
DEFINITION MODULE LBMFLYPars;

(*****

Module LBMFlightPars      (Version 2.0)

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Purpose  Reads parameters from 'Tab.7-14 Abteilungen.DAT' (a
         combination of tables 7 -14 from Fischlin 1983 but
         for each forest compartment
         instead of 'site') necessary for the model M11,
         migration within
         the Engadine valley. Then stores these parameters
         with new names
         for use in the module LBMFlight.

References

      Fischlin, A., 1982. Analyse eines Wald-Insekten-
      Systems: Der subalpine Lärchen-Arvenwald und der
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      Switzerland, pp. 294.

Programming

  o Design
    Bronwyn Price          22/03/2004

  o Implementation
    Bronwyn Price          22/03/2004

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Last revision of definition: 13/09/2005 BRP

*****)
```

```

FROM SimBase IMPORT Parameter;

(* ScienceLib *)
FROM LgMatrices    IMPORT LMatrix, notAllocatedLMatrix,
    MatrixExists, AllocMatrix, DeallocMatrix,
    SetColIds, GetColIds, NRows, NCols;
FROM LgMatIO      IMPORT WriteMatrix, SetMatrixOutputParams;

CONST
  nilSiteIndex = -1;
  fstSite = 1;
  UE = 0;
  maxSiteIndex = 420;
  fstDirection = 0;
  lastDirection = 7;

TYPE
  NeighbourDirection = [fstDirection..lastDirection];
  SiteAttribute = ARRAY [fstSite..maxSiteIndex] OF Parameter;
  DirectionParameter = ARRAY [fstSite..maxSiteIndex],
    [fstDirection..lastDirection] OF Parameter;
  AdjacentSite = ARRAY [UE..maxSiteIndex] OF ARRAY
    NeighbourDirection OF INTEGER;

  SiteParameter = RECORD
    c7,c8,c9,calmFrac,weakWindsFrac,strongWindsFrac:
    SiteAttribute;
  END;

VAR
  sp: SiteParameter;

PROCEDURE LoadParameters;

END LBMFLyPars.

```

```
IMPLEMENTATION MODULE LBMFLyPars;
```

```

(*
  Implementation and Revisions:
  =====

  Author   Date           Description of change
  -----
  AF       28/01/2004     First implementation
  BRP     15/03/2004     Mapping table parameters to new storable
                        parameters
  BRP     23/03/2004     Final Implmentation
  BRP     07/09/2005     Adaptation for use in M11 with 420
                        Abteliungen
                        Introduction of records ParsFromFile and
                        Neighbourhood
                        containing long matrices for parameters *)

```

```

(* MW *)
FROM SimBase IMPORT Parameter;

FROM ReadData IMPORT OpenDataFile, CloseDataFile,
  AtEOL, TestEOF, SkipHeaderLine,
  negLogDelta, GetMissingReal;

FROM DMLanguage IMPORT alloK;
FROM DMWindIO IMPORT WriteString, WriteReal, WriteInt, WriteLn;

FROM DMConversions IMPORT IntToString, StringToLongReal,
  LongIntToString, StringToInt, UndefLONGREAL;
FROM DMStrings IMPORT AssignString;
FROM DMPortab IMPORT SR, LR;
FROM DMMathLib IMPORT Real;

FROM LgMatrices IMPORT LMatrix, notAllocatedLMatrix,
  MatrixExists, AllocMatrix, DeallocMatrix,
  SetColIds, GetColIds, NRows, NCols;
FROM LgMatIO IMPORT WriteMatrix, SetMatrixOutputParams;

FROM LBMValley IMPORT
  Valley, UpperEngadine, Site, DoForAllSites, AppendSiteIndex,
  SiteIndex,
  Neighbourhood, nbr;

(* for MyReadData *)
IMPORT ReadData;
IMPORT DMFiles;
IMPORT DMConversions;
IMPORT DMStrings;
IMPORT DMEditFields;
IMPORT DMWindIO;
IMPORT DMWindows;
IMPORT DMSystem;
IMPORT DMEnterForms;
IMPORT DMMaster;
IMPORT Errors;

MODULE MyReadData;
(*****
  FROM ReadData IMPORT dataF, GetEOSCode, ErrMsgProc, Error,
    ErrorType, readingAborted, NumbType
  FROM DMFiles IMPORT Response, TextFile,
    GetExistingFile, Lookup, Reset, Close,
    EOF, Again, ReadChar, ReadChars, EOL;
  FROM DMConversions IMPORT IntToString, StringToInt,
    StringToLongInt,
    RealToString, StringToReal, StringToLongReal, RealFormat;
  FROM DMStrings IMPORT Concat, AssignString,
    String, NewString, PutString, Length;
  FROM DMEditFields IMPORT EditItem, PushButton,
    UseAsDefaultButton;

```

```

FROM DMWindIO IMPORT SelectForOutput,
  SetWindowFont, WindowFont, FontStyle, FontStyles,
  GetPos, SetPos, MaxCol,
  WriteLn, WriteInt, Write, WriteString, WriteReal,
  WriteLongReal, WriteLongInt, CellWidth;
FROM DMWindows IMPORT Window, nonexistent, WindowsDone,
  WindowKind, ScrollBars, CloseAttr, ZoomAttr, WFFixPoint,
  WindowFrame, CreateWindow, SetRestoreProc, DummyRestoreProc,
  AutoRestoreProc, GetWindowFrame, WindowExists, PutOnTop,
  CreateModalWindow, RemoveWindow,
  ModalWindowKind, UseWindowModally;
FROM DMSystem IMPORT ScreenWidth, ScreenHeight, MenuBarHeight;
FROM DMEnterForms IMPORT FormFrame, DefltUse, WriteLabel,
  IntField, RealField, UseEntryForm;
FROM DMMaster IMPORT SoundBell, Read;

EXPORT GetInt, GetReal, GetLongInt, GetLongReal,
  GetChars, SetReadingMode, GetReadingMode, ReadingModes,
  EnableTracing, DisableTracing, InsertEmptyLnsInTrace,
  traceWindow, CreateTraceWindow, RemoveTraceWindow;

TYPE
  ReadingModes = (freeFormat, tabDelimited,
                 lineOrientedFreeFormat fixedFormat);

VAR
  curReadingMode: ReadingModes;
  tracing : BOOLEAN;
  traceWindow: Window;

PROCEDURE SetReadingMode (rm: ReadingModes);
BEGIN
  curReadingMode := rm;
END SetReadingMode;

PROCEDURE GetReadingMode(VAR rm: ReadingModes);
BEGIN
  rm := curReadingMode;
END GetReadingMode;

PROCEDURE CreateTraceWindow;
  VAR wf: WindowFrame;
BEGIN
  wf.x:= 1; wf.y:= 1;
  wf.w:= ScreenWidth()-2; wf.h:= ScreenHeight()-
    MenuBarHeight()-2;
  CreateWindow(traceWindow,
    GrowOrShrinkOrDrag, WithoutScrollBars,
    WithCloseBox, WithoutZoomBox, bottomLeft,
    wf, 'Trace Reading', DummyRestoreProc);
  SetWindowFont(Monaco,9,FontStyle{ }); SetPos(1,1);
END CreateTraceWindow;

```

```
PROCEDURE RemoveTraceWindow;
BEGIN
  RemoveWindow(traceWindow);
END RemoveTraceWindow;

PROCEDURE EnableTracing;
BEGIN
  IF WindowExists(traceWindow) THEN
    PutOnTop(traceWindow);
    SelectForOutput(traceWindow);
  ELSE
    CreateTraceWindow;
  END(*IF*);
  WriteLn;
  WriteLn;
  WriteString("Trace reading enabled. "); WriteLn;
  WriteString("Please press always a key to continue reading
");
  WriteString("after an item has been displayed, unless you");
  WriteString("enter key:"); WriteLn;
  WriteString("'A' - aborts whole reading process"); WriteLn;
  WriteString("'N' - normal continuation without tracing");
  WriteLn;
  WriteLn;
  tracing := TRUE
END EnableTracing;

PROCEDURE DisableTracing;
BEGIN
  tracing := FALSE;
  SelectForOutput(traceWindow);
  WriteLn;
  WriteString("Trace reading disabled. "); WriteLn;
END DisableTracing;

PROCEDURE AskForCont;
CONST prompt = " (any|A|N)>"; lep = 11 (*Length(prompt)*);
VAR ch: CHAR; l,c: CARDINAL;
BEGIN
  GetPos(l,c); SetPos(l,MaxCol()-lep-5);
  WriteString(prompt); Read(ch); WriteLn;
  IF CAP(ch)='A' THEN
    readingAborted:=TRUE
  ELSIF CAP(ch)='N' THEN
    DisableTracing;
  END(*IF*);
END AskForCont;

PROCEDURE InsertEmptyLnsInTrace;
BEGIN
  IF tracing THEN
    SelectForOutput(traceWindow);
    WriteLn;
    WriteString("-----");
    WriteLn;
  END(*IF*)
END InsertEmptyLnsInTrace;
```

```

CONST
  buttonWidth = 10;

VAR
  (* error messages *)
  CurrentErrorMsg      : ErrMsgProc;
  curMinStr, curMaxStr : ARRAY [0..63] OF CHAR;
  errorWindow          : Window;
  termModDial, cancModDial : BOOLEAN;

  (*. handling of missing values .*)
  missingValC : CHAR;
  missingR    : REAL;
  missingLongR: LONGREAL;
  missingI    : INTEGER;
  missingLongI: LONGINT;
  EOS        : CHAR;

  (*. correct illegal values .*)
  curError   : Error;
  corrInt    : INTEGER;
  corrReal   : REAL;
  corrected  : BOOLEAN;

PROCEDURE SkipGap(VAR f: TextFile);
  VAR ch: CHAR;
BEGIN
  IF NOT EOF(f) AND (dataF.curChar <> EOS) THEN
    REPEAT
      ReadChar(f, ch)
    UNTIL (ch>" ") OR (dataF.curChar = EOS) OR EOF(f);
    Again(f);
  END(*IF*);
END SkipGap;

(*****
*##### Alerts #####*
*****)

PROCEDURE WriteAlert(error: Error);
  VAR curType: ErrorType;
BEGIN
  curType:=error.errorType;

  IF error.numbType=Real THEN
    RealToString(error.maxR, curMaxStr, 0, 3,
      ScientificNotation);
    RealToString(error.minR, curMinStr, 0, 3,
      ScientificNotation)
  ELSIF error.numbType=Integer THEN
    IntToString(error.maxI, curMaxStr, 0);
    IntToString(error.minI, curMinStr, 0)
  END;

```

```
SetWindowFont(Chicago, 12, FontStyle{});
SetPos(1, 2); WriteString("Datafile: "); SetPos(1, 15);
Write(""); WriteString(dataF.filename); Write("");
SetPos(2, 2);
CASE curType OF
    NoInt: WriteString("Integer expected but the following
illegal string      encountered:")
    | NoReal: WriteString("Real expected but the following
illegal string encountered:")
    | TooBig: WriteString("The following number too large for
given range:")
    | TooSmall: WriteString("The following number too small
for given range:")
    | NotEqual: WriteString("The following number differs from
expected value:")
    | EndOfFile: WriteString("End of file reached!")
    | FileNotFound: SetPos(4, 2); WriteString("File not
found")
    | DataFNotOpen: SetPos(4, 2); WriteString("The datafile
could not be opened!")
END(*CASE*);

IF (curType<>FileNotFound) AND (curType<>DataFNotOpen) THEN
    IF curType=EndOfFile THEN
        SetPos(3, 2);
        WriteString("Not enough data in data file. Stopped at:")
    END;

    SetPos(3, 20);
    IF (curType=NoInt) OR (curType=NoReal) THEN
        WriteString('') END;
    IF curType#EndOfFile THEN WriteString(error.strFound) END;
    IF (curType=NoInt) OR (curType=NoReal) THEN
        WriteString('') END;

    SetPos(4, 3); WriteString("Expected item"); SetPos(4, 20);
    Write("");
    WriteString(error.desc); Write("");
    SetPos(5, 3); WriteString("at line/location #");
    SetPos(5, 20);
    WriteInt(error.loc, 4);

    IF curType=TooBig THEN
        SetPos(6, 2); WriteString("Number should be ≤ ");
        WriteString(curMaxStr)
    ELSIF curType=TooSmall THEN
        SetPos(6, 2); WriteString("Number should be ≥ ");
        WriteString(curMinStr)
    ELSIF curType=NotEqual THEN
        SetPos(6, 2); WriteString("Number should be = ");
        WriteString(curMinStr)
    END(*IF*)
END(*IF*)
END WriteAlert;
```

```

PROCEDURE Abort;
BEGIN
  termModDial:=TRUE;
  RemoveWindow(errorWindow);
  HALT
END Abort;

PROCEDURE CorrectData;
  VAR corrDataForm: FormFrame;
BEGIN
  termModDial:=TRUE;
  RemoveWindow(errorWindow);
  WITH corrDataForm DO
    x:=-1;
    y:=-1;
    lines:=5;
    columns:=30
  END(*WITH*);
  IF curError.numbType=Integer THEN
    WriteLabel(1, 2, "Enter an INTEGER between");
    Concat(curMinStr, " and ");
    Concat(curMinStr, curMaxStr);
    WriteLabel(2, 2, curMinStr);
    IntField(3, 2, 10, corrInt, noDeflt, curError.minI,
             curError.maxI)
  ELSIF curError.numbType=Real THEN
    WriteLabel(1, 2, "Enter a REAL between");
    Concat(curMinStr, " and ");
    Concat(curMinStr, curMaxStr);
    WriteLabel(2, 2, curMinStr);
    RealField(3, 2, 10, corrReal, noDeflt, curError.minR,
             curError.maxR)
  END(*IF*);
  UseEntryForm(corrDataForm, corrected)
END CorrectData;

PROCEDURE Continue;
BEGIN
  termModDial:=TRUE;
  RemoveWindow(errorWindow)
END Continue;

PROCEDURE AbortReading;
BEGIN
  termModDial:=TRUE;
  RemoveWindow(errorWindow);
  readingAborted:=TRUE
END AbortReading;

PROCEDURE DefltErrorMsg(error: Error);
  VAR
    errorFrame: WindowFrame;
    contBut, newValBut,
    abortBut, abortReadBut,
    okBut, EOFBut, notOpBut : EditItem;
BEGIN
  WITH errorFrame DO

```



```

    w:=420;
    h:=160;
    x:=(ScreenWidth()-errorFrame.w) DIV 2;
    y:=(ScreenHeight()-errorFrame.h) DIV 2
END(*WITH*);
CreateModalWindow(errorWindow, DoubleFrame,
                  WithoutScrollBars, errorFrame,
                  AutoRestoreProc);
WriteAlert(error);
WITH error DO
  IF (errorType=NoInt) OR (errorType=NoReal) OR
     (errorType=NotEqual) OR
     (errorType=TooBig) OR (errorType=TooSmall) THEN
    PushButton(errorWindow, abortReadBut, 12, 44, 13,
              "Stop reading", AbortReading);
    PushButton(errorWindow, abortBut,      12, 20, 13,
              "Abort program", Abort);
    PushButton(errorWindow, newValBut,    140, 20, 19,
              "Enter correct value", CorrectData);
    PushButton(errorWindow, contBut,      320, 20, 11,
              "Continue", Continue);
    UseAsDefaultButton(newValBut)
  ELSIF errorType=FileNotFound THEN
    PushButton(errorWindow, okBut, 180, 20, 10, "OK",
              Continue);
    UseAsDefaultButton(okBut)
  ELSIF errorType=DataFNotOpen THEN
    PushButton(errorWindow, notOpBut, 160, 20, 10, "Abort",
              Abort);
    UseAsDefaultButton(notOpBut)
  ELSIF errorType=EndOfFile THEN
    PushButton(errorWindow, EOFBut, 160, 20, 10, "Abort",
              Abort);
    UseAsDefaultButton(EOFBut)
  END(*IF*)
END(*WITH*);
SoundBell;
UseWindowModally(errorWindow, termModDial, cancModDial)
END DeflterrorMsg;

CONST
  TAB = 11C;

PROCEDURE SkipGapTillTab(VAR dataF: TextFile);
  VAR ch: CHAR;
BEGIN
  IF NOT EOF(dataF) AND (dataF.curChar<>EOS)
    AND (dataF.curChar<>TAB) AND (dataF.curChar<>EOL)
  THEN
    REPEAT
      ReadChar(dataF, ch)
    UNTIL (ch>" ") OR (ch=EOS) OR (ch=TAB) OR (ch=EOL)
    OR EOF(dataF);
    IF (ch>" ") OR (ch=EOS) OR EOF(dataF) THEN Again(dataF)
    END;
  END(*IF*);
END SkipGapTillTab;

```

```

PROCEDURE ReadStringTillTab (VAR string: ARRAY OF CHAR);
  (* reads a string beginning from the current position until a
  character < " ", e.g. a TAB is encountered. *)
  VAR
    i,n: INTEGER; ch: CHAR;
  BEGIN
    IF NOT EOF(dataF) THEN
      i:= 0; n:= HIGH(string);
      ReadChar(dataF,ch); IF ch=TAB THEN ReadChar(dataF,ch) END;
      WHILE (ch>=" ") AND (i<=n) AND NOT EOF(dataF) AND
        (ch<>EOS) DO
        string[i]:= ch;
        ReadChar(dataF,ch);
        INC(i);
      END(*WHILE*);
      IF (ch>=" ") AND (i<=n) THEN string[i]:= ch; INC(i); END;
      IF (ch<>EOL) AND (ch<>EOS) THEN Again(dataF) END;
      IF i<=n THEN string[i]:= 0C END;
    ELSE
      (* handle error *) HALT;
    END(*IF*);
  END ReadStringTillTab;

PROCEDURE GetChars (VAR string: ARRAY OF CHAR);
  BEGIN
    IF NOT readingAborted THEN
      ReadStringTillTab(string);
      IF tracing THEN
        WriteString("GetChars: "); WriteString(string);
        Write("");
        AskForCont;
      END(*IF*);
    END(*IF*);
  END GetChars;

PROCEDURE SkipComment; (*allows nested comments*)
  VAR
    end: BOOLEAN;
    ch: CHAR;
  BEGIN
    end:=FALSE;
    ReadChar(dataF, ch);
    REPEAT
      IF ch<>"*" THEN
        ReadChar(dataF, ch);
        IF ch="(" THEN
          ReadChar(dataF, ch);
          IF ch="*" THEN
            SkipComment;
          END;
        END;
      ELSE (* ch = "*" *)
        ReadChar(dataF, ch);
        end:= ch=")";
      END(*IF*);
    UNTIL end;
  END SkipComment;

```

```

PROCEDURE SkipGapOrComment;
  (*. skips all characters <= " " and all text enclosed in
  comment
  * brackets as used in Modula-2, i.e. "(* ..... *)" .*)
VAR
  ch: CHAR;
  textEncountered: BOOLEAN;
BEGIN
  IF NOT EOF(dataF) THEN
    textEncountered := FALSE;
    REPEAT
      SkipGap(dataF);
      ReadChar(dataF, ch);
      IF ( ch = "(" ) THEN
        ReadChar(dataF, ch);
        IF ( ch = "*" ) THEN      (* comment *)
          SkipComment;
        ELSE
          textEncountered := TRUE;
          Again(dataF);
          Again(dataF);
        END; (* IF *)
      ELSE
        textEncountered := TRUE;
        Again(dataF);
      END; (* IF *)
    UNTIL textEncountered;
  END; (* IF *)
END SkipGapOrComment;

PROCEDURE ReadCharsUnlessAComment(VAR string: ARRAY OF CHAR);
  (*. reads a string beginning from the current position until
  * a character <= " " or a comment is encountered. .*)
VAR
  i,n: INTEGER;
  ch1, ch2: CHAR;
BEGIN
  IF NOT readingAborted THEN
    ch2 := 0C;
    IF NOT EOF(dataF) THEN
      i:= 0; n:= HIGH(string);
      ReadChar(dataF,ch1); IF NOT EOF(dataF) THEN
        ReadChar(dataF,ch2) END;
      WHILE (ch1>" ") AND (i<=n) AND NOT EOF(dataF)
        AND NOT ((ch1="(") AND (ch2="*")) DO
        string[i]:= ch1;
        ch1 := ch2;
        ReadChar(dataF,ch2);
        INC(i);
      END(*WHILE*);
      IF EOF(dataF) THEN
        IF (ch1>" ") THEN string[i]:= ch1; INC(i); END;
      ELSE
        Again(dataF)
      END;
    END;
  END;

```

```

        END;
        Again(dataF);
        IF i<=n THEN string[i]:= 0C END;
    ELSE
        curError.errorType:=EndOfFile;
        CurrentErrorMsg(curError) ( * contains HALT * )
    END(*IF*);
END(*IF*);
END ReadCharsUnlessAComment;

PROCEDURE GetInt(d: ARRAY OF CHAR; locNr: INTEGER;
                VAR x: INTEGER; min,max: INTEGER);

VAR
    s: ARRAY [0..255] OF CHAR;
    legalNum: BOOLEAN;
BEGIN
    IF NOT readingAborted THEN
        AssignString(d, curError.desc);
        curError.loc:=locNr;
        SkipGapOrComment; ReadCharsUnlessAComment(s);
        StringToInt(s,x,legalNum);
        IF (s[0]=missingValC) AND (s[1]=0C) THEN
            x:= missingI; legalNum:= TRUE;
        END(*IF*);
        IF (NOT legalNum) OR
            (legalNum AND NOT (x=missingI) AND ((x<min)
            OR (x>max)))
        THEN
            AssignString(d, curError.desc);
            AssignString(s, curError.strFound);
            curError.maxI:=max;
            curError.minI:=min;
            curError.numbType:=Integer;
            corrected:=FALSE;
            IF NOT legalNum THEN
                curError.errorType:=NoInt;
            ELSIF min=max THEN
                curError.errorType:=NotEqual;
            ELSIF x>max THEN
                curError.errorType:=TooBig;
            ELSIF x<min THEN
                curError.errorType:=TooSmall;
            END(*IF*);
            CurrentErrorMsg(curError);
            IF corrected THEN x:=corrInt; corrected:=FALSE END;
        END(*IF*);
        IF tracing THEN
            WriteString("GetInt (");
            WriteString(d); WriteString("; at #");
            WriteInt(locNr,0); WriteString("): ");
            WriteInt(x,7); AskForCont;
        END(*IF*);
    END(*IF*);
END GetInt;

```

```
PROCEDURE GetReal(d: ARRAY OF CHAR; locNr: INTEGER;
                 VAR x: REAL; min,max: REAL);
VAR
  s: ARRAY [0..255] OF CHAR;
  legalNum: BOOLEAN;
BEGIN
  IF NOT readingAborted THEN
    AssignString(d, curError.desc);
    curError.loc:=locNr;
    SkipGapOrComment; ReadCharsUnlessAComment(s);
    StringToReal(s,x,legalNum);
    IF (s[0]=missingValC) AND (s[1]=0C) THEN
      x:= missingR; legalNum:= TRUE;
    END(*IF*);
    IF (NOT legalNum) OR
      (legalNum AND (x<>missingR) AND ((x<min) OR (x>max)))
    THEN
      AssignString(s, curError.strFound);
      curError.maxR:=max;
      curError.minR:=min;
      curError.numbType:=Real;
      corrected:=FALSE;
      IF NOT legalNum THEN
        curError.errorType:=NoReal;
      ELSIF min=max THEN
        curError.errorType:=NotEqual;
      ELSIF x>max THEN
        curError.errorType:=TooBig;
      ELSIF x<min THEN
        curError.errorType:=TooSmall;
      END(*IF*);
      CurrentErrorMsg(curError);
      IF corrected THEN x:=corrReal; corrected:=FALSE END;
    END(*IF*);
    IF tracing THEN
      WriteString("GetReal (");
      WriteString(d); WriteString("; at #");
      WriteInt(locNr,0); WriteString("): ");
      WriteReal(x,12,4); AskForCont;
    END(*IF*);
  END(*IF*);
END GetReal;

PROCEDURE GetLongInt(d: ARRAY OF CHAR; locNr: INTEGER;
                    VAR x: LONGINT; min,max: LONGINT);
VAR
  s: ARRAY [0..255] OF CHAR;
  legalNum: BOOLEAN;
  minlint, maxlint: LONGINT;
BEGIN
  IF NOT readingAborted THEN
    AssignString(d, curError.desc);
    curError.loc:=locNr;
    SkipGapOrComment; ReadCharsUnlessAComment(s);
    StringToLongInt(s,x,legalNum);
    IF (s[0]=missingValC) AND (s[1]=0C) THEN
```

```

    x:= missingI; legalNum:= TRUE;
END(*IF*);
IF (NOT legalNum) OR
    (legalNum AND NOT (x=missingLongI) AND ((x<min)
OR (x>max)))
THEN
    AssignString(d, curError.desc);
    AssignString(s, curError.strFound);
    maxlint := MAX(INTEGER);
    minlint := MIN(INTEGER);
    IF ABS(max) <= maxlint THEN curError.maxI:=max ELSE
        curError.maxI:=MAX(INTEGER) END;
    IF ABS(min) >= minlint THEN curError.minI:=min ELSE
        curError.minI:=MIN(INTEGER) END;
    curError.numbType:=Integer;
    corrected:=FALSE;
    IF NOT legalNum THEN
        curError.errorType:=NoInt;
    ELSIF min=max THEN
        curError.errorType:=NotEqual;
    ELSIF x>max THEN
        curError.errorType:=TooBig;
    ELSIF x<min THEN
        curError.errorType:=TooSmall;
    END(*IF*);
    CurrentErrorMsg(curError);
    IF corrected THEN x:=corrInt; corrected:=FALSE END;
END(*IF*);
IF tracing THEN
    WriteString("GetLongInt (");
    WriteString(d); WriteString("; at #");
    WriteInt(locNr,0); WriteString("): ");
    WriteLongInt(x,14); AskForCont;
END(*IF*);
END(*IF*);
END GetLongInt;

PROCEDURE GetLongReal(d: ARRAY OF CHAR; locNr: INTEGER;
    VAR x: LONGREAL; min,max: LONGREAL);
VAR
    s: ARRAY [0..255] OF CHAR;
    legalNum: BOOLEAN;
BEGIN
    IF NOT readingAborted THEN
        AssignString(d, curError.desc);
        curError.loc:=locNr;
        SkipGapOrComment; ReadCharsUnlessAComment(s);
        StringToLongReal(s,x,legalNum);
        IF (s[0]=missingValC) AND (s[1]=0C) THEN
            x:= missingR; legalNum:= TRUE;
        END(*IF*);
        IF (NOT legalNum) OR
            (legalNum AND (x<>missingLongR) AND ((x<min)
OR (x>max)))
        THEN
            AssignString(s, curError.strFound);

```

```

        curError.maxR:=max;
        curError.minR:=min;
        curError.numbType:=Real;
        corrected:=FALSE;
        IF NOT legalNum THEN
            curError.errorType:=NoReal;
        ELSIF min=max THEN
            curError.errorType:=NotEqual;
        ELSIF x>max THEN
            curError.errorType:=TooBig;
        ELSIF x<min THEN
            curError.errorType:=TooSmall;
        END(*IF*);
        CurrentErrorMsg(curError);
        IF corrected THEN x:=corrReal; corrected:=FALSE END;
    END(*IF*);
    IF tracing THEN
        WriteString("GetLongReal (");
        WriteString(d); WriteString("; at #");
        WriteInt(locNr,0); WriteString("): ");
        WriteLongReal(x,12,4); AskForCont;
    END(*IF*);
    END(*IF*);
    END GetLongReal;
BEGIN
    CurrentErrorMsg:=DefltErrorMsg;
    readingAborted:=FALSE;
    dataF.curChar:= 0C;
    missingValC := "N";
    missingR := 0.0;
    missingLongR := 0.0D;
    missingI := 0;
    missingLongI := 0D;
    EOS := 37C; (* ASCII us (Unit Separator) *)
    SetReadingMode(freeFormat);
    END MyReadData;
(*****
TYPE
    ParsFromFile = RECORD
        weakWindFrac, strongWindFrac, areaFrac, dist,
        adjacent: LMatrix;
        colNo, firstCol,lastCol: INTEGER;
        dataRowNo, lineNo,skipRows,
        fstDataRow,lstDataRow: INTEGER;
        END(*RECORD*);

CONST
    myModule = "LBMFLyPars";

VAR
    pff: ParsFromFile;

    PROCEDURE GetErrMsg (msgnr: INTEGER; VAR msg: ARRAY OF CHAR);
BEGIN
    CASE msgnr OF

```

```

| Errors.onlyAnInsert:
    AssignString("Error encountered: Δ",msg);
ELSE
    msg[0] := 0C;
    (* signals to Errors to look for other sources *)
    END(*CASE*);
END GetErrMsg;

PROCEDURE WarnAndAbort;
    VAR w: ARRAY [0..255] OF CHAR;
BEGIN (* WarnAndAbort *)
    w := "Sorry, allocation of data has to be aborted";

Errors.Info(Errors.onlyAnInsert,GetErrMsg,myModule,"InitData",w);
    END WarnAndAbort;

PROCEDURE AllocateMatrices ( VAR(*In/Out*) resCode: INTEGER);
    VAR err: ARRAY [0..255] OF CHAR;
BEGIN (* AllocateTheMatrix *)
    resCode:= allOk;
    IF resCode<>allOk THEN RETURN END;
    AllocMatrix(nbr.c10, nbr.dataRowNo,nbr.nColNo,
    UndefLONGREAL(), resCode,err);
    AllocMatrix(nbr.c11, nbr.dataRowNo, nbr.nColNo,
    UndefLONGREAL(), resCode,err);
    AllocMatrix(nbr.c12, nbr.dataRowNo,nbr.nColNo,
    UndefLONGREAL(), resCode,err);
    AllocMatrix(nbr.c15, nbr.dataRowNo, nbr.nColNo,
    UndefLONGREAL(), resCode, err);
    AllocMatrix(nbr.adjSite, nbr.dataRowNo,nbr.nColNo,
    UndefLONGREAL(), resCode, err);
    AllocMatrix(nbr.w, nbr.dataRowNo, nbr.nColNo,
    UndefLONGREAL(), resCode, err);
    AllocMatrix(nbr.v, nbr.dataRowNo,nbr.nColNo,
    UndefLONGREAL(), resCode, err);
    AllocMatrix(nbr.cfw, nbr.dataRowNo, nbr.nColNo,
    UndefLONGREAL(), resCode, err);
    AllocMatrix(nbr.cfv, nbr.dataRowNo,nbr.nColNo,
    UndefLONGREAL(), resCode,err);
    AllocMatrix(nbr.uww, nbr.dataRowNo, nbr.nColNo,
    UndefLONGREAL(), resCode, err);
    AllocMatrix(nbr.uwv, nbr.dataRowNo,nbr.nColNo,
    UndefLONGREAL(), resCode,err);
    AllocMatrix(nbr.dww, nbr.dataRowNo, nbr.nColNo,
    UndefLONGREAL(), resCode, err);
    AllocMatrix(nbr.dwv, nbr.dataRowNo,nbr.nColNo,
    UndefLONGREAL(), resCode,err);
    AllocMatrix(nbr.phi, nbr.dataRowNo, nbr.nColNo,
    UndefLONGREAL(), resCode,err);
    AllocMatrix(nbr.the, nbr.dataRowNo,nbr.nColNo,
    UndefLONGREAL(), resCode,err);
    AllocMatrix(nbr.theD, nbr.dataRowNo, nbr.nColNo,
    UndefLONGREAL(), resCode,err);
    AllocMatrix(nbr.theU, nbr.dataRowNo,nbr.nColNo,
    UndefLONGREAL(), resCode,err);

```



```

AllocMatrix(nbr.theC, nbr.dataRowNo, nbr.nColNo,
  UndefLONGREAL(), resCode, err);
AllocMatrix(nbr.distAdj, nbr.dataRowNo, nbr.nColNo,
  UndefLONGREAL(), resCode, err);
AllocMatrix(nbr.distAdjC, nbr.dataRowNo, nbr.nColNo,
  UndefLONGREAL(), resCode, err);
AllocMatrix(nbr.distAdjD, nbr.dataRowNo, nbr.nColNo,
  UndefLONGREAL(), resCode,
  err);
AllocMatrix(nbr.distAdjU, nbr.dataRowNo, nbr.nColNo,
  UndefLONGREAL(), resCode,
  err);
AllocMatrix(nbr.w1, nbr.dataRowNo, nbr.tColNo,
  UndefLONGREAL(), resCode, err);
AllocMatrix(nbr.a1, nbr.dataRowNo, nbr.tColNo,
  UndefLONGREAL(), resCode, err);
AllocMatrix(nbr.w2, nbr.dataRowNo, nbr.tColNo,
  UndefLONGREAL(), resCode, err);
AllocMatrix(nbr.s1, nbr.dataRowNo, nbr.tColNo,
  UndefLONGREAL(), resCode, err);
AllocMatrix(nbr.s2, nbr.dataRowNo, nbr.tColNo,
  UndefLONGREAL(), resCode, err);
AllocMatrix(nbr.femfly, nbr.dataRowNo, nbr.tColNo,
  UndefLONGREAL(), resCode,
  err);
AllocMatrix(pff.weakWindFrac, pff.dataRowNo, pff.colNo,
  UndefLONGREAL(),
  resCode, err);
AllocMatrix(pff.strongWindFrac, pff.dataRowNo, pff.colNo,
  UndefLONGREAL(),
  resCode, err);
AllocMatrix(pff.areaFrac, pff.dataRowNo, pff.colNo,
  UndefLONGREAL(), resCode,
  err);
AllocMatrix(pff.dist, pff.dataRowNo, pff.colNo,
  UndefLONGREAL(), resCode,
  err);
AllocMatrix(pff.adjacent, pff.dataRowNo, pff.colNo,
  UndefLONGREAL(), resCode,
  err);
IF resCode<>allOk THEN
Errors.Info(resCode, GetErrMsg, myModule, "AllocateMatrices", err);
  END (*IF*);
END AllocateMatrices;

PROCEDURE InitMatrices;
BEGIN (* InitMatrices *)
  nbr.c10 := notAllocatedLMatrix;
  nbr.c11 := notAllocatedLMatrix;
  nbr.c12 := notAllocatedLMatrix;
  nbr.c15 := notAllocatedLMatrix;
  nbr.adjSite := notAllocatedLMatrix;
  nbr.w := notAllocatedLMatrix;
  nbr.v := notAllocatedLMatrix;
  nbr.cfw := notAllocatedLMatrix;
  nbr.cfv := notAllocatedLMatrix;

```

```

nbr.uww := notAllocatedLMatrix;
nbr.uwv := notAllocatedLMatrix;
nbr.dww := notAllocatedLMatrix;
nbr.dwv := notAllocatedLMatrix;
nbr.phi := notAllocatedLMatrix;
nbr.the := notAllocatedLMatrix;
nbr.theD := notAllocatedLMatrix;
nbr.theU := notAllocatedLMatrix;
nbr.theC := notAllocatedLMatrix;
nbr.distAdj := notAllocatedLMatrix;
nbr.distAdjC := notAllocatedLMatrix;
nbr.distAdjD := notAllocatedLMatrix;
nbr.distAdjU := notAllocatedLMatrix;
nbr.w1 := notAllocatedLMatrix;
nbr.a1 := notAllocatedLMatrix;
nbr.w2 := notAllocatedLMatrix;
nbr.s1 := notAllocatedLMatrix;
nbr.s2 := notAllocatedLMatrix;
nbr.femfly := notAllocatedLMatrix;
nbr.nColNo:= 0;
nbr.tColNo:= 0;
nbr.firstNCol:= 0;
nbr.lastNCol:= 0;
nbr.firstTCol:= 0;
nbr.lastTCol:= 0;
nbr.dataRowNo:= 0;
nbr.lineNo:= 0;
nbr.skipRows:= 0;
nbr.fstDataRow:= 0;
nbr.lstDataRow:= 0;
pff.weakWindFrac:= notAllocatedLMatrix;
pff.strongWindFrac:= notAllocatedLMatrix;
pff.areaFrac:= notAllocatedLMatrix;
pff.dist:= notAllocatedLMatrix;
pff.adjacent:= notAllocatedLMatrix;
pff.colNo:= 0;
pff.firstCol:= 0;
pff.lastCol:= 0;
pff.dataRowNo:= 0;
pff.lineNo:= 0;
pff.skipRows:= 0;
pff.fstDataRow:= 0;
pff.lstDataRow:= 0;
END InitMatrices;

PROCEDURE Cleanup;
BEGIN (* Cleanup *)
  IF MatrixExists(pff.weakWindFrac) THEN
    DeallocMatrix(pff.weakWindFrac) END;
  IF MatrixExists(pff.strongWindFrac) THEN
    DeallocMatrix(pff.strongWindFrac)
    END;
  IF MatrixExists(pff.areaFrac) THEN DeallocMatrix(pff.areaFrac)
  END;
  IF MatrixExists(pff.dist) THEN DeallocMatrix(pff.dist) END;
  IF MatrixExists(pff.adjacent) THEN DeallocMatrix(pff.adjacent)
  END;

```

```

END Cleanup;

PROCEDURE InitData ;
  VAR open: BOOLEAN; fn: ARRAY [0..127] OF CHAR;
      siteName, valleySide, exposition, adjList: ARRAY [0..127] OF
  CHAR;
  larches: LONGINT; area, forestedArea: REAL;
  calmFrac, weakWindsFrac, strongWindsFrac: SiteAttribute;
  resCode, s, siteid, nrAdjSites, j, i: INTEGER;
PROCEDURE MapParamtersToNewParameters;
BEGIN (* MapParamtersToNewParameters *)
  FOR i:= fstSite TO maxSiteIndex DO
    sp.c7[i] := calmFrac[i];
    sp.c8[i] := weakWindsFrac[i];
    sp.c9[i] := strongWindsFrac[i];
    FOR j := fstDirection TO lastDirection DO
      nbr.c10^[i]^[j+1] := pff.weakWindFrac^[i]^[j+1] ;
      nbr.c11^[i]^[j+1] := pff.strongWindFrac^[i]^[j+1] ;
      nbr.c12^[i]^[j+1] := pff.areaFrac^[i]^[j+1] ;
      nbr.c15^[i]^[j+1] := pff.dist^[i]^[j+1] ;
      nbr.adjSite^[i]^[j+1] := pff.adjacent^[i]^[j+1];
    END(*FOR*);
  END(*FOR*);
END MapParamtersToNewParameters;
BEGIN
  resCode:= allOk;
  fn := "Tab. 7-14 Abteilungen.DAT";
  (*. EnableTracing; .*) DisableTracing;
  Cleanup;
  InitMatrices;
  nbr.nColNo:= lastDirection + 1;
  nbr.tColNo:= maxSiteIndex;
  nbr.dataRowNo:= maxSiteIndex;
  pff.colNo:= lastDirection + 1;
  pff.dataRowNo:= maxSiteIndex;
  AllocateMatrices(resCode);
  IF resCode<>allOk THEN Cleanup; WarnAndAbort; RETURN END;
  OpenDataFile(fn, open(*. opened .*));
  SetReadingMode(tabDelimited);
  IF open(*. opened .*) THEN
    SkipHeaderLine;
    SkipHeaderLine;
    FOR i:= fstSite TO maxSiteIndex DO
      TestEOF; GetInt("site #", i, siteid, i, i);
      TestEOF; GetChars(siteName);
      TestEOF; GetChars(valleySide);
      TestEOF; GetChars(exposition);
      TestEOF;
      GetLongInt("larches", i, larches, 0, MAX(LONGINT) (*100000*));
      TestEOF; GetReal("Site area [ha]", i, area, 0.0, 850.0);
      TestEOF; GetReal("Forested site area [ha]", i, forestedArea,
        0.0, area);
      TestEOF; GetChars(adjList);
      TestEOF; GetInt("Nr. adjacent sites", i, nrAdjSites, 0, 8);
      FOR j := fstDirection TO lastDirection DO
        TestEOF;

```

```

    GetLongReal("Adjacentsite",i,pff.adjacent^[i]^[j+1],
      LR(Real(fstSite)),LR(Real(max SiteIndex)));
    TestEOF; GetLongReal("Mean distance to adjacentsite",i,
      pff.dist^[i]^[j+1], 0.0D,20.0D);
    TestEOF; GetLongReal("Adjacent site area fraction",i,
      pff.areaFrac^[i]^[j+1], 0.0D,2000.0D);
  END(*FOR*);
  TestEOF; GetReal("Calm wind system",i,calmFrac[i],
    0.0,100.0);
  TestEOF; GetReal("Weak wind system",i,weakWindsFrac[i],
    0.0,100.0);
  FOR j:= fstDirection TO lastDirection DO
    TestEOF;
    GetLongReal("Weak winds",i,pff.weakWindFrac^[i]^[j+1],
      0.0D,100.0D);
  END(*FOR*);
  TestEOF;
  GetReal("Strong wind system",i,strongWindsFrac[i],
    0.0D,100.0D);
  FOR j:= fstDirection TO lastDirection DO
    TestEOF;
    GetLongReal("Strong winds",i,
      pff.strongWindFrac^[i]^[j+1], 0.0D,100.0D);
  END(*FOR*);
  InsertEmptyLnsInTrace;
END(*FOR*);
CloseDataFile;
END(*IF*);
MapParamtersToNewParameters;
Cleanup;
END InitData;

PROCEDURE LoadParameters;
BEGIN (* LoadParameters *)
  InitData;
END LoadParameters;

(*****
(*#####  Module Management  #####*)
(*****

PROCEDURE InitLBMFLyPars;
BEGIN (*InitLBMFLyPars*)
  LoadParameters
END InitLBMFLyPars;

BEGIN (* LBMFLyPars *)
  InitLBMFLyPars;
END LBMFLyPars.

```

LBMMONIT

```

DEFINITION MODULE LBModMonit;

(*****

Module LBModMonit      (Version 1.0)

  Copyright (c) 2005 by Andreas Fischlin
  and Swiss Federal Institute of Technology Zurich ETHZ

Purpose  Monitors various objects from LBM model
         by writing their values onto files

Remarks This module is part of LBM model
         implementation M11

Programming

  o Design
    Andreas Fischlin      09/02/2005

  o Implementation
    Andreas Fischlin      09/02/2005

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  <http://www.sysecol.ethz.ch>

  Last revision of definition:  14/11/2005  BRP

***** )

FROM SimBase IMPORT AuxVar;
FROM LBMValley IMPORT Site;

TYPE
  ObjectSensor = PROCEDURE (VAR(*speed-up*) Site): AuxVar;

PROCEDURE StartMonitorObj(objs: ObjectSensor; fn: ARRAY OF
                        CHAR);
PROCEDURE StopMonitorObj(objs: ObjectSensor);

END LBModMonit.

```

```

IMPLEMENTATION MODULE LBModMonit;

(*
  Implementation and Revisions:
  =====

  Author   Date       Description of change
  -----   -
  AF       09/02/2005  First implementation
*)

(* MW *)
FROM SimBase IMPORT AuxVar, InstallClientMonitoring;

(* LBM *)
FROM LBMValley IMPORT Site, UpperEngadine, DoForAllSites;

VAR
  oneSensor: ObjectSensor;

PROCEDURE OpenFiles;
BEGIN (* OpenFiles *)

END OpenFiles;

PROCEDURE DoMonitor (VAR site: Site);
  VAR x: AuxVar;
BEGIN (* DoMonitor *)
  x := oneSensor(site);
END DoMonitor;

PROCEDURE Monitor;
BEGIN (* Monitor *)
  DoForAllSites(UpperEngadine, DoMonitor)
END Monitor;

PROCEDURE CloseFiles;
BEGIN (* CloseFiles *)

END CloseFiles;

PROCEDURE StartMonitorObj(objs: ObjectSensor; fn: ARRAY OF
                           CHAR);
BEGIN (* StartMonitorObj *)
  oneSensor := objs;
END StartMonitorObj;

PROCEDURE StopMonitorObj(objs: ObjectSensor);
BEGIN (* StopMonitorObj *)
END StopMonitorObj;

(*****
 *#####  Module Management  #####*)
(*****

```

```
PROCEDURE InitLBModMonit;  
  BEGIN (*InitLBModMonit*)  
    InstallClientMonitoring(OpenFiles,Monitor,CloseFiles);  
  END InitLBModMonit;  
  
BEGIN (* LBModMonit *)  
  InitLBModMonit;  
END LBModMonit.
```

LBMVALLEY

```

DEFINITION MODULE LBMValley;

(*****

Module LBMValley      (Version 1.0)

  Copyright (c) 2005 by Andreas Fischlin
  and Swiss Federal Institute of Technology Zurich ETHZ

Purpose  Provides sites and site specific data
         for an entire valley as needed by the
         larch bud moth system

Remarks This module provides a common base
         for model objects needed by several
         submodels modeling the population
         dynamics of larch bud moth

Programming

  o Design
    Andreas Fischlin           08/02/2005

  o Implementation
    Bronwyn Price             07/09/2005

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  <http://www.sysecol.ethz.ch>

Last revision of definition:  07/09/2005  BRP

*****
)

FROM SimBase IMPORT StateVar, NewState, Parameter, OutVar,
              AuxVar;

FROM LgMatrices  IMPORT LMatrix, notAllocatedLMatrix,
                      MatrixExists,
                      AllocMatrix, DeallocMatrix,
                      SetColIds, GetColIds, NRows, NCols;
FROM LgMatIO     IMPORT WriteMatrix, SetMatrixOutputParams;

```



```

CONST
  nilSiteIndex = -1;
  UE = 0;
  fstSite = 1;
  maxSiteIndex = 420;
  fstDirection = 0;
  lastDirection = 7;

TYPE
  SiteIndex = INTEGER;
  NbrIndex = INTEGER;

  SiteState = RECORD
    rt: StateVar; rt1: NewState;
    (* Raw fiber content (% fresh
    weight) *)
    et: AuxVar; (*Larch bud moth eggs (individuals)*)
    def: AuxVar;
    gfec: AuxVar;
    f: AuxVar;
  END(*RECORD*);

  SiteParameters = RECORD
    c4,c5,p1,p2,p14,nrt, cf7, cf8, cf9:
    Parameter;
  END(*RECORD*);

  SiteOutput = RECORD
    yt: OutVar;      (* output: simulated larval
    density for each site *)
    ytLn: OutVar;   (* output: ln of simulated
    larval density for
    each site *)
  END(*RECORD*);

  Site = RECORD
    six: SiteIndex;
    x: SiteState;
    p: SiteParameters;
    o: SiteOutput;
  END(*RECORD*);

  SiteProc = PROCEDURE(VAR Site);

  Valley = POINTER TO ValleyDescriptor;
  ValleyDescriptor = RECORD
    from,till: SiteIndex;
    site: ARRAY [fstSite..maxSiteIndex]
    OF Site;
  END(*RECORD*);

  Neighbourhood = RECORD
    c10, c11, c12,c15,adjSitew,v,cfw,cfv,uww,
    uwv,dww,dwv,phi,the,theD,theU,theC,
    distAdj,distAdjC,distAdjD,distAdjU,

```

```
(* Parameters for neighbour sites in 8 compass
directions *)
w1,a1,w2,s1,s2,femfly: LMatrix;
(* Parameters for Target sites *)
nColNo, tColNo,(* number of columns in data
matrix *)
firstNCol,lastNCol, firstTCol,lastTCol: INTEGER;
dataRowNo, (* number of rows in data matrix *)
lineNo,skipRows, fstDataRow,lstDataRow: INTEGER;
END;

VAR
undefValley: Valley; (* read only *)
UpperEngadine: Valley; (* initiate it with PrepareValley if
you wish to use it *)
r: ARRAY [nilSiteIndex..maxSiteIndex],
[fstDirection..lastDirection]
OF Parameter;
nbr: Neighbourhood;

PROCEDURE PrepareValley(VAR v: Valley; from,till: SiteIndex);
PROCEDURE ValleyExists(v: Valley): BOOLEAN;
PROCEDURE DiscardValley(VAR v: Valley);

PROCEDURE DoForAllSites(VAR(*speed-up*) v: Valley; action:
SiteProc);

PROCEDURE AppendSiteIndex(s: ARRAY OF CHAR; six: SiteIndex;
VAR d: ARRAY OF CHAR);

END LBMValley.
```

LBMOBS

```
DEFINITION MODULE LBMObsLbm;
```

```
(*****
```

```
Module LBMObsLbm
```

```
Purpose Simulates the real larch bud moth system in the  
Upper Engadine Valley as a parallel model.
```

```
Method Observed larval densities in larvae/kg larch  
branches as sampled from the Upper Engadine Valley  
are simulated by means of a ModelWorks submodel.
```

```
Data from Fischlin & Baltensweiler (1979),  
Fischlin (1982, page 90, Table 10) and from  
Baltensweiler & Fischlin (1987).
```

```
Remark The data are read from a file only once during model  
declaration and are loaded into memory for subsequent  
usage (comparison, identification) during a RAMSES  
session (Fischlin, 1991).
```

```
References
```

```
Fischlin, A. & Baltensweiler, W., 1979. Systems analysis  
of the larch bud moth system. Part I: the larch-larch  
bud moth relationship. Mitt. Schweiz. Ent.  
Ges., 52: 273-289.
```

```
Fischlin, A., 1982. Analyse eines Wald-Insekten-Systems:  
Der subalpine Lärchen-Arvenwald und der graue  
Lärchenwickler Zeiraphera diniana Gn.  
(Lep., Tortricidae). Diss. ETH No. 6977, Swiss Federal  
Institute of Technology: Zürich, Switzerland, pp. 294.
```

```
Baltensweiler, W. & Fischlin, A., 1988. The larch bud  
moth in the Alps. In: Berryman, A.A. (ed.), Dynamics of  
forest insect populations: patterns, causes, implications.  
Plenum Publishing Corporation, New York a.o.,  
pp. 331-351.
```

```
Fischlin, A., 1991. Interactive modeling and simulation  
of environmental systems on workstations. In: Möller,  
D.P.F. (ed.), Analysis of Dynamic Systems in Medicine,  
Biology, and Ecology. Springer, Berlin a.o.,  
pp. 131-145.
```

```
Programming
```

```
o Design  
Andreas Fischlin 01/05/87
```

o Implementation
 Andreas Fischlin 01/05/87

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 <http://www.sysecol.ethz.ch>

Last revision of definition: 07/09/2005 BRP

*****)

CONST

(*larch bud moth-Zeiraphera diniana Gn (Lep., Tortricidae): *)

yUnit = "#/kg"; (* y larval densities *)
 yLL = 0.0; (*minimum on graph scale for larval
 densities *)
 yUL = 600.0; (*maximum on graph scale for larval
 densities *)
 yDLLTol = yLL; (* lower limit for y' tolerated in input *)
 yDULTol = 1000.0; (* upper limit for y' tolerated in input *)
 negLogDelta = 0.01; (*offset used to plot log scale if values
 <= 0*)

(*

Larch Bud Moth System in the Upper Engadine:

=====

The following variables may be freely used in another
 submodel,
 typically to compare simulation results of a simulation model
 with the observed values

*)

CONST

lbmObsUEDescr = "Larval densities Upper Engadine (|| model)";
 kMin = 1949; (* first year sampled in UE *)
 kMax = 2002; (* last year sampled in UE *)
 fstSite = 1;
 lastSite = 420;

VAR

yMinDash: REAL; (* minimum annual value found in anyone
 site *)
 yMeanDash: REAL; (*average annual value for whole valley *)
 yMaxDash: REAL; (* maximum annual value found in anyone
 site *)
 yMinDashLn: REAL; (* ln of minimum annual value found in
 any one site *)
 yMeanDashLn: REAL; (* ln of average annual value for whole

```

        valley *)
yMaxDashLn: REAL;    (* ln of maximum annual value found in
                    any one site *)
trees: ARRAY [fstSite..lastSite] OF REAL;

PROCEDURE AssignDataUE; (* assigns data to above vars for
                    current time *)
PROCEDURE AssignInitLarvDens; (* assigns initial larval
                    density for each site*)

PROCEDURE UseObservationsUE; (* activates the || model Upper
                    Engadine *)
PROCEDURE ObservationsUEIsInUse(): BOOLEAN;
PROCEDURE UnuseObservationsUE; (* deactivates the || model Upper
                    Engadine *)

(*
The Subalpine Larch Bud Moth System in the Alps:
=====
The following variables may be freely used in another
submodel,
typically to compare simulation results of a simulation model
with the observed values
*)

CONST
  kMinSA = -4; kMaxSA = 4;
  lbmObsSADescr = "Larval densities Subalpine LBM-System (||
                    model)";

VAR
YMinDash: REAL;    (*minimum annual value found in a valley *)
YMeanDash: REAL;   (* average annual value for whole Alps *)
YMaxDash: REAL;    (* maximum annual value found in a valley *)
YMinDashLn: REAL;  (* ln of minimum annual value found in a
                    valley *)
YMeanDashLn: REAL; (* ln of average annual value for whole
                    alps *)
YMaxDashLn: REAL;  (* ln of maximum annual value found in a
                    valley *)

PROCEDURE AssignDataSA; (* assigns data to above vars for
                    current time *)

PROCEDURE UseObservationsSA; (* activates the || model Subalpine
                    System *)
PROCEDURE ObservationsSAIsInUse(): BOOLEAN;
PROCEDURE UnuseObservationsSA; (* deactivates the || model
                    Subalpine System *)

END LBMObsLbm.

```

IMPLEMENTATION MODULE LBMObsLbm;

(*

Implementation and Revisions:

=====

Author	Date	Description of change
-----	----	-----
af	../12/86	First implementation (just lbm densities from Auer's «Raupenzensus»)
af	01/05/87	Changed for use in Vorlesung Systemanalyse
af	01/06/88	Extension for needle lengths
af	04/06/88	Extension for Subalpine System
af	21/01/89	Removing of larch data by distributing observations of larch, larch bud moth, and parasitism into several separate modules
af	26/08/89	Instead of ObsUtils now module ReadData used
af	03/04/90	Update for new ReadData
af	15/08/91	Extended till 1990
af	03/11/91	Fixing of overall module usage
af	05/03/93	- UseObservationsUE and UseObservationsSA no longer empty if MDeclared(xyz)=TRUE - Extended till 1992
af	06/04/93	missingVal := DMConversions.UndefREAL()
af	30/05/95	Extended till 1994
af	02/06/02	Adding AboutLBMObs
af	05/06/02	- Aux modules (SubmodelSet, IdentParMod, and DrawParSpace now in AuxLib (RAMSES >= 3.0.2fc12) - kmaxIf introduced to support use of this implementatin for teaching (default = 1986)
af	09/06/02	- ForgetobsModSATime introduced - SASystem goes away gracefully by calling ForgetobsModSATime - DoOutputUE no longer manages curve attributes (obsolete with new ModelWorks)
brp	10/02/05	Added InitDataSD to read in initial larval density for each of 20 sites in the UE valley from file LBMObsLBMSD.DAT
brp	01/09/05	Adjusted for use in M11 (Abteilung resolution) InitDataUE updated to read abteilungen tree numbers from a file.

*)

```
(* DM core *)
IMPORT DMConversions;
FROM DMWindIO IMPORT WriteString, WriteLn,
    SetWindowFont, FontStyle, WindowFont, GetPen,
    DisplayPredefinedPicture;
FROM DMWindows IMPORT RectArea, UpdateAllWindows;

(* DM optional *)
IMPORT DMMathLib;

(* MW *)
FROM SimBase IMPORT
    Model, DeclM, MDeclared, RemoveM, IntegrationMethod,
    SetSimTime, SetGlobSimPars, SetDefltGlobSimPars,
    NoInitialize, NoInput, NoDynamic, NoTerminate, NoAbout;

(* MW for local modules *)
IMPORT SimBase;

(* AuxLib for local modules *)
IMPORT ReadData;

(* Aux *)
FROM IdentParMod IMPORT
    identifyParModDescr, InstallMeasurement, DeinstallMeasurement,
    HideParFromIdentification;
FROM SubmodelSet IMPORT AddNotifierIfActivated,
    AddNotifierIfDeactivated;

VAR
    obsModUE, obsModSA: Model;
    obsModUEInited, obsModSAInited: BOOLEAN;

PROCEDURE Round(x: REAL): INTEGER;
BEGIN
    RETURN TRUNC(x+0.1)
END Round;

MODULE UESystem;
(*****)

    FROM DMConversions IMPORT UndefREAL, IsUndefREAL;
    FROM DMMathLib IMPORT Ln;

    FROM SimBase IMPORT
        DeclSV, DeclMV, StashFiling, Tabulation, Graphing,
        CurrentTime, GetCurveAttrForMV, SetCurveAttrForMV,
        SetDefltCurveAttrForMV, Stain, LineStyle,
        SetMonInterval, Parameter, RTCType, DeclP;

    FROM ReadData IMPORT OpenDataFile, CloseDataFile, GetReal,
        GetInt, GetChars, AtEOL, TestEOF,
        SkipHeaderLine, negLogDelta, SetMissingReal,
        GetMissingReal;
```

```

IMPORT
  kMin, kMax,
  yMinDash, yMeanDash, yMaxDash,
  yMinDashLn, yMeanDashLn, yMaxDashLn,
  yUnit, yLL, yUL, yDLLTol, yDULTol,
  trees, obsModUE, obsModUEInited,
  Round, HideParFromIdentification;

EXPORT InitDataUE, OutputUE, InstallObjsUE, InitializeUE,
  kmaxIf;

CONST
  fstSite = 1;
  lastSite = 420;

VAR
  (*storage for observations*)
  yMinD, yMeanD, yMaxD: ARRAY [kMin..kMax] OF REAL;
  tree: ARRAY [fstSite..lastSite] OF REAL;
  missingVal: REAL;
  minLineStyle, meanLineStyle, maxLineStyle: LineStyle;
  minLnLineStyle, meanLnLineStyle, maxLnLineStyle: LineStyle;

  (* time *)
  k,i: INTEGER;
  kmaxIf: Parameter;

  visDefTh, visDefThLn: Parameter;

PROCEDURE InitializeUE;
  VAR curSt: Stain; curSym: CHAR;
BEGIN
  GetCurveAttrForMV (obsModUE, yMinDash,curSt, minLineStyle,
                    curSym);
  GetCurveAttrForMV (obsModUE, yMeanDash,curSt, meanLineStyle,
                    curSym);
  GetCurveAttrForMV (obsModUE, yMaxDash,curSt, maxLineStyle,
                    curSym);
  GetCurveAttrForMV (obsModUE, yMinDashLn,curSt,
                    minLnLineStyle, curSym);
  GetCurveAttrForMV (obsModUE, yMeanDashLn,curSt,
                    meanLnLineStyle, curSym);
  GetCurveAttrForMV (obsModUE, yMaxDashLn,curSt,
                    maxLnLineStyle, curSym);
  IF minLineStyle=invisible THEN minLineStyle := spotted END;
  IF meanLineStyle=invisible THEN meanLineStyle := unbroken
  END;
  IF maxLineStyle=invisible THEN maxLineStyle := minLineStyle
  END;
  IF minLnLineStyle=invisible THEN minLnLineStyle := spotted
  END;
  IF meanLnLineStyle=invisible THEN meanLnLineStyle :=
  unbroken END;
  IF maxLnLineStyle=invisible THEN maxLnLineStyle :=
  minLnLineStyle END;
END InitializeUE;

```



```

PROCEDURE DoOutputUE(k: INTEGER);
BEGIN
  IF (k>=kMin) AND (k<=kMax) THEN
    yMinDash:= yMinD[k];
    IF NOT IsUndefREAL(yMinDash) THEN
      yMinDashLn:= Ln(negLogDelta+yMinDash);
    ELSE
      yMinDashLn:= missingVal (*. Ln(negLogDelta) .*);
    END(*IF*);

    yMeanDash:= yMeanD[k];
    IF NOT IsUndefREAL(yMeanDash) THEN
      yMeanDashLn:= Ln(negLogDelta+yMeanDash);
    ELSE
      yMeanDashLn:= missingVal (*. Ln(negLogDelta) .*);
    END(*IF*);

    yMaxDash:= yMaxD[k];
    IF NOT IsUndefREAL(yMaxDash) THEN
      yMaxDashLn:= Ln(negLogDelta+yMaxDash);
    ELSE
      yMaxDashLn:= missingVal (*. Ln(negLogDelta) .*);
    END(*IF*);

  ELSE
    yMinDash:= missingVal;      (* stands for undefined *)
    yMeanDash:= missingVal;
    yMaxDash:= missingVal;
    yMinDashLn:= missingVal (*. Ln(negLogDelta) .*);
    yMeanDashLn:= missingVal (*. Ln(negLogDelta) .*);
    yMaxDashLn:= missingVal (*. Ln(negLogDelta) .*);
  END(*IF*);
  FOR i:= fstSite TO lastSite DO
    tree[i]:= trees[i];
  END(*FOR*);
END DoOutputUE;

PROCEDURE InitDataUE;
  VAR year,abt: INTEGER; open: BOOLEAN; fn,ID: ARRAY [0..127]
    OF CHAR;
BEGIN
  fn := "LBMObsLbm.DAT";
  OpenDataFile(fn,open);
  IF open THEN
    SkipHeaderLine;
    FOR k:= kMin TO kMax DO
      TestEOF; GetInt("year",k,year,k,k);
      TestEOF; GetReal("yMean'",k,yMeanD[k],
        yDLLTol,yDULTol);
      TestEOF; GetReal("yMIN'",k, yMinD[k], yDLLTol,yDULTol);
      TestEOF; GetReal("yMAX'",k, yMaxD[k],
        yDLLTol,yDULTol);
    END(*FOR*);
  CloseDataFile;
  DoOutputUE(kMin);

```

```

    obsModUEInited := TRUE;
END(*IF*);
visDefTh := 100.0;
visDefThLn := Ln(negLogDelta+visDefTh);

fn := "TreesAB.DAT";
OpenDataFile(fn,open);
IF open THEN
    SkipHeaderLine;
    FOR i:= fstSite TO lastSite DO
        TestEOF; GetInt("Abt",i,abt,i,i);
        TestEOF; GetChars(ID);
        TestEOF; GetReal("trees",i,trees[i], 0.0,511147.0);
    END(*FOR*);
    CloseDataFile;
    DoOutputUE(kMin);
    obsModUEInited := TRUE;
END(*IF*);
END InitDataUE;

PROCEDURE OutputUE;
BEGIN
    DoOutputUE(Round(CurrentTime()));
END OutputUE;

PROCEDURE InstallObjsUE;
BEGIN (* InstallObjsUE *)

    DeclMV(yMinDash, yLL, yUL,
        "Minimum larval density per site - yMIN'",
        "yMinDash", yUnit, notOnFile, notInTable,
        notInGraph);
    SetDefltCurveAttrForMV (obsModUE, yMinDash,
        turquoise,minLineStyle,0C);

    DeclMV(yMeanDash, yLL, yUL,
        "Average larval density in valley - y'", "yMeanDash",
        yUnit, notOnFile, writeInTable, notInGraph);
    SetDefltCurveAttrForMV (obsModUE, yMeanDash,sapphire,
        meanLineStyle,'*');

    DeclMV(yMaxDash, yLL, yUL,
        "Maximum larval density per site - yMAX'",
        "yMaxDash", yUnit,notOnFile, notInTable, notInGraph);
    SetDefltCurveAttrForMV (obsModUE, yMaxDash,turquoise,
        maxLineStyle,0C);

    DeclMV(yMinDashLn, Ln(negLogDelta), Ln(yUL),
        "Ln of Minimum larval density per site - Ln(yMIN')",
        "yMinDashLn", yUnit,notOnFile, notInTable, notInGraph);
    SetDefltCurveAttrForMV (obsModUE, yMinDashLn,turquoise,
        minLineStyle,0C);

    DeclMV(yMeanDashLn, Ln(negLogDelta), Ln(yUL),
        "Ln of average larval density in valley - Ln(y')",
        "yMeanDashLn", yUnit, notOnFile, notInTable, isY);

```

```

SetDeflCurveAttrForMV (obsModUE, yMeanDashLn, sapphire,
                        meanLineStyle, '*');

DeclMV(yMaxDashLn, Ln(negLogDelta), Ln(yUL),
        "Ln of Maximum larval density per site - Ln(yMAX)",
        "yMaxDashLn",
        yUnit,
        notOnFile, notInTable, notInGraph);
SetDeflCurveAttrForMV (obsModUE, yMaxDashLn, turquoise,
                        maxLineStyle, 0C);

DeclMV(visDefTh, yLL, yUL, "Larval density of visible damage",
        "visDefTh", "lbm/kg", notOnFile, notInTable, notInGraph);
SetDeflCurveAttrForMV (obsModUE, visDefTh, coal,
                        unbroken, 0C);

DeclMV(visDefThLn, Ln(negLogDelta), Ln(yUL),
        "Ln of Larval density of visible damage",
        "visDefThLn", "lbm/kg", notOnFile, notInTable,
        notInGraph);
SetDeflCurveAttrForMV (obsModUE, visDefThLn, sapphire,
                        unbroken, 0C);

DeclP(kmaxIf, 1986.0(*default needed for teaching VSysOek *),
      FLOAT(kMin), FLOAT(kMax), noRtc,
      "Last year measurements are used for identification",
      "kmaxIf", "a");
HideParFromIdentification(obsModUE, "kmaxIf", TRUE);

SetMonInterval(1.0);

END InstallObjsUE;

BEGIN
SetMissingReal(DefReal());
GetMissingReal (missingVal);
minLineStyle := spotted;
meanLineStyle := unbroken;
maxLineStyle := minLineStyle;
END UESystem;
(*****

MODULE SASystem;
(*****

FROM DMMathLib IMPORT Ln;
FROM DMConversions IMPORT DefReal, IsDefReal;

FROM SimBase IMPORT
DeclSV, DeclMV, StashFiling, Tabulation, Graphing,
CurrentTime, GetCurveAttrForMV, SetCurveAttrForMV,
SetDeflCurveAttrForMV, Stain, LineStyle,
SetMonInterval, Parameter;

FROM ReadData IMPORT OpenDataFile, CloseDataFile, GetReal,
GetInt,
AtEOL, TestEOF, SkipHeaderLine,
negLogDelta, SetMissingReal, GetMissingReal;

```

```

IMPORT
  kMinSA, kMaxSA,
  YMinDash, YMeanDash, YMaxDash,
  YMinDashLn, YMeanDashLn, YMaxDashLn,
  yUnit, yLL, yUL, yDLLTol, yDULTol,
  obsModSA, obsModSAInited,
  Round;

EXPORT InitDataSA, OutputSA, InstallObjsSA;

VAR
  (*storage for observations*)
  ND, YD, XD: ARRAY [kMinSA..kMaxSA] OF REAL;
  missingVal: REAL;

  (* time *)
  k: INTEGER;
  visDefTh, visDefThLn: Parameter;

PROCEDURE DoOutputSA(k: INTEGER);
  VAR i,n: INTEGER; sum: REAL;
BEGIN
  IF (k>=kMinSA) AND (k<=kMaxSA) THEN
    YMinDash:= ND[k];
    YMeanDash:= YD[k];
    YMaxDash:= XD[k];
    IF NOT IsUndefREAL(YMinDash) THEN
      YMinDashLn:= Ln(negLogDelta+YMinDash)
    ELSE
      YMinDash:= UndefREAL();
      YMinDashLn:= UndefREAL();
    END(*IF*);
    IF NOT IsUndefREAL(YMeanDash) THEN
      YMeanDashLn:= Ln(negLogDelta+YMeanDash)
    ELSE
      YMeanDash:= UndefREAL();
      YMeanDashLn:= UndefREAL();
    END(*IF*);
    IF NOT IsUndefREAL(YMaxDash) THEN
      YMaxDashLn:= Ln(negLogDelta+YMaxDash)
    ELSE
      YMaxDash:= UndefREAL();
      YMaxDashLn:= UndefREAL();
    END(*IF*);
  ELSE
    YMinDash:= UndefREAL();      (* stands for undefined *)
    YMeanDash:= UndefREAL();
    YMaxDash:= UndefREAL();
    YMinDashLn:= UndefREAL();
    YMeanDashLn:= UndefREAL();
    YMaxDashLn:= UndefREAL();
  END(*IF*);
END DoOutputSA;

```

```

PROCEDURE InitDataSA;
  VAR open: BOOLEAN; year: INTEGER; fn: ARRAY [0..127] OF
    CHAR;
BEGIN (*InitDataSA*)
  fn := "LBMObsLbmSA.DAT";
  OpenDataFile(fn,open);
  IF open THEN
    SkipHeaderLine;
    FOR k:= kMinSA TO kMaxSA DO
      TestEOF; GetInt("year",k,year,k,k);
      TestEOF; GetReal("N",k, ND[k], yDLLTol,yDULTol);
      TestEOF; GetReal("Y",k, YD[k], yDLLTol,yDULTol);
      TestEOF; GetReal("X",k, XD[k], yDLLTol,yDULTol);
    END(*FOR*);
    CloseDataFile;
    DoOutputSA(kMinSA);
    obsModSAInited := TRUE;
  END(*IF*);
  visDefTh := 100.0;
  visDefThLn := Ln(negLogDelta+visDefTh)
END InitDataSA;

PROCEDURE OutputSA;
BEGIN
  DoOutputSA(Round(CurrentTime()))
END OutputSA;

PROCEDURE InstallObjsSA;
BEGIN
  DeclMV(YMinDash, yLL, yUL,
    "Minimum larval density per valley - N'", "YMinDash",
    yUnit, notOnFile, notInTable, notInGraph);
  SetDefltCurveAttrForMV(obsModSA, inDash,sapphire,spotted,0C);

  DeclMV(YMeanDash, yLL, yUL,
    "Average larval density in Alps - Y'", "YMeanDash",
    yUnit, notOnFile, writeInTable, notInGraph);
  SetDefltCurveAttrForMV (obsModSA, YMeanDash,ruby,
    unbroken,'*');

  DeclMV(YMaxDash, yLL, yUL,
    "Maximum larval density per valley - X'", "YMaxDash",
    yUnit,notOnFile, notInTable, notInGraph);
  SetDefltCurveAttrForMV (obsModSA, YMaxDash,sapphire,
    spotted,0C);

  DeclMV(YMinDashLn, Ln(negLogDelta), Ln(yUL),
    "Ln of Minimum larval density per valley - Ln(N'",
    "YMinDashLn", yUnit, notOnFile, notInTable, isY);
  SetDefltCurveAttrForMV (obsModSA, YMinDashLn,sapphire,
    spotted,0C);

  DeclMV(YMeanDashLn, Ln(negLogDelta), Ln(yUL),
    "Ln of average larval density in Alps - Ln(Y'",
    "YMeanDashLn", yUnit, notOnFile, notInTable, isY);
  SetDefltCurveAttrForMV (obsModSA, YMeanDashLn,ruby,
    unbroken,'*');

```

```

DeclMV(YMaxDashLn, Ln(negLogDelta), Ln(yUL),
      "Ln of Maximum larval density per valley - Ln(X')",
      "YMaxDashLn", yUnit, notOnFile, notInTable, isY);
SetDefltCurveAttrForMV (obsModSA, YMaxDashLn, sapphire,
      spotted, 0C);

DeclMV(visDefTh, yLL, yUL, "Larval density of visible
      damage", "visDefTh", "lbm/kg", notOnFile, notInTable,
      notInGraph);
SetDefltCurveAttrForMV (obsModSA, visDefTh, coal,
      unbroken, 0C);
DeclMV(visDefThLn, Ln(negLogDelta), Ln(yUL),
      "Ln of Larval density of visible damage",
      "visDefThLn", "lbm/kg", notOnFile, notInTable,
      notInGraph);
SetDefltCurveAttrForMV (obsModSA, visDefThLn, sapphire,
      unbroken, 0C);

      SetMonInterval(1.0);
END InstallObjsSA;

BEGIN
  SetMissingReal(undefREAL());
  GetMissingReal( missingVal );
END SASystem;
(*****

PROCEDURE AboutLBMObsProc(picID: INTEGER; s: ARRAY OF CHAR);
  CONST picH = 133; picW = 247; VAR r: RectArea;
  PROCEDURE AllowForColorDrawing; BEGIN UpdateAllWindows END
AllowForColorDrawing; (* Fixes a ModelWorks 3 problem *)
BEGIN
  SetWindowFont(Monaco, 9, FontStyle{});
  WriteString(""); WriteLn;
  SetWindowFont(Chicago, 12, FontStyle{});
  WriteString("Parallel Model of Larch Bud Moth Densities ");
  WriteLn;
  WriteString("Observed in the Upper Engadine Valley since
  1949"); WriteLn;
  SetWindowFont(Monaco, 9, FontStyle{});
  WriteString(""); WriteLn;
  WriteString("Purpose Simulates the real larch bud moth system
  in the");
  WriteLn;
  WriteString("Upper Engadine Valley as a parallel model.");
  WriteLn;
  WriteString(""); WriteLn;
  WriteString("Method Observed larval densities in larvae/kg
  larch"); WriteLn;
  WriteString("branches as sampled from "); WriteString(s);
  WriteLn;
  WriteString("are simulated by means of a ModelWorks
  submodel."); WriteLn;
  WriteString(" "); WriteLn;
  WriteString("Data from Fischlin & Baltensweiler (1979),
  Fischlin (1982,");

```

```
WriteLn;
WriteString("page 90, Table 10) and from Baltensweiler &
Fischlin (1987).");
WriteLn;
WriteString(""); WriteLn;
WriteString("Remark The data are read from a file only once
during model");
WriteLn;
WriteString("declaration and are loaded into memory for
subsequent");
WriteLn;
WriteString("usage (comparison, identification) during a
RAMSES session.");
WriteLn;
WriteString(""); WriteLn;
WriteString("References"); WriteLn;
WriteString(" "); WriteLn;
WriteString("Fischlin, A. & Baltensweiler, W., 1979. Systems
analysis of ");
WriteLn;
WriteString("the larch bud moth system. Part I: the larch-
larch bud moth");
WriteLn;
WriteString("relationship. Mitt. Schweiz. Ent. Ges., 52:
273-289.");
WriteLn;
WriteString(""); WriteLn;
WriteString("Fischlin, A., 1982. Analyse eines Wald-Insekten-
Systems: Der");
WriteLn;
WriteString("subalpine Lärchen-Arvenwald und der graue
Lärchenwickler");
WriteLn;
WriteString("Zeiraphera diniana Gn. (Lep., Tortricidae).
Diss. ETH No. ");
WriteLn;
WriteString("6977, Swiss Federal Institute of Technology:
Zürich,"); WriteLn;
WriteString("Switzerland, pp. 294."); WriteLn;
WriteString(""); WriteLn;
WriteString("Baltensweiler, W. & Fischlin, A., 1988. The
larch bud moth ");
WriteLn;
WriteString("in the Alps. In: Berryman, A.A. (ed.), Dynamics
of forest");
WriteLn;
WriteString("insect populations: patterns, causes,
implications. Plenum");
WriteLn;
WriteString("Publishing Corporation, New York a.o., pp. 331-
351."); WriteLn;
WriteString(""); WriteLn;
WriteString("Programming"); WriteLn;
WriteString(" "); WriteLn;
WriteString("o Design"); WriteLn;
WriteString("Andreas Fischlin 01/05/87"); WriteLn;
WriteString(""); WriteLn;
```

```

WriteString("o Implementation"); WriteLn;
WriteString("Andreas Fischlin          01/05/87"); WriteLn;
WriteString(""); WriteLn;
WriteString(""); WriteLn;
WriteString("Swiss Federal Institute of Technology Zurich ETHZ
"); WriteLn;
WriteString("Terrestrial Systems Ecology"); WriteLn;
WriteString("Universitätstrasse 16 "); WriteLn;
WriteString("CH-8092 Zurich "); WriteLn;
WriteString("SWITZERLAND "); WriteLn;
WriteString(""); WriteLn;
WriteString("URLs: "); WriteLn;
WriteString("<mailto:RAMSES@env.ethz.ch> "); WriteLn;
WriteString("<http://www.sysecol.ethz.ch> "); WriteLn;
WriteString("A.Fischlin, Systems Ecology, ETHZ, 01/05/87");
WriteLn;
WriteLn;
WriteString("          ");
GetPen(r.x,r.y); r.w := picW; r.h := picH; DEC(r.y,r.h);
AllowForColorDrawing;
DisplayPredefinedPicture("",picID,r);
END AboutLBMObsProc;

PROCEDURE IniteIdentification;
BEGIN (* IniteIdentification *)
  IF MDeclared(obsModUE) THEN
    (* Identify only till kmaxIf for compatibility with Lekkas
    et al., 1977
    and use in Vorlesung Systemökologie *)
    InstallMeasurement(yMeanDash,FLOAT(kMin),kmaxIf);
    SetSimTime(FLOAT(kMin),FLOAT(kMax));
  ELSE
    InstallMeasurement(YMeanDash,FLOAT(kMinSA),FLOAT(kMaxSA));
    SetSimTime(FLOAT(kMinSA),FLOAT(kMaxSA));
  END(*IF*);
END IniteIdentification;

PROCEDURE DiscardIdentification;
BEGIN (* DiscardIdentification *)
  DeinstallMeasurement;
END DiscardIdentification;

PROCEDURE ForgetobsModSATime;
CONST dummy = 0.1;
BEGIN
  SetDefltGlobSimPars(FLOAT(kMin), FLOAT(kMax), dummy, dummy,
  1.0, 1.0);
  SetGlobSimPars(FLOAT(kMin), FLOAT(kMax), dummy, dummy, 1.0,
  1.0);
END ForgetobsModSATime;

PROCEDURE AssignDataUE;
BEGIN
  OutputUE
END AssignDataUE;

```



```
PROCEDURE AboutLBMObs;
  CONST mothID = 1007;
BEGIN
  AboutLBMObsProc(mothID, "the Upper Engadine Valley")
END AboutLBMObs;

PROCEDURE UseObservationsUE;
BEGIN
  IF NOT MDeclared(obsModUE) THEN
    DeclM(obsModUE, discreteTime,
          InitializeUE, NoInput, OutputUE, NoDynamic,
          NoTerminate,
          InstallObjsUE, lbmObsUEDescr,
          "Obs_LBM_UE", AboutLBMObs);
  IF NOT obsModUEInited THEN InitDataUE END;
  ForgetobsModSATime;
  END(*IF*);
END UseObservationsUE;

PROCEDURE ObservationsUEIsInUse(): BOOLEAN;
BEGIN
  RETURN MDeclared(obsModUE)
END ObservationsUEIsInUse;

PROCEDURE UnuseObservationsUE;
BEGIN
  IF MDeclared(obsModUE) THEN
    RemoveM(obsModUE);
    DeinstallMeasurement;
  END(*IF*);
END UnuseObservationsUE;

PROCEDURE AssignInitLarvDens;
BEGIN (* AssignInitLarvDens *)
  InitDataUE;
END AssignInitLarvDens;

PROCEDURE AssignDataSA;
BEGIN
  OutputSA
END AssignDataSA;

PROCEDURE AboutLBMObsSA;
  CONST UEID = 1000;
BEGIN
  AboutLBMObsProc(UEID, "11 valleys through the Alps")
END AboutLBMObsSA;

PROCEDURE UseObservationsSA;
  CONST dummy = 0.1;
BEGIN
  IF NOT MDeclared(obsModSA) THEN
    DeclM(obsModSA, discreteTime,
          NoInitialize, NoInput, OutputSA, NoDynamic,
          NoTerminate, InstallObjsSA, lbmObsSADescr,
          "Obs_LBM_SA", AboutLBMObsSA);
```

```
IF NOT obsModSAInited THEN InitDataSA END;
SetDefltGlobSimPars(FLOAT(kMinSA), FLOAT(kMaxSA), dummy,
                    dummy, 1.0, 1.0);
SetGlobSimPars(FLOAT(kMinSA), FLOAT(kMaxSA), dummy, dummy,
               1.0, 1.0);
END(*IF*);
END UseObservationsSA;

PROCEDURE ObservationsSAIsInUse(): BOOLEAN;
BEGIN
  RETURN MDeclared(obsModSA)
END ObservationsSAIsInUse;

PROCEDURE UnuseObservationsSA;
BEGIN
  IF MDeclared(obsModSA) THEN
    RemoveM(obsModSA);
    DeinstallMeasurement;
  END(*IF*);
END UnuseObservationsSA;

BEGIN
  obsModSAInited := FALSE;
  obsModUEInited := FALSE;
  AddNotifierIfDeactivated(lbmObsSADescr, ForgetobsModSATime);
  AddNotifierIfActivated(identifyParModDescr, IniteIdentification);
  AddNotifierIfDeactivated(identifyParModDescr, DiscardIdentification);
END LBMObsLbm.
```

CURRICULUM VITAE

Surname Price
First name Bronwyn
Date of Birth 13.02.1977
Place of Birth Melbourne, Australia
Nationality British and Australian

Secondary Education

1988-1994 Ashwood Secondary College, Melbourne, Australia

Tertiary Education

1995-1999 B.Sc (Hons) Environmental Science, The University of Melbourne, Australia
1997 Exchange program towards above B.Sc, Kings College London, U.K.

Employment History

February 2001- October 2001 Research Assistant in GIS
The University of Gloucestershire, Cheltenham, UK

November 2001-February 2002 Project Assistant, Event Co-ordination
ICLEI (International Council for Local Environmental Initiatives)
Freiburg im Breisgau, Germany

March 2002 – present Ph.D. student
Terrestrial Systems Ecology Group, Institute of Terrestrial Ecology, Swiss Federal Institute of Technology (ETH)
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