Predisposition Assessment Modelling

For *Ips typographus* (L.) Bark Beetle in Austrian Forests

Nuno Jorge Nunes Esteves

Dissertation submitted for obtaining the degree of
Master in Environmental Engineering

Supervisor : Prof. Doutor Maria Rosa Santos de Paiva
Co-Supervisor : Dr. Dipl. Ing. Sigrid Netherer

Examination Committee

Chairperson: Prof. Doutor Nuno Videira
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Statement of copyright

A quiet secluded life in the country, with the possibility of being useful to people to whom it is easy to do good, and who are not accustomed to have it done to them; then work which one hopes may be of some use; then rest, nature, books, music, love for one's neighbour—such is my idea of happiness.

Lev Nikolayevich Tolstoy

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Resumo

Na Europa Central e em particular na Áustria, infestações do escolitídeo *Ips typographus (L.)* têm atingido, nas últimas décadas, níveis preocupantes causando danos florestais, especialmente em abetos (*Picea* spp.) que atingiram 3 milhões de m^3 de madeira danificada em 2009. Nos sistemas naturais, estes eventos resultam geralmente de um conjunto de fatores com um carácter dinâmico, sendo os mais relevantes as tempestades de vento e neve, que quando estudadas numa perspetiva integrada, determinam um nível de predisposição a infestações por *I. typographus*.

O trabalho apresentado nesta dissertação constitui o desenvolvimento de um Modelo de Predisposição relativamente ao escolitídeo *I. typographus* para a Floresta de Rosalia no distrito de Viena, Áustria. As características referentes ao terreno e povoamento podem ser traduzidas por parâmetros que, por sua vez, são estudados usando Sistemas de Informação Geográfica. É assim possível obter resultados quanto à predisposição a tempestades de neve e vento e consequentemente predisposição para infestações de insetos, aspetos estes que formaram a base para o desenvolvimento do modelo apresentado. Os parâmetros referentes às características das árvores e terreno, foram obtidos através de um inventário, sendo posteriormente analisados e pontuados de acordo com um Sistema de Predisposição, baseado em indicadores anteriormente formulados.

Os resultados quanto à predisposição da Floresta de Rosalia foram analisados numa perspetiva espacial e processados estatisticamente. Para este local, os resultados revelaram que o seu nível de predisposição ao ataque por *I. typographus* se situa numa classe "Média". Os principais fatores que determinaram a sua inclusão nesta classe foram o facto de o povoamento possuir uma estrutura de idades bastante diversificada e de a proporção da espécie hospedeira, *Picea abies*, no povoamento ser de apenas de 20%.

O modelo desenvolvido nesta tese permite não só obter resultados quanto à predisposição do arvoredo e terreno de acordo com um Sistema de Predisposição extensivamente utilizado e melhorado, mas também pode servir como base para condições e cenários diferentes, por outras organizações que procurem desenvolver planos de proteção e gestão contra risco de infestações de *I. typographus.*

Palavras-chave

Floresta, Predisposição, *Ips typographus,* Silvicultura, Sistemas de Informação Geográfica

Abstract

Over the last decades outbreaks of the bark beetle *Ips typographus* (L.) assumed a high importance in forestry due to the economic losses caused, amounting to 3 million m^3 the volume of wood damaged in 2009 in Austria. In natural systems, such events result from a dynamic interaction among several factors, the integrated analysis of which can depict the predisposition level of a stand, or site, to *I. typographus* outbreaks.

The objective of this thesis was the development of a Predisposition Model for Rosalia Forest, located in the state (Land) of Vienna in Austria. Wind and snow storms are two of the main factors that lead to a higher level of risk, as high quantities of fallen timber become available, constituting a favourable breeding habitat for *I. typographus* communities to proliferate. Terrain and stand related data can be translated into parameters that are registered and studied using Geographic Information Systems, in order to obtain predisposition results to wind and snow damage and ultimately overall predisposition assessments to insect infestations.

Stand and site related parameters from spatial and inventory data were analysed and scored according to an Assessment System previously formulated. In order to allow for different analysis and adjustments the Model was developed in a mask-like structure.

Results on predisposition for the Rosalia Forest were spatially analysed and statistically processed. It was concluded that the majority of the stand area fell in the Medium predisposition class. This was due to the diversified age structure of the stand as well as to a relatively low proportion of the host species *Picea abies* present in this site. The model developed not only allows for the assessment of bark beetle predisposition according to an Assessment System based on an extensive compilation of literature, but can also be used as a working tool for further sites and scenarios by entities aiming at the management of the risk of *I. typographus* infestations.

Keywords

Forestry, Predisposition, *Ips typographus*, Silviculture, Geographic Information Systems

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Acronyms

DPSIR – Driving Forces, Pressures, State, Impacts and Responses

EC – European Commission

ERM – Environmental Risk Management

EU – European Union

GDP – Gross Domestic Product

GVA – Gross Value Added

IFFF – Institute for Forest Entomology, Forest Pathology and Forest Protection

MCDA – Multi-Criteria Decision Analysis

LCA – Life Cycle Analysis

RA – Risk Assessment

WTP – Willingness to Pay

Chapter 1

Introduction

1.1 Background and motivation

Forests have been described as multifunctional, serving economic, social and environmental purposes, and acting as habitats for animals and plants while playing a key role in mitigating climate change and other essential environmental services (European Comission, 2013).

Between services and functions that ecosystems provide, the inherent values that benefit humankind can be divided into two types: use values and non-use values. The first include economic benefits from the direct and indirect use of the forest. Direct use values refer to the actual use of a good or a service, e.g. fuelwood, timber, game, edible plants, or non-extractive such as tourism. These values have been usually described with statistical data for whole regions, such as contribution to GDP and valuation of production, which have their own issues concerning the representativeness of welfare (Constanza, et al., 1997). Indirect use values on the other hand, are associated with functional benefits related to environmental services such as carbon sequestration, the ability to reduce soil erosion and the provision of a habitat to protect biodiversity.

Non-use values include existence values, option values and bequest values. The first category reflects benefits from the fact that a certain good, or service exists and it is preserved. Option values consist of the potential use, direct or indirect of a given good or service, e.g. value of preserving biodiversity or genetic material, to ensure the option of having these goods in the future. Bequest values refer to benefits from ensuring that certain goods will be preserved for future generations.

Holistic assessments of how different services and respective values behave, are crucial to inform decision making processes in natural systems management. Approaches such as DPSIR, LCA, RA and Predisposition Analysis have allowed for the construction and analysis of scenarios where systems variables and states sensibility, productivity and integrity can be simulated for different conditions. With the validation of the obtained results, responses can be formulated thus increasing sustainability in a given system and reducing exposure to risk to a certain pressure (Moberg, 2006).

Such principles were integrated in the EU strategy for forests, considering 2020 objectives, aiming to identify the key aspects needed to strengthen sustainable forest management, one of which is the control and optimization of predisposition to disturbances. Tools such as Predisposition Assessment Systems (PAS) have been developed in recent years that can assist foresters in this task and consequently contribute to protect the values associated with forests (Führer & Nopp, 2001).

Forests continuously provide services and resources, which are vital to ensure human welfare on our planet (Constanza, et al., 1997). As such it is essential to appraise them within these frameworks, considering and analysing as representative as we can the dynamic processes that are intrinsic to natural environments.

1.2 Ecological and Economic Importance of *Ips typographus*

1.2.1 Forest sector description in the EU and Austria in particular

Forests and other wooded lands cover 40% of EU's land area and the general quality of forest resources and forest management has remained fairly stable over the past decades, estimates indicating that it has increased in some respects. Still some significant problems exist in many countries, e.g. fires in the Mediterranean regions, defoliation and outbreaks of pests and diseases throughout the continent, among others (UNECE, FAO, 2011).

The forest sector has been economically defined to cover production, trade and consumption of forest products and services, as well as forest resources. Its contribution to GDP in Europe is 127.3 billion Euro, having its strongest macroeconomic importance in North (2.2%) and Central-Eastern Europe (1.6%). The countries in which this sector is particularly important are Finland, Latvia, Sweden (3 to 5% of GDP) and Austria, Belarus and Estonia (2 to 3% of GDP) (UNECE, FAO, 2011).

Since 1950 the area of forest available for wood supply has been steadily rising in Europe, having increased 11% in Western Europe by 2000 (UNECE, FAO, 2005). This trend could be explained by driving forces such as management decisions, natural causes, policy decisions as well as changes in the definition of forest itself which lead to a consequent growing stock of wooded land classified by broadleaves and conifers and availability for wood supply. Although this trend of growing stock is rising, currently only 60-70% of the annual increment is being cut. On the other hand harvest rates are expected to increase by around 30% by 2020, largely by the expected prominent role of and demand for wood-based energy where Europe's demand is expected rise from 13 million (2012) to 25 million to 30 million tonnes a year by 2020 (International Wood Markets Group, 2013).

Employment on the forest sector has always been an important contributor to rural economies, representing the main source of income for almost four million people in Europe, from which 750 000 work in forestry. Even though there are many different trends among regions in the EU, while global employment numbers in the sector continue to decline (UNECE, FAO, 2011). In terms of damage, estimates of 2011 pointed to 20% of trees in the EU being classified as either damaged or dead. Damage in forest areas mainly result from a combination of biotic damage agents, such as insect attacks, fungal diseases and abiotic damage agents like anthropogenic factors, climatological, hydrological, geophysical and meteorological causes (Moore & Allard, 2011).

In Austria, forests cover an estimated 4 million hectares of land, making it almost half of the country's federal territory. They are predominantly privately owned (70%), with a share of 16% federal or publicly owned forest areas and estimates point to 64% of Austrian forests having a predominant economic function. About one third of the total forest area is managed by large forest enterprises but still a considerable part of its privately owned share represent the livelihood of many family farms on a small scale basis which help sustain many regional economies (Bundesministerium für Land- und

Forstwirtschaft, Umwelt und Wasserwirtschaft, 2013). Around 80% of the forest area is covered by coniferous species, mainly Norway spruce (*Picea abies*) and the dominant broadleaf species is beech (*Fagus sylvatica*). Topographically the forest area reaches from 100 m to 1 800 m above sea level and a medium slope of 40% (Schadauer, et al., 2006).

Even though in Austria the output of the forest industry between 2007 and 2009 mirrored the economic crisis that affected the economy on a global scale partially due to the decrease in roundwood prices, though it has since then recovered, with an estimate GVA of 1 169.4 million € in 2012 (Statistik Austria, 2013). The country is notoriously known for its economic wood-related activity, ranking fifth regarding coniferous sawnwood, eighth in paper and paperboard and ninth in wood based panels at global lever, 2010 data. (Schwarzbauer, et al., 2012).

Concerning the area of forest classified by number of tree species occurring by forest type, the largest fraction of the Austrian forest falls within the 1 and 2-3 tree species classes and within a total of 479 000 hectares under the Natura 2000 (UNECE, FAO, 2011). In ecological terms the largest threats are posed by bark beetles and wind damage as a calamity agent and fungal diseases, with high damage potentials to entire tree stands (UNECE, FAO, 2011).

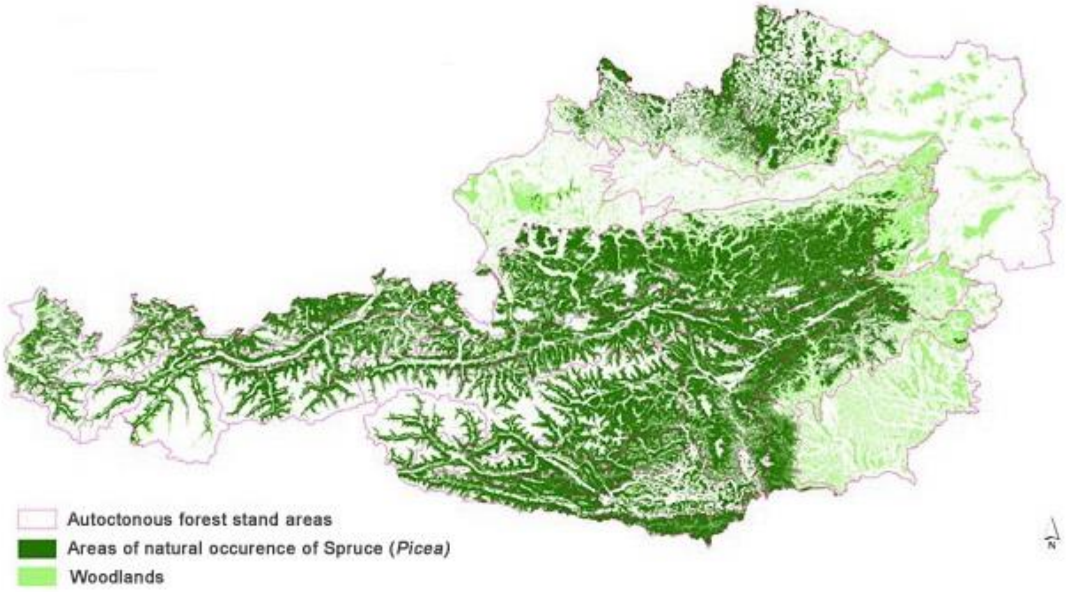


Figure 1.1 Distribution of *Picea* spp. (spruce) in Austria (Waldwissen, 2013).

Fungi can potentially deteriorate wood quality. Recently a novel pathogen was identified on ash (*Fraxinus* spp.) that moved from Asia to Europe, *H. pseudoalbidus* which has been related to enormous losses of vitality and dieback of highly important tree species all over Europe (Pautasso, et al., 2013).

The condition of the forests is monitored on a permanent basis through surveys such as the Austrian Forest Inventory (AFI), the Forest Damage Monitoring System (FDMS) and surveys conducted by the

OBF (Austria Federal Forests). The AFI for example, is constructed and produced by the Federal Research and Training Centre for Forests, Natural Hazards and Landscapes (BFW) and provides comprehensive and basic data for forest management on all governing levels (Schadauer, et al., 2006). These reports have shown that problems arise mainly when several damage factors occur during the same time such as air pollution, wind-throw, snow storms or insect related calamities.

1.2.2 Bark Beetle Outbreaks

Disturbances such as snow breakage, storm throw and insect infestations represent important components in decision-making, for forest management. In 1990 and 1999, Central Europe was deeply affected by the ‘Vivian/Wiebke’ storms. The total damages that resulted were estimate in 290 million m^3 of fallen timber (Wermelinger, 2002), resulting in a decline of stability which gave rise to an enormous propagation of the European spruce bark beetle, *Ips typographus* (L.). Since then the spruce bark beetle has been described as one of the main drivers of disturbances in spruce dominated forest in Europe, for their particular susceptibility (Müller, et al., 2008).

Bark beetles play an important role in natural ecosystems. The interactions between these insects and their host have evolved over some 200 million years ago through continuous adaptation and counter-adaptation. Bark beetles such as *Ips typographus* deposit their eggs in galleries excavated in the phloem, cambium and outer sapwood of trees and successful broods flourish with the death of these tissues (Christiansen, et al., 1987). Broods feed on such tissues and during their latent or low population levels, they preferably attack felled trees, or trees temporally weakened by extreme weather conditions or other destructive agents (Edmonds & Gara, 1999).

Outbreaks of *I. typographus* were found to be highly correlated with stand conditions, changes in weather conditions, e.g. precipitation level, wind throw and temperature fluctuations and site-related properties such as slope, terrain morphology and exposure to wind. Since forest areas in Austria are extensive and predominantly influenced by an alpine climate, they can in general terms, be considered as being exposed to a fairly high risk of bark beetle outbreaks.

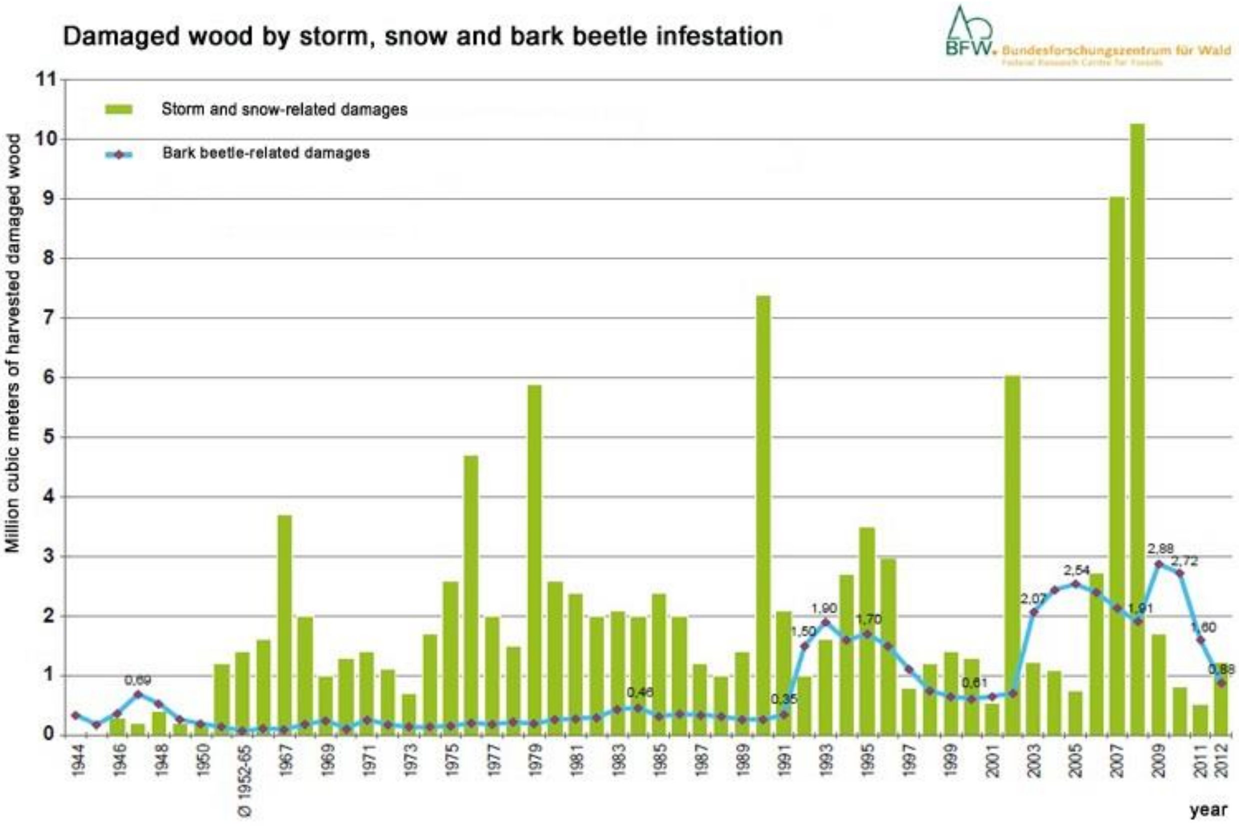


Figure 1.2 Evolution of damage costs related to snow, storms and bark beetle outbreaks in Austria from 1944 to 2012 (Federal Research Centre for Forests, 2012).

Another condition that enhances this risk is the fact that after the Second World War, most of the areas which were aforestated in Central Europe were planted mainly with spruce, which in Austria accounts for an estimate of 1 million hectares (Netherer, et al., 2005). The trend of the damage caused by bark beetle between 2006 and 2008, demonstrating a slight decrease after reaching a maximum in 2005. However this trend was interrupted in 2009 as a result of the hurricane and snow breakage events resulting in a total of 2.87 million cubic meters of damaged wood.

1.3 State of the art on *Ips typographus* Research

Risk management is a mechanism for managing exposure to risk that enables us to recognise the events that may result in unfortunate or damaging consequences in the future, their severity, and how they can be controlled (Dickson, 1995). As such it requires as a prerequisite an environmental RA (risk assessment) which can be described generally by the following equation:

$$\text{(1)} \quad R(X) = \int_{X}^{\infty} f(X) * D(X)dX$$

- X – Random event/Hazard
- R(X) – Risk associated with event X

- f(X) – Probability of occurrence of event X
- D(X) – Damages/Consequences of event X

Within this process, when verified and established the scope and variables that are in play, there is a need to analyse how exposed to a risk a natural system, e.g. a forest, is to a disturbance – predisposition to risk. The damage function can be formulated through ascertaining the predisposition associated with the underlined disturbances, the capacity to withhold certain thresholds and their effects. The probability function of a certain event is formulated by ascertaining the likelihood of such an event to occur, e.g. in flood risk, the probability function is established by the magnitude of a precipitation event characteristic to a given year period, commonly denominated as return period. For the same example, the damage function is usually represented in monetary terms, by the buildings, crops, equipment, cars and others, that would be inside the flooding area.

Risk assessment in forests have been conducted for several disturbances agents such as wind damage, insect outbreaks and wildfires. This tool has been a key aspect of Decision Support Systems (DSS) when it comes to ecosystems management, by allowing for disturbance exposure minimization actions which can not only provide information to maintain a systems' productivity and balance, but can also lead, in extreme weather conditions, to saving human lives.

An RA model concerning bark beetle outbreaks can be described with the following component sequence:

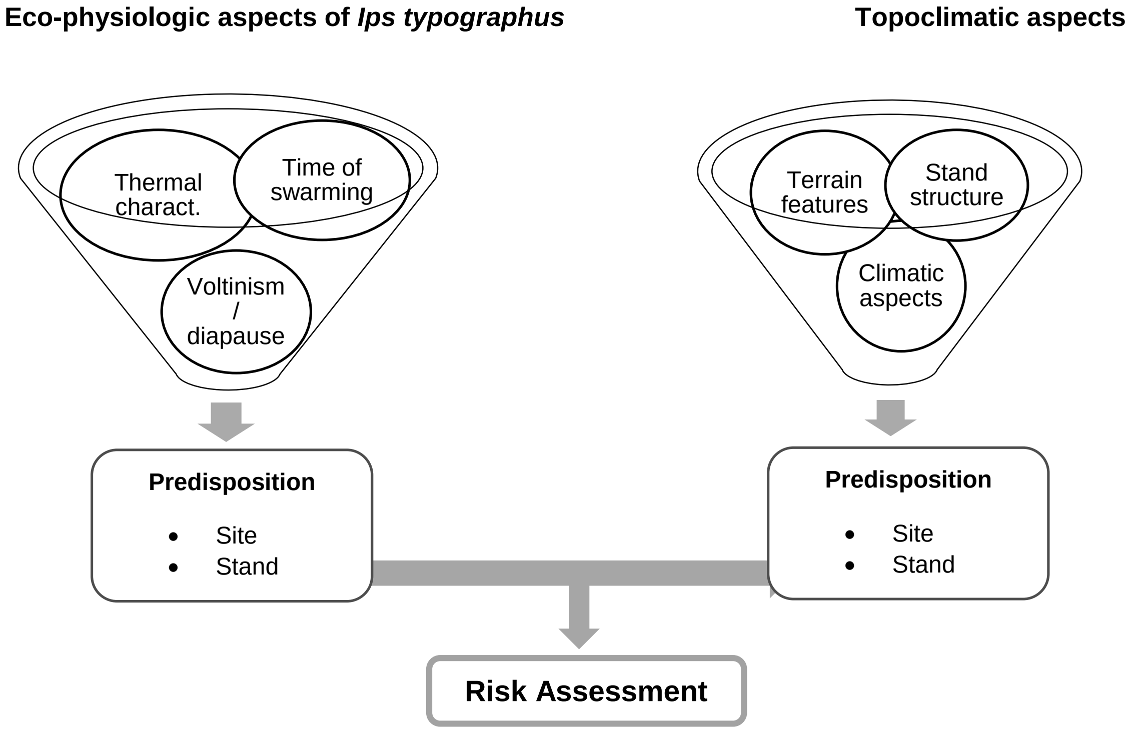


Figure 1.3 RA structure for the study of bark beetle outbreaks (adapted from Netherer et al. 2004).

According to the theory of predisposition and trigger, the origin of forest damages is based on the combination of favourable spatial and temporal conditions in susceptible forest trees and of different disturbance factors (Führer, 1987). The eco-physiological and topoclimatic aspects have been extensively described and simulated in the past 20 years with the purpose of reducing risk, and consequently the damage that *I. typographus* outbreaks might cause.

Several of these studies have been performed in Central Europe concerning the factors that are intrinsic to an increase in exposure to an outbreak, their impacts, risk management options, among others. (Schwarzbauer, et al., 2012) (Seidl, et al., 2008) (Kazda & Pichler, 1998). Although the dynamics that lead to an infestation, as with all natural systems, are considerably complex and sensible, compilations and analysis of these studies have allowed to narrow down the main influences behind these outbreaks (Wermelinger, 2004).

For the purposes of this document, the dynamic predisposition assessment system (PAS) from which the main indicators were compiled, for the stand and site used as reference was the one used by Netherer and Nopp-Mayr (2005) in the High Tatra Mountains (Netherer & Nopp-Mayr, 2005). This DPAS considers 17 indicators, divided in the structure already discussed, stand and site-related. It was concluded that the results obtained with this model were in agreement with the hypothesis formulated by the authors, where an increased score of indicator weight, or predisposition, signifies a high probability of damage and that actual infestations or damages, will occur more frequently in high scoring locations (Netherer, et al., 2005).

Another important model that has been developed in recent years for *I. typographus* development assessment was PHENIPS. This tool allows for the calculation of the microclimatic conditions required for bark beetles seasonal development based on the spatial and temporal simulation of the sites digital elevation model (DEM). After its validation PHENIPS was applied to Kalkalpen National Park in Austria and was found to be able to monitor the actual state of development of the bark beetles at specific stand/tree level levels by explicitly considering effects of regional topography and stand conditions, based on local air and bark temperatures (Baier, et al., 2007).

1.3.1 ArcGIS and MapModels

GIS models that established a connection between decision analysts and computer system design when it comes to geographical data treatment can be highly usefull in risk assessment procedures. The software chosen to perform the analysis on this field was ESRI's ArcGIS and its former suite, ArcView a powerful and flexible tool for spatial analysis, data management, mapping and visualization, advanced editing, geocoding and map projections. In 2010 ESRI was found to have more than 40% of the entire GIS marketshare, used by more than 300 000 organizations worldwide (ARC, 2011).

Initial versions of the software (pre-1999), allowed users to view spatial data, create layered maps and perform basic spatial studies. Besides its basic features, recent versions of ArcGIS now possess extensions such as *Geostatistical Analyst* and *Spatial Analyst* that bring large benefits to investigate and derive new information from existing data. Currently ESRI is devoted to facilitate access to maps in a cloud-based platform, ArcGIS Online (Anon., 2013). This version keeps in with the on-the-move, online network and app-friendly information technology for GIS software, turning map creation, exploration and publishing available for any device that supports it.

In 2002 a graphical modelling language based on the early ArcView 3.0® was developed at the Institute of Regional Science of the Vienna University of Technology denominated MapModels. It contained a basic function library with various flowchart elements for a range of analysis operations including application of, a highly useful concept for spatial analysis, fuzzy logic (Benedikt, et al., 2002). Its purpose was to act as a Spatial Decision Support System where users with Avenue™ programming skills could extend and/or customize the set according to their preferences (Netherer, et al., 2002). Two of its most relevant features were the built-in *fuzzify* function that enabled one to construct an ‘award-penalty’ score system based on past literature, and the fact that elements on display were active and could be connected to link and process information within flowcharts.

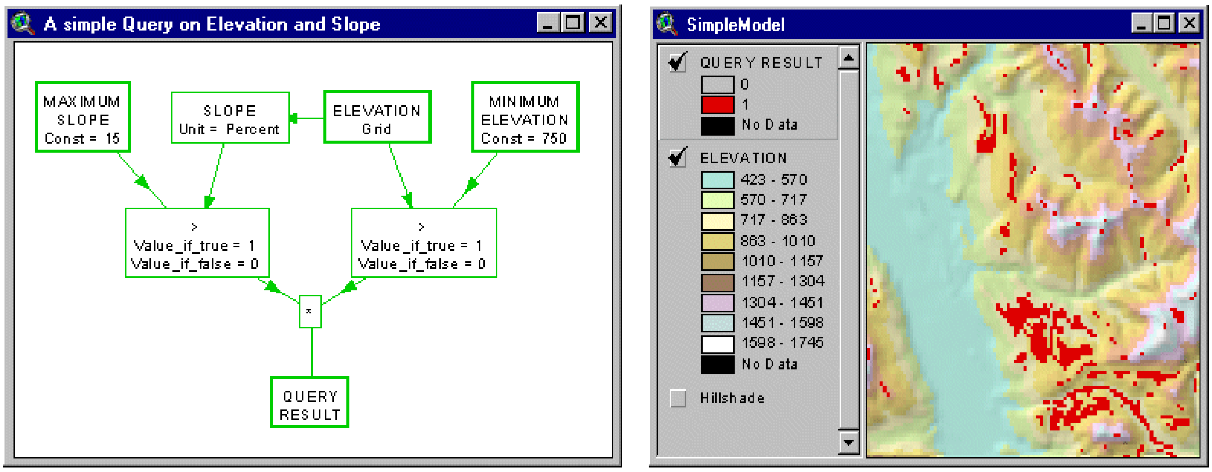


Figure 1.4 An example of a simple spatial query in MapModels and its respective display, for areas with a maximum slope of 15% and an elevation over 750 meters.

1.3.2 Model Builder

ModelBuilder is an application used to create, edit and manage models through the tools and attributes of ArcMap. These designable models are workflows that string together nodes and variables, where the output of a model or tool is the input of a consequent process (ESRI, 2006). Similarly to the work area of ArcMap, in ModelBuilder when a tool is inserted, a dialog box is prompted and when a file is added it is assigned connectable node.

Workflow in Modelbuilder is determined by data input, process configuration or alteration and model running. Any change in a parameter or input data will automatically reset the model, erasing any consequent output data.

Figure 1.5 Example creation of a raster file with all forest areas from the Stands layer through the workflow basis of ModelBuilder.

Nodes with identical functions or positions have specific colours. Blue coloured oval nodes represent input data, orange nodes represent tools and green oval nodes represent output data. All input or outputs nodes can be configured to be model parameters, thus becoming an essential component to be indicated by the user or extracted from an initial model and used on a following model, as indicated for the *Stands* input file on Fig. 1.5.

Tool nodes can be configured to expose all existing parameters that prompt when the function is selected. This allows a user to customize the conditions in which the tools will operate and output data can be introduced in functions not only as input data but also as function parameters. The nodes that result from each desired parameter to be exposed, is identified with a light blue colour.

A user can also add Environment settings which affect a tool´s result but contrary to other tool parameters, many of these settings when selected do not appear on the dialog box of a tool. A simple example of a use of these settings is applying the Extent Environment setting which allows a certain analysis to be limited to a selected geographic area, defining a new area for the resulting output data.

One other valuable feature of ModelBuilder are the iterator tools. These tools grant the possibility to filter or select different operations on files, according to the preferences stated or reference values in which the operations will be based. One of them is the *For* iterator where interval values for a particular process are assigned, directing different processes for the corresponding input values.

1.3.3 Rosalia Roof Project

In October 2011 a case study Rosalia Roof Project was launched by the Institute for Forest Entomology, Forest Pathology and Forest Protection (IFFF) of University of Natural Resources and Life Sciences. Besides the IFFF, the Institute of Botany and the Institute of Forest Ecology of the same University, also participated in the Roof Project which is expected to end in October of 2014. The aim of the project is the development of a model suited for dynamic evaluation of tree and stand disposition to bark beetle outbreaks.

Apart from temperature, which is a vital condition to the proliferation of a bark beetle population, shortage in water supply due to drought events, or unfavourable site conditions, have also been associated with infestations.

The structure of the evaluation for the roof project was based on the water supply and deficit which may lead to drought stress in terms of tree physiology and ultimately turning them more attractive and less resistant to bark beetle attacks. The tree physiology-related methods used in the project included tree water status, content and potential analysis as well as resin and bark anatomy study. The methods used for bark beetle assessment included monitoring of pheromone traps, their phenology at the site and induced attacks.

The test area consisted of six plots. Two of them were control plots with no cover to allow for the comparison of test conditions with regular functioning conditions in the site. Four plots were fully (2) and semi covered (2), allowing for severity assessment in drought effects. In each of these plots, 3 trees were analysed for the physiological parameters mentioned and subjected to induced bark beetle attacks.

Figure 1.6 Photograph of one of the semi-covered plots (Esteves 2013).

These induced attacks consisted of exposing the trees, during a 24 hours period, to a framed box with 20 beetles per box where the number of successful borings and defended borings were registered. Chronologically the project was designed for a sequence of irrigations, monitoring periods and induced attacks.

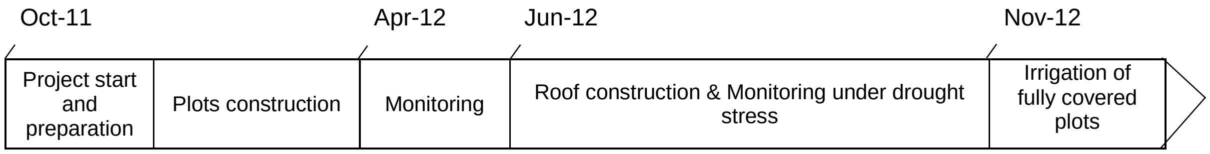


Figure 1.7 Chronology of the Rosalia Roof Project in 2011 and 2012.

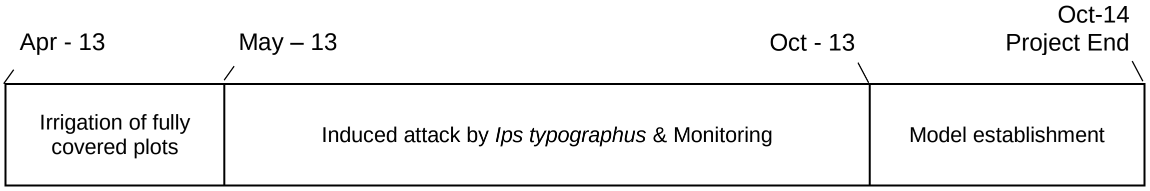


Figure 1.8 Chronology of the Rosalia Roof Project in 2013 and 2014.

The methods used to assess climate and soil parameters were soil hydrological recordings, specifically soil moisture, water potential and temperature, and climate related data: air temperature, precipitation, relative humidity, wind speed and global radiation.

1.4 Objectives

The objectives set out initially to be accomplished focused on the development of a predisposition model on the ArcGIS ModelBuilder software and how its performance concerning the application of data from previous studies into indicators of predisposition of a certain site.

- Develop a structure for the model allowing for a separate analysis, at stand and site level, of hazards resulting from attacks of the bark beetle *Ips typographus*;
- Integrate the data generated by the Predisposition Assessment Systems as indicator weights;
- Ensure flexibility in the model in order to allow for different input conditions according to the user’s desired scope or choice of procedure;
- Construct customizable *fuzzify* functions to different analysis conditions in order to establish normalized scores.

Chapter 2

Materials and Methods

2.1 Data and Model Concept

2.1.1 Forest Inventory data

The data used for the development of this model and in particular for the stand-related analysis, originated from an inventory conducted by the ÖBF (Austrian Federal Forests). The OBF is responsible for the monitoring and management of 15% of the Austrian forest area, representing the largest profit-oriented organization in Austria in charge of natural environments. Besides management and reporting services on behalf of the Austrian government, the OBF also promotes public awareness to locals and visitors, as well as partnering with research projects that incorporate their sustainability and conservation objectives (AG, 2013).

The data from the inventory showed that 20% of the tree species identified were spruce, a well-known host for bark beetles especially in areas with frequent windthrow events (Fahse & Heurich, 2011). The stand is located within an altitude range of 400 and 650 meters. The average value of canopy closure was 48.7% and a water supply average of “Moderately Moist”.

The values of water supply for the stand fell within the “Xeric” to “Moderately Moist” categories. Reported stem damages was minimal, with an inventory scale average value of 0.0023.

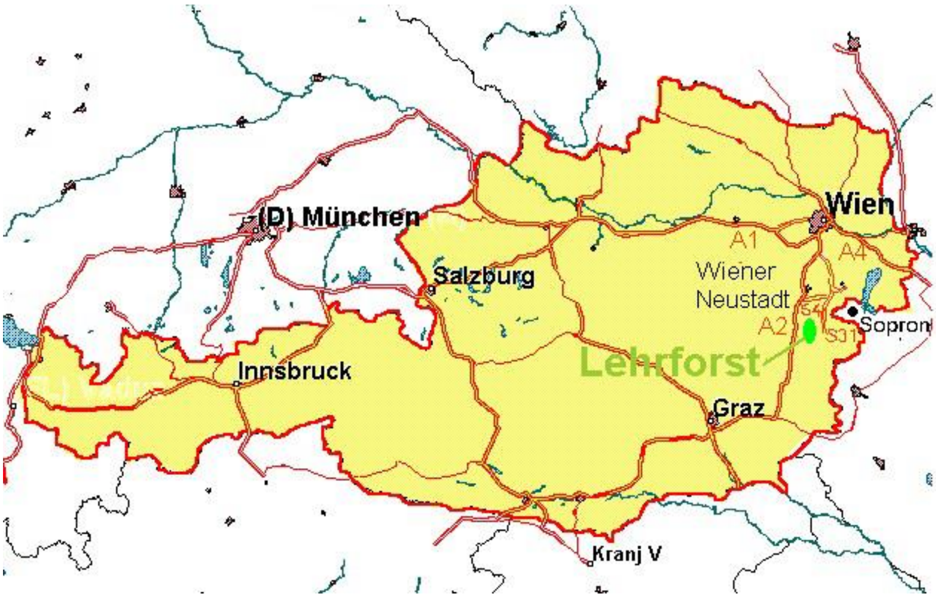


Figure 2.1 Location of the Rosalia Forest referred to as Lehforst (Teaching forest grounds).

The data were obtained from surveys conducted in Rosalia Forest on a 10-years basis, on which the parameters such as proportion of each tree species, water supply classes and yield classes, among others are assessed and registered. Scoring of the parameters either follows a classification system established by the OBF or relates to common Austrian yield tables. The data was processed in order to render values compatible with the tools of ArcGIS ModelBuilder and the desired outcome format

(Table 3.1). The potential number of *I. typographus* generations in the study area, which is a main criterion within predisposition assessment, was fixed at two, based on previous modelling activities by use of PHENIPS (Baier, et al., 2007).

The conversion from raw data to adaptable values, was made through conditional functions, statistical analysis and interpretation of the code established by the ÖBF. These codes were linked to the water supply characteristic of each area of the stand, which were identified by a single ObjectID.

The inquiry of the proportion of different species and age class was defined only for the top layer. The parameter age class was only registered for the predominant tree species in the top layer. For the bonity parameter the same principle was applied, where only the predominant tree species, with the highest proportion in the top layer, was evaluated for its yield class.

In the Gleysol parameter, organic wet soils were also taken into account. The scales adopted for these parameters, were adjusted to the DPAS rating system (See section 2.1.6) and later joined with the shapefile, through the same ObjectID.

Parameter	**Classes of value**
Forest area	Yes/No (1/0)
Proportion of spruce	0 - 100%
Proportion of pine	0 - 100%
Proportion of spruce and fir	0 - 100%
Proportion of spruce, pine and fir	0 - 100%
Proportion of deciduous trees	0 - 100%
Canopy closure	0.0 - 2.0
Stand age	year
Water supply	0 - 7
Bonity	0 - 20
Stem damage	0 - 5
Gleysol or with distinct stagnic properties	Yes/No (1/0)

Table 2.1 Parameters gathered from the inventory of Rosalia Forest stand and classes of value after the process of initial data transformation.

Regarding the data on the proportion of species from the stand file, 1.2% of the values were missing or, in some cases, the species label was not mentioned. The problem posed by the missing data was addressed by integrating the values in a category that considered other deciduous tree species so that the proportions that were identified could be integrated into the dataset.

2.1.2 Rosalia Forest Shapefile and DEM

The data in Excel spreadsheet format was joined with the shapefile from the stand area in Rosalia forest through a specific command in ArcMap (See Section 2.2.3). This file allows for the insertion of the data into the corresponding areas, thus granting a possibility to perform a wide variety of study operations, in this case a predisposition assessment.

Concerning GIS file formats, Shapefiles store non-topological geometry and attribute information for the spatial features in a data set and can support point, line and area (polygon) features. The geometry for a feature is stored as a shape comprising a set of vector coordinates. For the purposes of the model, the shapefile contained area data on the stands in polygon shape (ESRI (Environmental Systems Research Institute), 1998).

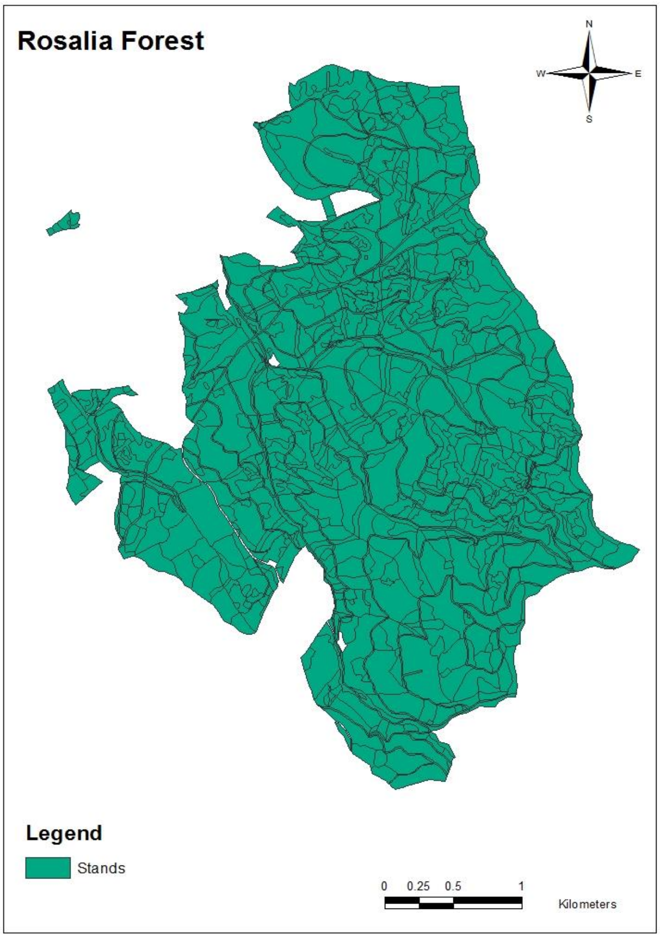


Figure 2.2 Shapefile map of Rosalia Forest stand.

Site related parameters where analysed through the Digital Elevation Model, here after called DEM. This file as well as the DEM, were provided by the Bundesamt für Eich- und Vermessungswesen (BEV), which is a subordinate federal agency of the Federal Ministry of Research and Economy. The main tasks carried out by the BEV are geoinformation surveying and measurement, as well as the calibration of this information. The DEM provided is part of a national geodatabase compiled by the Department of Geomatics, the Austrian Spatial Data Infrastructure.

Spatial data files are an essential part of planning, management and protection of natural systems. As such they provide key information throughout a wide variety of fields of study like agriculture, forestry, homeland security, civil and energy engineering, among others.

DEMs are commonly used in spatial characterization processes in a wide variety of fields of study. DEM data is stored as a point elevation data on either grid, or triangular integrated network (TIN), or as vectorized contours stored in a digital line graph. Grid format is most widely used.

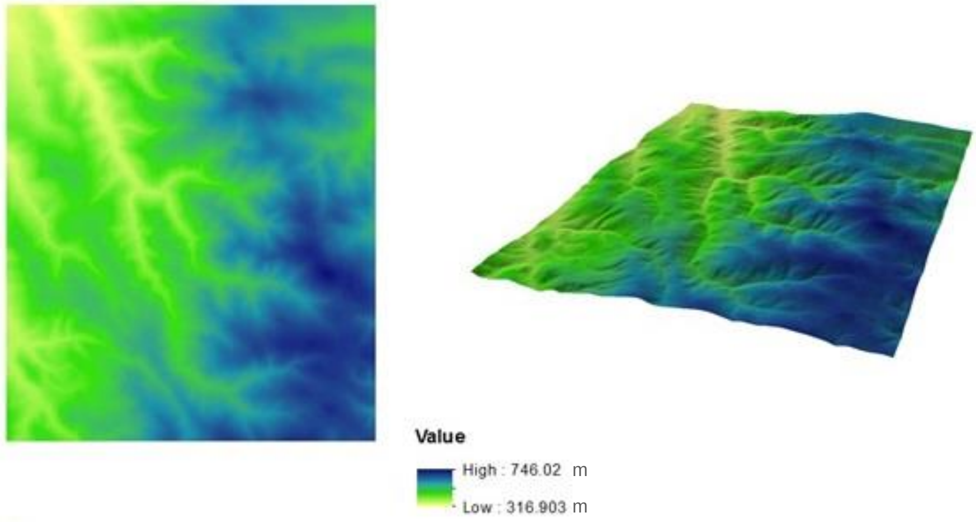


Figure 2.3 TIN (left) and DEM (right) of the Rosalia forest stand area viewed in ArcScene.

The DEM used in this work included the stand site, making it possible to analyse both data sources. The main properties of the DEM (see Table 2.2), were compatible with the shapefile, allowing for spatial and statistical analysis to be carried out in the course of the development of the model.

Property	**Value**
Cell size (X,Y)	10, 10
Format	GRID
Pixel Type	Floating point
Spatial Reference	MGI_Transverse_Mercator

Table 2.2 DEM properties in ArcMap System.

2.1.3 Structure

Based on a comprehensive review of research papers and expert knowledge (Nopp 1999; Netherer and Nopp-Mayr, 2005), the predisposition of a forest environment to biotic and abiotic damage agents incorporates two main components: the condition of the stand and the characteristics of the site. Following the approach of Speight and Wainhouse (1989) and Berryman (1986) relevant indicators were defined and scored according to their influence on the global predisposition to bark beetle outbreaks within these two components of the Predisposition Assessment System (DPAS).

Since the stand and site were analysed separately, the overall predisposition was concomitantly separately developed. Predisposition to snow and wind damage was analysed by discrete assessment systems and results were integrated in the bark beetle PAS. These analyses were performed through submodels having as input the initial datasets and as outputs the indicator results to be ultimately combined. According to the PAS, for site level predisposition, both the DEM and shapefile were also integrated in the final model as the slope and altitude are indicator parameters (Fig. 2.4).

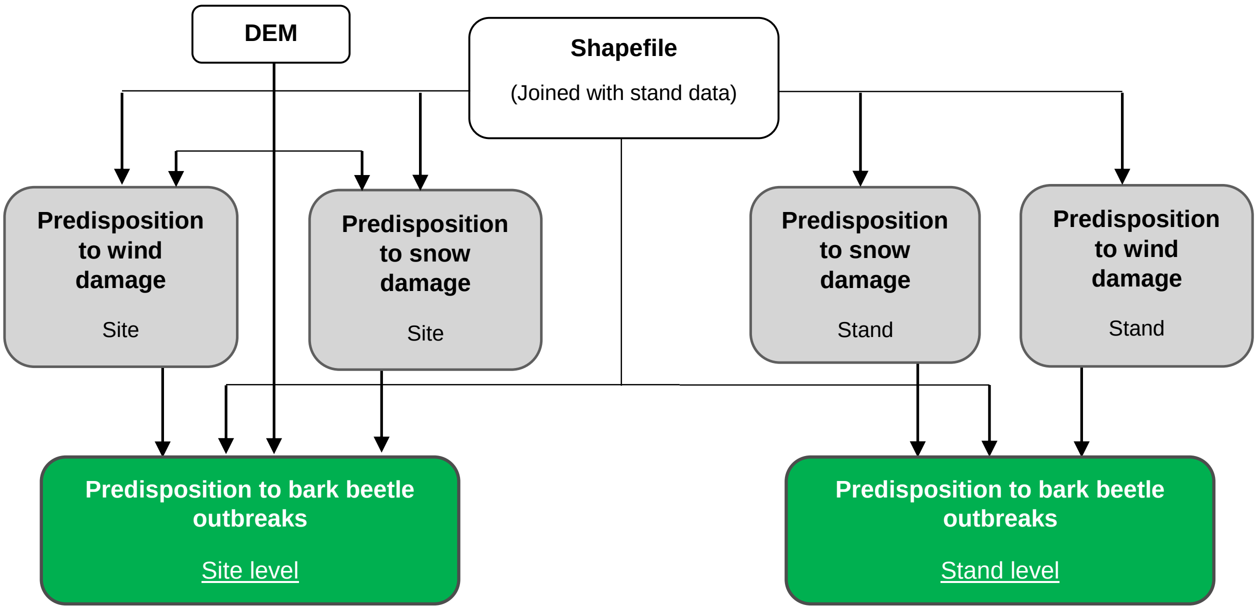


Figure 2.4 Model structure for predisposition assessment for *Ips typographus*

In Fig. 2.4 a simplified view of the structure of the model is represented, as some of the four submodels, required the preparation of the source files, particularly the DEM. An example of these preparation steps is the Smooth submodel, where ArcGIS tools were applied to even certain surfaces of the DEM, but where no indicators were applied. This ‘smoothed’ DEM provided the new elevation data to be applied in all subsequent models.

2.1.4 PAS approach

The values established by PAS resulted from the product between relative scores within an indicator and the relative importance of an indicator (weighting). The resulting values from this product are the relative weights and consequently the scores for each indicator. The break values for which a defined score is assigned, is denominated as fuzzy number.

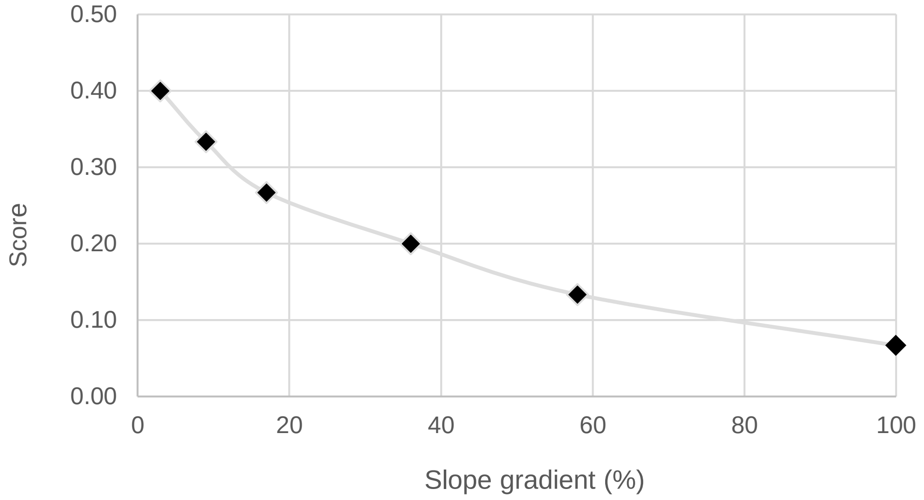


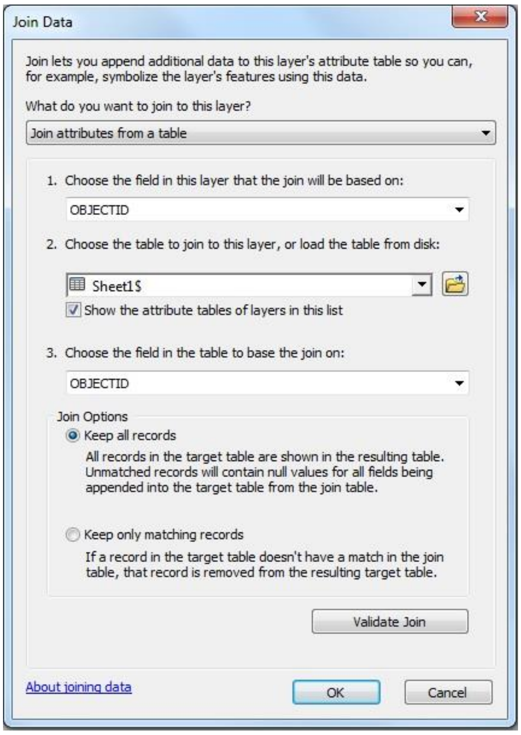
Figure 2.5 Graphical display of the fuzzy number grading in the Slope Gradient indicator regarding predisposition to wind damage on site level.

Upon the confirmation of the relative scores, one can estimate a set of values corresponding to their score using fuzzy numbers logic. In Fig. 2.5 the slope gradient values are graded within a [0, 0.40] interval. This principle was applied to the parameters that were defined within the scope of the system and ultimately summed, with their respective weight. Depending on the stand data, the indicators were either continuously or discretely weighed.

2.1.5 Data join

Before proceeding with the model construction in ModelBuilder, two of the original datasets, the shapefile and excel data from the forest inventory needed to be adapted and joined afterwards joined. As mentioned in Section 2.1.2., the stands data contained in the excel file were fitted to the indicator classes needed to rate the areas predisposition to wind and storm damage and subsequently for bark beetle outbreaks.

The function used to associate this data with the areas that they describe was the *Join* command of ArcMap. Joining data commands are typically used to append the fields of one table to those of another through an attribute or field common to both tables. In this case the common field would be the identification area number, *ObjectID*.



Join lets you append additional data to this layer's attribute table so you can, for example, symbolize the layer's features using this data.

What do you want to join to this layer?

Join attributes from a table

1. Choose the field in this layer that the join will be based on:

OBJECTID

2. Choose the table to join to this layer, or load the table from disk:

Sheet1$

☑ Show the attribute tables of layers in this list

3. Choose the field in the table to base the join on:

OBJECTID

Join Options

● Keep all records

All records in the target table are shown in the resulting table. Unmatched records will contain null values for all fields being appended into the target table from the join table.

○ Keep only matching records

If a record in the target table doesn't have a match in the join table, that record is removed from the resulting target table.

Figure 2.6 Join command dialog box in ArcMap prompted from the shapefile, being Sheet1 the excel sheet to be joined with the table of the shape file.

The resulting output file from this command is the shapefile containing all the necessary information for the consequent model operations, remaining in FLOAT format.

2.1.6 Indicators: stand and site level

The indicator values for stand level of the PAS, regarding wind, snow and bark beetle damage, related to four parameter categories: tree species composition, structure, vitality and predisposition to wind and snow damages (Table 2.3 and Table 2.4).

Level	Parameter	Criterion
Stand	Species composition	Proportion of spruce (%)
		Proportion of deciduous trees (%)
		Proportion of larch, pine and fir (%)

Structure	Stand Age - Alterklasse (years)
	Canopy closure (%)
	Phase of stand development (years)
	Stand Edges
Vitality	Stem damages
Predisposition to	Wind Damage (%)
	Snow Damage (%)

Table 2.3 List of all PAS indicators on stand level.

Level	Parameter	Criterion
Site	Generation factor	Temperature
	Soil	Hydrology
		Gleysol
		Bonity (Productivity)
	Terrain	Altitude (m)
		Slope (%)
		Morphology
	Predisposition to	Wind damage (%)
		Snow damage (%)

Table 2.4 List of all PAS indicators on site level.

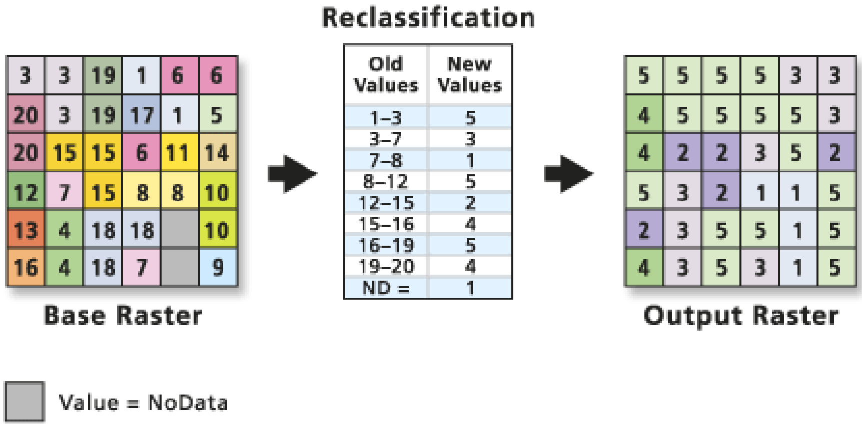
2.2 Indicator scoring tools

2.2.1 Reclassify

In order to incorporate the values of each indicator into the model, a transformation of the scale of the initial data or of the output results of the submodel was needed. ArcGIS has several tools that allow to manage the data according to the objective of the user. Toolboxes such as Spatial Analyst, Spatial Statistics, Analysis, 3D Analyst, Data Management, among others provide, for example tools that transform value intervals and classes on data, calculate new fields and data attributes or join fields from different files.

Another function that allows for the transform input data into new values, according to the PAS is the *Reclassify* tool from the *Spatial Analyst* toolbox. With *Reclassify* the user selects the target-reclass field and constructs its reclassification from old values to new values. Although it is a considerably flexible tool in terms of freedom to choose reclassification methods and intervals, this tool is restrictive when trying to reclass continuous data and still maintain its continuous attribute.

A common example of an application of this tool is land use categorization. For example, using as an input raster data water availability, ranked from 1 to 20, 20 being a perfectly water supplied area, it would be possible establish the land uses for each area, irrespectively of the planning purpose - agricultural, forestry, or urban, with new classes, from 1 to 5 (Fig 2.7).



Reclassification

3	3	19	1	6	6
20	3	19	17	1	5
20	15	15	6	11	14
12	7	15	8	8	10
13	4	18	18	▨	10
16	4	18	7	▨	9

Base Raster

Old Values	New Values
1–3	5
3–7	3
7–8	1
8–12	5
12–15	2
15–16	4
16–19	5
19–20	4
ND =	1

5	5	5	5	3	3
4	5	5	5	5	3
4	2	2	3	5	2
5	3	2	1	1	5
2	3	5	5	1	5
4	3	5	3	1	5

Output Raster

▨ Value = NoData

Figure 2.7 Land use reclassification example through the Reclassify tool.

This tool was used to generate in several indicator parameters in the PAS and intermediate steps in the submodels for discrete indicator values. A very useful aspect of this tool is that, if desired, the user can avoid highly time-consuming tasks like explicitly specifying individual values on the input raster and its corresponding alternative value especially for FLOAT (numeric characters with fractional values) format data.

2.2.2 Fuzzy Membership

Another tool that enables a user to perform an indicator-like ranking of results and translating them into a fuzzy set is the *Fuzzy Membership* function from the *Spatial Analyst* toolbox. Fuzzy sets are defined by assigning to every object a membership grade to the whole that represents a concept

This tool transforms the data from the input raster into a 0 to 1 range, indicating the strength of a membership within its dataset with 1 being absolutely in the set. This strength evaluation can be based on several fuzzification algorithms. Each one of the algorithms available in the *Fuzzy Membership* tool in ArcGIS defines a continuous function and each function captures a different type of transformation (ESRI, 2013).

Membership Function	Description
Gaussian	Membership defined through a Gaussian or normal distribution based on a midpoint indicated by the user with a defined spread decreasing to zero.
Large	Large input values have a membership closer to 1. The user provides de midpoint, which is assigned a membership of 0.5, with a defined spread.
Linear	Membership defined by a linear transformation between the user-specified minimum value, which gets an attributed membership of 0, and maximum value, which is assigned a membership of 1.
MSLarge	Membership defined through a function based on the mean and standard deviation, with larger values having a membership closer to 1.
MSSmall	Membership defined through a function based on the mean and standard deviation, with the smaller values having a membership closer to 1.
Near	Membership defined through a function around a specific value which is provided by the user as well as a specific spread decreasing to zero.
Small	Membership defined by a function where the smaller input values are attributed a membership closer to 1 and both the midpoint and spread are provided by the user.

Table 2.5 Description of the function in Fuzzy Membership tool (Adapted from ArcGIS Resource Center overview of fuzzy classes).

An important aspect of this tool is that when the input are continuous values, they remain continuous i.e. the only aspect that is modified is the range in which they are represented. This property is the result of the application of a function instead of combining several values into one single category, which is the method that the *Reclassify* tool applies.

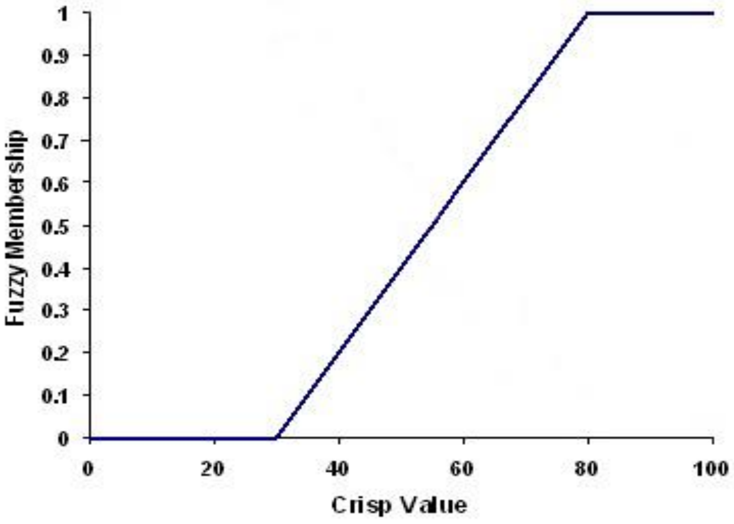


Figure 2.8 Linear fuzzy membership with 30 as the minimum value and 70 as the maximum value.

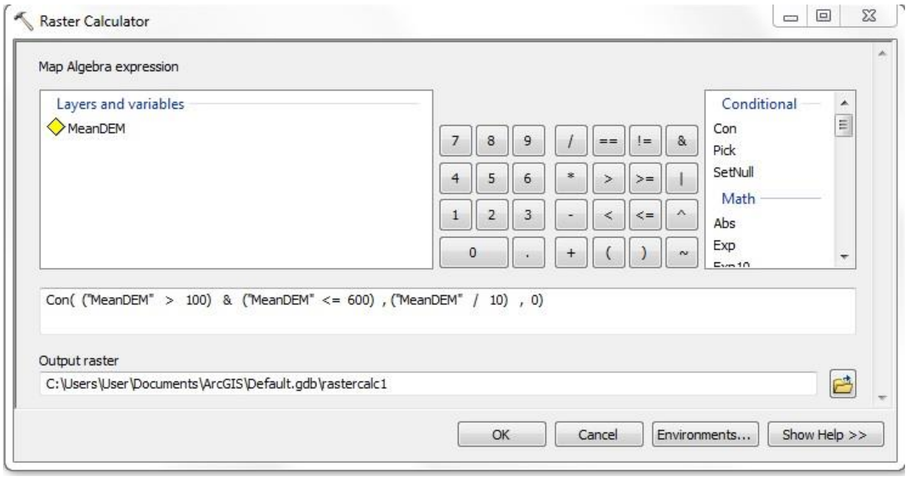
The approach carried out with a linear fuzzy membership indicates that a dataset, within a 0 to 1 range, receives a membership value based on a linear scale with a large input value being assigned a greater possibility, i.e. is placed closer to 1. However, this presents some operational issues in particular for more complex membership studies, for alternative membership ranges, among other conditions that would require a more customizable tool.

2.2.3 Linear and Sine Fuzzify Function

The use of *Fuzzy Membership* proved to have several limitations and uncovered the need of a more customizable tool. A fuzzify function was thus developed, allowing the user to fix the start and ending points of the membership ranges, as well as to select the type of function on which to base the membership.

ArcGIS has a wide variety of tools, besides those mentioned in Section 2.2.1 and 2.2.2, and script functionalities, but still the editing of the tools is still restricted. For the desired purposes of the PAS, a hybrid tool for ArcMap was developed which would integrate fuzzy membership principles and support the customizing and management of the properties of the analysis.

The basis for this hybrid tool was *Raster Calculator.* This calculator-like tool provides a powerful mechanism to perform multiple tasks, based on Map Algebra syntax (Fig 2.9). A user provides variables and layers as inputs and constructs its operation through the operators and functions that the tool has incorporated. These operators include simple mathematical functions, conditional clause functions, trigonometric functions and dataset analysts such as null-value finders (*Isnull* tool).



```
Con( ("MeanDEM"  >  100)  &  ("MeanDEM" <= 600) , ("MeanDEM"  /  10)  ,  0)
```

Output raster

C:\Users\User\Documents\ArcGIS\Default.gdb\rastercalc1

Figure 2.9 Raster calculator dialog box where a conditional (Con) function is used. MeanDEM as input Layer and map algebra expression where the desired operation is to divide all values between 100 and 600 inclusive of the input file by 10. All other values are assigned a value of 0.

By taking advantage of the third section of this function, which refers to the values that are not included in the first expression, a user can extend the calculation substantially. If we consider the example given in Fig. 2.9, in order to perform a different calculation for altitudes above 600 meters, it is only necessary to include another conditional function and the corresponding algebra expression in the third section of the first conditional function (Equation 2).

Equation 2.1

$$\text{Con((“\%MeanDEM\%”} > 100) \,\&\, (\text{“\%MeanDEM\%”} <= 600) , (\text{“\%MeanDEM\%”} \;/\; 10) , \text{Con} ((\text{“\%MeanDEM\%”} > 600), 2 , 0)))$$

In Equation 2.1 for values above 600 meters, considering the data from the file “MeanDEM”, the value 2 is attributed. For values that do not fall within the range of the analysis, from 100 to infinity, the value 0 is attributed. This feature enables the user to diversify its analysis, apply different methods to the data range in an efficient way by resorting to just one tool.

This is a key aspect to be considered for the construction of indicators that simultaneously do not behave linearly and do not fall within the 0 – 1 scale, both of which preclude the use of the Fuzzy Membership tool. A possible way to include this tool in the construction of the indicator is to perform an initial reclassification of the data, through the *Reclassify* tool, and then apply the Fuzzy Membership function.

However this would only analyse a single linear section of an indicator. For example in the Slope gradient (Fig. 2.8) the scores do not follow a linear trend for each fuzzy number so that it would be necessary to integrate two different tools (*Reclassify* and *Fuzzy Membership)* for each one of the trends. This would not only make the analysis more complex and consequently more prone to carrying calculation errors but also more time consuming if the calculation parameters would have to be altered.

Considering the advantages and disadvantages of each calculation process, it was decided that integrating equations that would represent the behaviour of the indicators for each interval in a single tool would be the most efficient and straightforward procedure to integrate the PAS into the model. The basis for these calculations was the *Raster Calculator* tool and the input are the values prepared in Excel and the Layer file to which the indicators will be applied.

Firstly, in order to describe a linear trend one must calculate its slope and interception on the y-axis. A slope constitutes the rate at which an ordinate of a point of a line on a coordinate plane changes with respect to a change in the abscissa. In an indicator construction scope this represents the quotient between two ranges: parameter values and corresponding indicator scores.

Knowing the slope, the y-axis interception value is given by inserting any corresponding values in the equation.

Equation 2.2

$$y(x) = \overbrace{\boxed{\frac{y_2 - y_1}{x_2 - x_1}}}^{\text{Slope}} * (x - x_2) + y_2$$

Using Equation 2.2 as a basis the function for both negative and positive linear slope indicator trends is obtained. When the objective is to rank the score of a parameter, the fuzzy logic should be applied and the border fuzzy numbers used as direct input for each trend. In sequence the equation obtained is then inserted it in the Raster Calculator tool. This methodology enables the data to be calculated and scored while maintaining their continuous attribute.

The use of this type of logic can be exemplified by considering a continuous dataset file that will be the object of an indicator score analysis. This indicator will have two trend scoring patterns with the following scores:

Criterion	Indicator	Score
C	≤ x_1	V_1
	x_2	V_2
	≥ x_3	V_3

Table 2.6 Scoring example table for a non-linear trend indicator. V1 > V3 >V2 results into a decreasing trend from V1 to V2 and in an increasing trend from V2 to V3.

The resulting two equations (Equation 2.3 and Equation 2.4) based on Eq. 2.2 and correspondent graphics that describes the trends and border score values are the following:

Equation 2.3 $$v_i(x) = \frac{v_2 - v_1}{x_2 - x_1} * (x - x_2) + v_2$$

and

Equation 2.4 $$v_{ii}(x) = \frac{v_3 - v_2}{x_3 - x_2} * (x - x_3) + v_3$$

In both equations, x represents the input data value for which a score value will be calculated, being all other values parameters that refer to the slope and y-axis, in this case v-axis, of the indicator linear function.

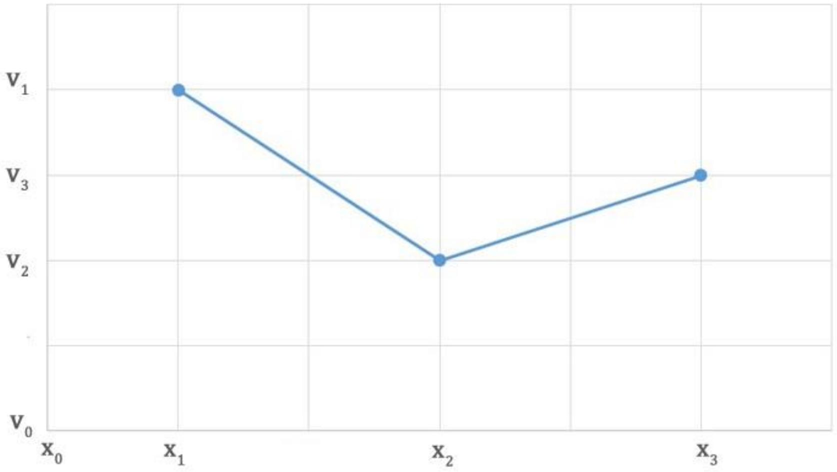


Figure 2.10 Example of a non-linear indicator trend.

If the calculation of more trends and respective indicator values is needed, the same logic will be extended and integrated in the raster calculator tool. For the example presented above with the values from Table 2.6 the Map algebra that would incorporate the Raster Calculator tool of ArcMap is the following, for a given file with the name ‘Data’:

Con((“%Data%” >= x1) & (“%Data%” <= x2) , (((v2 - v1) / (x2 - x1)) * (“%Data%” – x2)) + v2 , Con((“%Data%” > x2) , (((v3 – v2) / (x3 – x2)) * (“%Data%” – x3)) + v3, x1))

With the introduction of a second conditional clause (*Con)*, the values from x2 and on, are affected by the second linear equation, thus following the scores previously established in the PAS.

The second category of function that was used in the construction of this model was the sine function. This function is one of the basic functions encountered in trigonometry, the others being cosecant, cosine, cotangent, secant and tangent. The sine function has a period of 2π.

As this category of function behaves as a wave, a mathematical curve, it is often applied in physics, signal processing and many other fields. The most basic form of a sinus function, as a function of time is the following:

Equation 2.5
$$y(t) = A\ \sin(\omega t + \ \varphi)$$

- A – Wave amplitude, the peak deviation of the function from zero;
- ω $(2\pi * f)$ – Angular frequency, the change of rate of the function argument;
- φ – The phase, specifies where the oscillation is at t = 0.

This initial equation has to be adapted to a format allowing to incorporate values from the PAS and to apply them to the range of values of a map. Hence reformulation of this equation was conducted where the initial and final fuzzy numbers, and the initial point of the function considering a sinus-shaped function, are provided by the user.

Equation 2.6
$$f(x) = \ |f_1 - f_2| * \sin\left(\left(\frac{\pi}{0.5}\right) * (x + x_i)\right) + f_1$$

After the scoring range is set, a sine function can be constructed that behaves in a smoother manner considering a change in trend signal. A clear example for indicator function construction would be an indicator with a rank between 0.25 and 0.75, for values between 0 and 6, with the following behaviour:

Equation 2.7
$$f(x) = \begin{cases} 0.25\,, & x \leq 1 \\ 0.25 * (x - 2) + 0.5, & 1 < \ x \leq 2 \\ 0.25 * \ \sin\left(\left(\frac{\pi}{0.5*4}\right) * (x - 2)\right) + 0.5\,, & 2 < x \leq 4 \\ -\,0.25 * (x - 5) + 0.25, & 4 < x \leq 5 \\ 0.25\,, & x > 5 \end{cases}$$

In this example both linear and sinus trends are represented. In the second and fourth conditional statements, the range of values is graded according to a linear trend. However in the third conditional, contrary to applying two more linear conditionals to express the change in signal of the first derivative of the scoring range, a sinus trend is applied. The goal in implementing this trend is to simulate a more gradual and less abrupt change in slope.

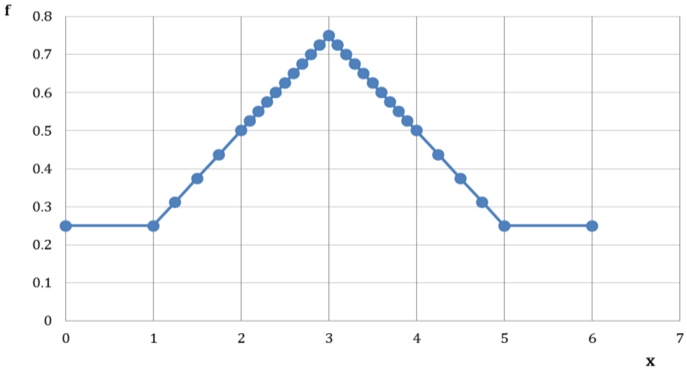


Figure 2.11 Graphical representation of equation 2.7 with linear trends for a hypothetical scoring of features with values ranging from 0 to 6

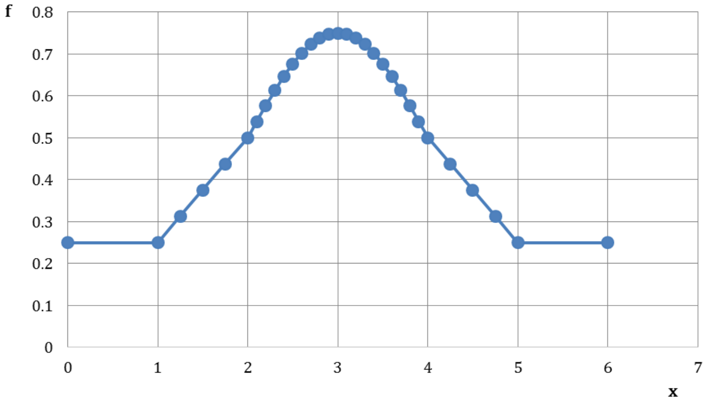


Figure 2.12 Graphical representation of equation 2.7 with linear and sinus trends for an hypothetical scoring of features with values ranging from 0 to 6.

In this example, should a linear conditional statement be applied to the interval between the values 2 and 4, it would have to be divided between two separate linear trends (Fig. 2.11). Consequently the change would not be as gradual as when a sinus function is applied, as exemplified by equation 2.7 (Fig. 2.12).

2.3 Preparatory Models

2.3.1 Data Preparation Models

Smooth Model

The initial step in developing the predisposition model would be to adjust the initial DEM to a smoother surface. The importance of undergoing this process resides in the adjustment of values that might misrepresent the area, values that suddenly change or cells with lack of data. All these occurrences potentially influence data processing flow or process data in an imprecise or misrepresentative way.

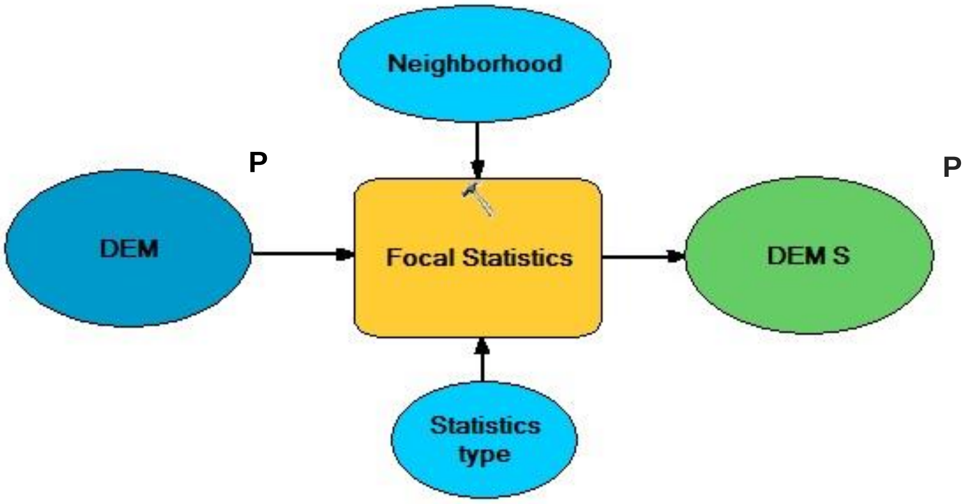


Figure 2.13 Workflow of the Smooth Model. The output raster DEM S signalled with a P indicating it as a Model Parameter.

The tool used to adjust the DEM was *Focal Statistics*, from the *Spatial Analyst* toolbox. This tool calculates for each input cell location a statistic of the values within a specified neighbourhood around it. The neighbourhood classes that the tool provides are Annulus, Circle, Rectangle, Wedge, Irregular and Weight and the statistics units can either be cell or map based. The type of statistics applied to the file was Mean, for a circle neighbourhood and cell size of 3 units.

The output file be like the input Elevation file, denominated DEM S for the consequent models, making this the first step after the joining of the excel data with the shapefile (Section 3.2.1).

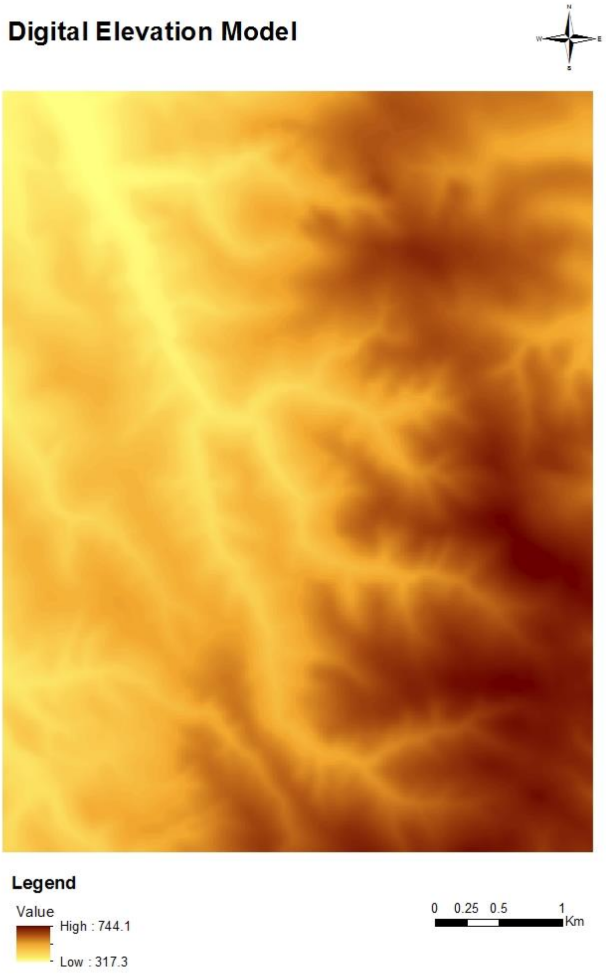


Figure 2.14 Output rastermap from the Smooth Model.

Aspect Model

From previous analysis on the Rosalia forest, the value of aperture angle was 270° and orientation was 315°. The value for orientation referred to the predominant wind direction observed in the site during past studies. As wind is an important component of the PAS, it was essential to develop an Aspect-based raster file where the slopes that had the same orientation as a certain wind direction would be defined.

Considering these objectives two integrated submodels were developed: the *Adjust* and *Aspect* model. The goal of the *Adjust* would be to adapt the DEM to a custom aspect. The first tool to be used would be the *Aspect* tool. This tool allows a user to identify the direction of a slope through a compass direction. A value of 0 degrees indicates North and 180° degrees indicates South-oriented slopes.

With the previous value of orientation of 315° one can adapt the original range of values from the *Aspect* tool using map algebra. The *Adjust* submodel performs this range adaptation and prepares it for the *Aspect* model.

Figure 2.15 Output rastermap from the Adjust submodel.

The input data is a value that constitutes the difference between a constant of 180 and the predominant wind orientation, and the DEM. The file that results from the map algebra operations in the model is a map with the desired aperture angle of 315º. The calculation sequence on the Adjust model were acquired from previous spatial analysis performed by the IFFF on MapModels (Netherer, et al., 2002). Following the application of this model, the procedure of converting the adjusted aspect range of values to a normalized range of values within the aperture angle is conducted in the Aspect model.

Two linear fuzzy membership functions were applied considering the previously stated aperture angle and orientation values. One of the fuzzy membership function ranked from 0 to 1 the output rastermap from the Adjust model in an increasing trend from 0º to 180º and the second ranked in a decreasing trend from 180º to 360º. The application of this procedure means that the same value of 0.5 was attributed for a slope with a direction of 270º or 90º, in reference to the 315º orientation angle.

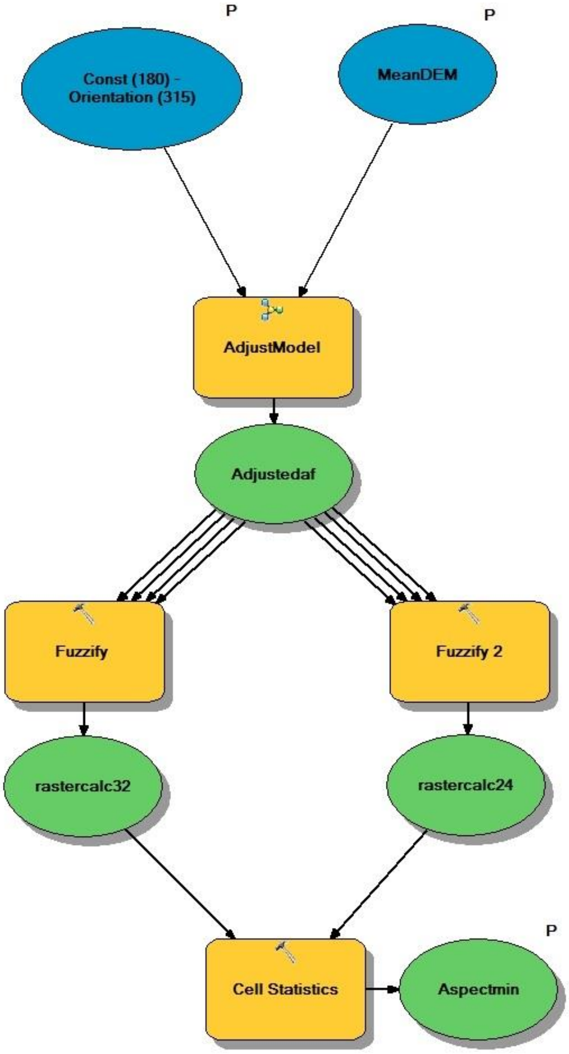


Figure 2.16 Workflow of the Aspect Model with theAdjust submodel integrated.

As a result of the application of this model, the slope aspect was graded from 0 to 1, within the parameters established initially, being the value 1 attributed to slopes perpendicularly exposed to a wind direction of Northwest, 315º. This file served as input for the Terrain Morphology.

Low-Middle-High Slopes and Range submodel

Slope characterization for the Rosalia forest is a key component of the predisposition assessment. This terrain feature is the first derivative of a surface and has both magnitude and direction. It can be derived from the TIN or DEM using tools that GIS software, such as ArcGIS provide (Li, et al., 2010). In the Low-Middle-High Slope Model, the goal was to describe the slopes into 3 categories, each with their corresponding interval.

The calculation would be based on two separate procedures. One would be to establish an euclidean range for areas characterized by water flow from the prepared DEM and the other to identify and also establish and Euclidean range for convex surface areas. The final step consists in dividing the resulting rastermaps and applying a Range Model where the low, middle and high denominated slopes can be identified.

For the first procedure, several spatial analyst tools were used. In the first calculation the *Flow Direction* tool is applied. With this tool, one creates a raster of flow direction from each cell to its steepest downslope neighbour, thus providing useful hydrological information that would serve as input for the *Flow Accumulation* tool. Here the values are evaluated to describe a flow pattern as the accumulated weight of all cells flow into each downward sloping cell in the output raster.

Based on past research, specifically early model constructions with MapModels (See section 1.3.1) it was established that a threshold of 1000 flow accumulation cell values would represent a considerable water flow. With this value, a conditional tool (*Con)* was implemented, assigning a value of 1 to all cell values above or equal to the pre-established 1000 accumulation value and 0 otherwise. The result of this calculation produced a raster file with all designated water flows for the Rosalia forest.

This file is the input for the *Euclidean Distance* tool. This tool calculates for each cell, the distance to the closest source and a value of zero is appointed to a legitimate source. The aim of this process is to construct a range of values representing the relative proximity to water flow-supportable terrain. The output file would be denominated “riverseucl”.

Simultaneously the DEM file was also analysed for convex-shaped terrain. The first tool to be used should be the *Focal Statistics* with a neighbourhood of 6 cells, larger than the one used in the Smooth Model (see section 2.3.1) in order to expand the analysis range further and include possible outlier terrain surfaces. The following tool applied should be a *Curvature* tool where the curvature of a surface is calculated on a cell-by-cell basis, assigning a positive value for convex surfaces, 0 for plain surfaces and negative values for concave surfaces.

Similarly to the process conducted to obtain a *Euclidean distance* raster file of the previously threshold for the defined river areas, a threshold for convex areas was defined using a conditional tool (*Con*). The threshold level selected was 0.3 so that only distinct convex surfaces would be included.

The resulting raster file, ConvexPoints (Fig. 2.17), constitutes the input for the *Euclidean distance* tool and was also used in the subsequent submodel Terrain Morphology – Snow Damage. The output from this tool represents the relative distance from convex area to which a value of zero will be asigned. With both *Euclidean distance* tool-originated files, a quocient between the *riverseucl* file and a file corresponding to the sum of both the *riverseucl* and *conveucl* was applied. The output file from this division represents the normalized values of river-like surfaces, in this case low slopes, from all convex surfaces. Instead of analysing the slopes in terms of percentage or grade rise, with this file one yields a range of slopes with the terrains that result from the *riverseucl* as referrence.

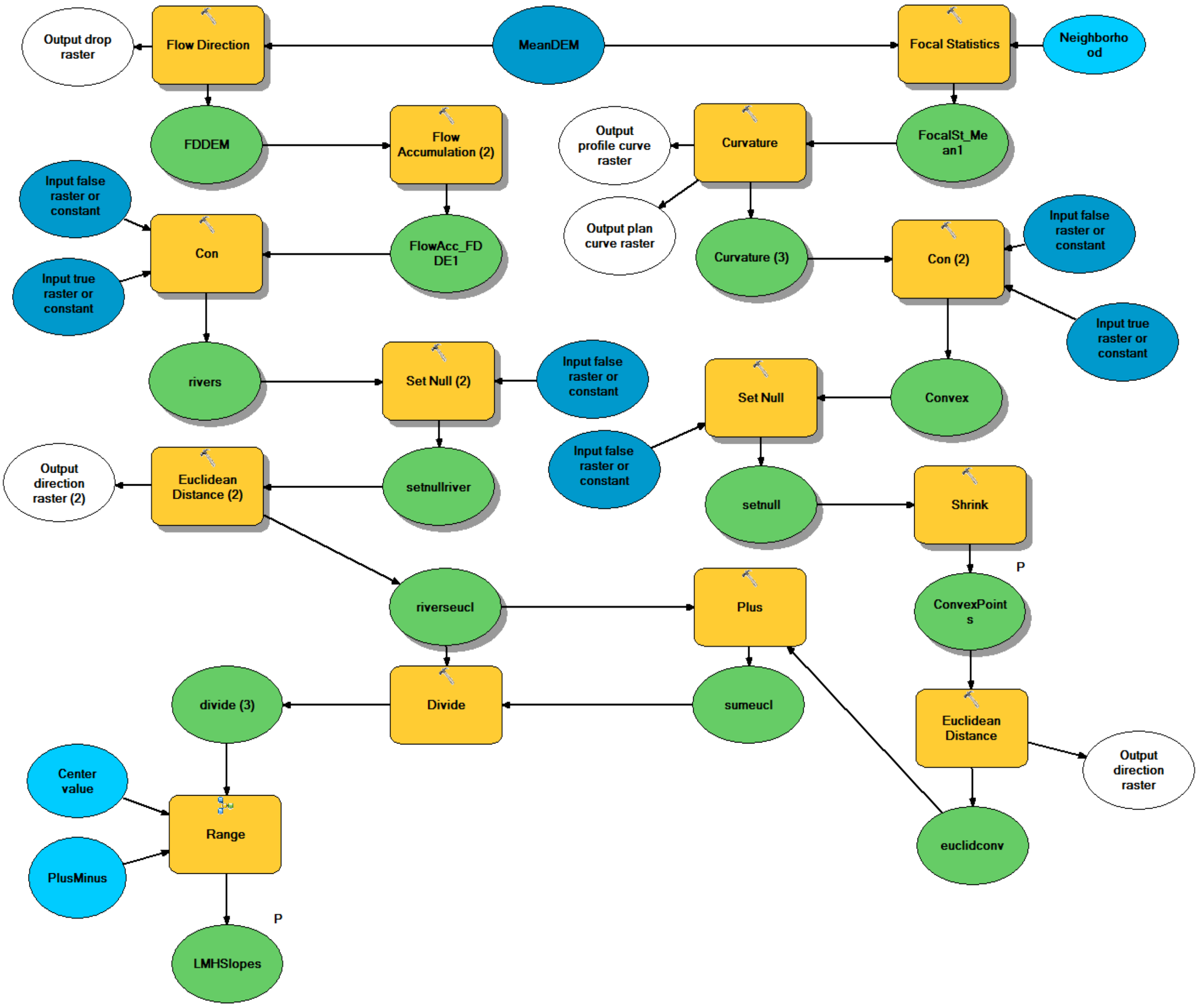


Figure 2.17 Workflow of the Low-Middle-High Slopes model and the integration of the Range Model. The output files to be used on subsequent submodels signalled with the Model Parameter symbol (P).

All non-coloured nodes represent inherent output rastermaps with no use for the PAS, therefore no calculation steps associated with them nor intermediate values are generated.

The final step consists in defining the range for low, middle or high slopes. This procedure was conducted through a mask submodel denominated Range (Annex A). This submodel has as prerequisite parameters, besides an input raster file, a centre value and a range value.

All raster values above a threshold of centre value plus range value were designated as high slopes, all values under a threshold of centre value minus range value were designated as low slopes and all in between middle slopes. With this last step the user obtains a map where low, middle and high slopes are differentiated according to specific threshold values using as reference the surfaces designated as rivers.

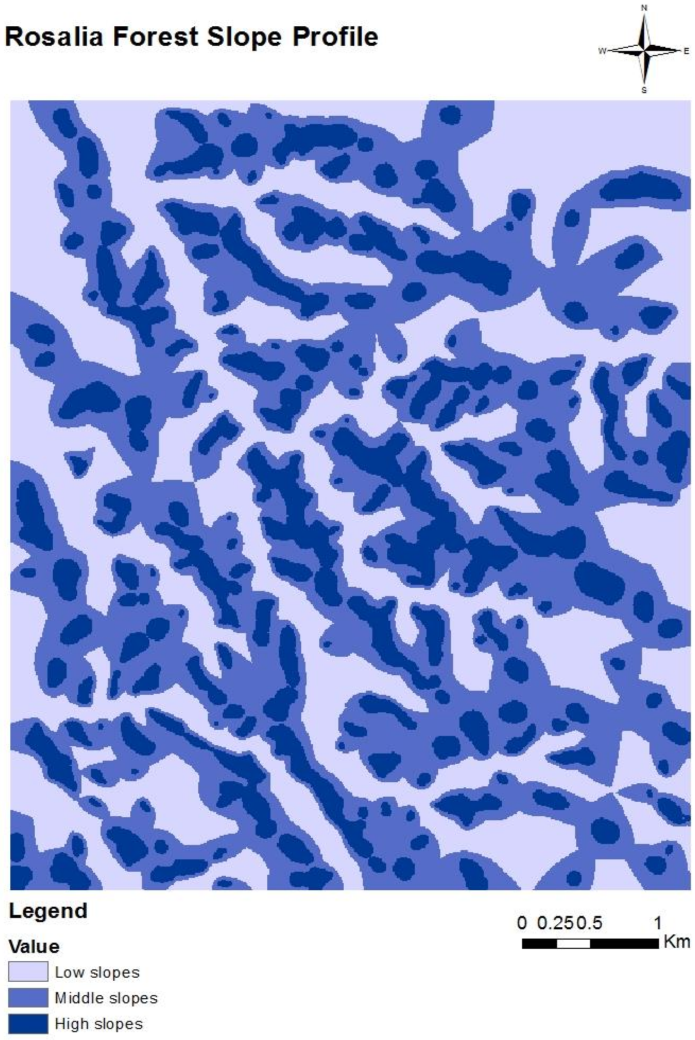


Figure 2.18 Output rastermap from the Low Middle High Slopes submodel with the three desired slope categories.

2.3.2 Terrain Morphology Models

In order to perform an assessment of the predisposition of a forest to outbreaks of bark beetles, several types of factors must be taken into account. Among them, snow and wind damage, as well as terrain-related characteristics are essential parameters needed to infer the characteristics of the study area.

With these considerations in mind, a terrain morphology study was constructed through submodels for each of the mentioned components. In these models, the Fuzzify is introduced in order to score wind classes and slope gradients according to their respective indicator scores.

Terrain Morphology – Snow Damage

Considering the Predisposition to Snow Damage on site level model, one of the indicators in the PAS is terrain morphology. This indicator was prepared, similarly to *Terrain Morphology Wind Damage*, in a submodel designated *Terrain Morphology – Snow Damage.* The goal was to process data from the DEM, ConvexPoints and WindClass (from T. Morph. – Wind Damage model) files through map algebra and reclassifications in order to obtain a normalized range of values corresponding to the level of predisposition to snow damage.

The initial step was to obtain a file where the slopes could be compared between the convex points file and the DEM. The convex points file originated from the Low-Middle-High slopes submodel. The *Slope* tool was then applied to the DEM in order transform the values from the slopes in degrees. This tool allows a user to identify the slopes in degrees or percentage by identifying the rate of maximum change in z-value from each cell. The output rastermap from the *Slope* tool was reclassified through a *Reclassify* tool (See section 2.2.1) as well as the Points rastermap. Their reclassification was formulated according to the range of slopes that each rastermap will be representing.

The following step was undertaken to apply the *Cell Statistics* tool. This tool allows for the calculation of a per-cell statistic from multiple raster with a wide range of statistics parameters such as mean, majority, maximum, median, minimum, among others. The statistical parameters applied between the two files was maximum, aiming to maintain, by excess, the reclassified slope ranges. The outcome of this calculation was a rastermap where the convex areas, identified by the reclassification of the Points rastermap, overlapsed the areas with the same slope in the reclassified Slopes rastermap as they were identified with a higher value (Annex A -5).

The resulting file served as input for four *Fuzzify* tools (See section 2.2.3). The fuzzy number values integrated in these tools score the input file for luff, angular, parallel and lee-oriented wind directions.

Level	Parameter	Criterion	Indicator	Relative score
Site	Exposure to wind	Luff	Convex	0.33
			Slope	0.33
			Other	0.07
		Angular	Convex	0.46
			Slope	0.46
			Other	0.2
		Parallel	Convex	0.46
			Slope	0.46
			Other	0.2
		Lee	Convex	1
			Slope	1
			Other	0.74

Table 2.7 PAS values for the Exposure to wind parameter.

The *Pick* tool was the next tool applied to the four rastermaps. The position raster used was the Wind Class rastermap developed in the submodel Terrain Morphology – Wind Damage. The input values contained the scores for each individual wind direction on the full map and the WindClass file would place the scores according to the area to which they belong.

As the Terrain Morphology parameter according to the PAS range from 0 to 1, the final procedure was to normalize the results. This was conducted by dividing the output rastermap from the *Pick* tool, by its maximum. The resulting output raster file from this submodel was integrated in the Predisposition to Snow Damage – Site level submodel which consequently would integrate the final Predisposition to Bark Beetle Outbreaks – Site level.

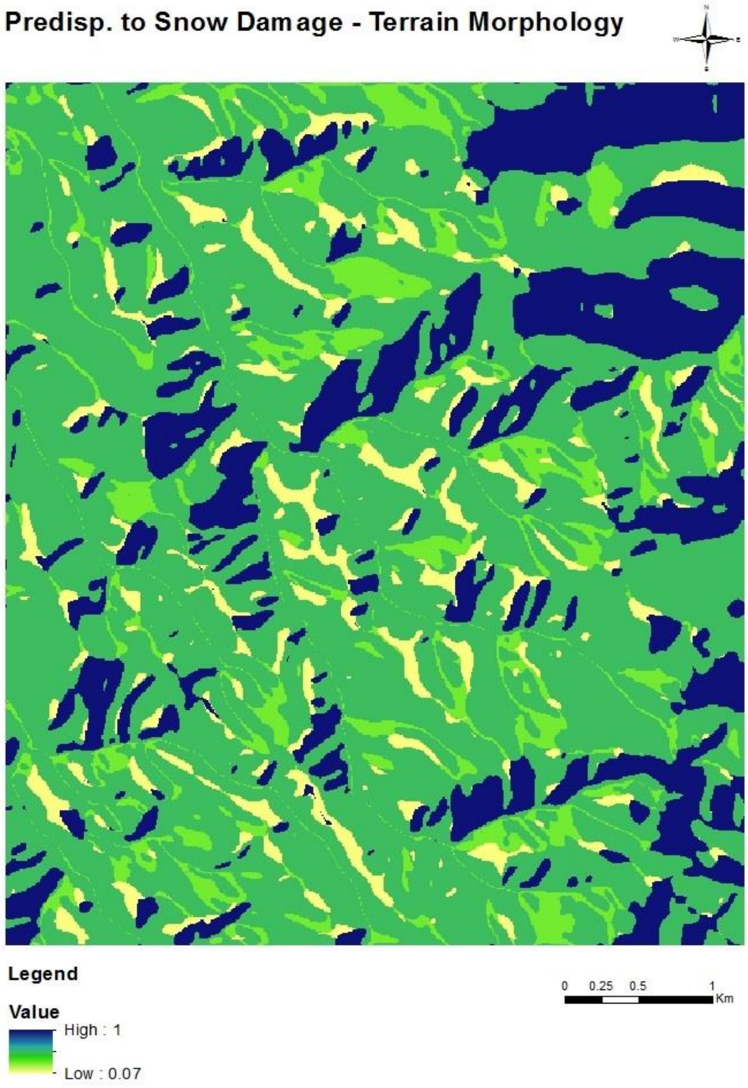


Figure 2.19 Output rastermap from the Terrain Morphology Snow submodel.

Terrain Morphology – Wind Damage

One of the necessary preparatory submodels was the Terrain Morphology submodel on wind damage. The resulting output rastermap serves as input for the submodel Predisposition Wind Damage site level which subsequently is integrated in the final Predisposition Models at site and stand level. The objective of this model was to calculate a rastermap by processing both output data from the Aspect model and obtain a WindClass file, and the Low-Middle-High slopes file (See section 2.3.1) with normalized values for the wind damage criterion from the PAS.

The first tool applied to the Low-High-High slopes file was the *Fuzzify* tool. Four *Fuzzify* tools were applied, for Luff, Angular, Parallel and Lee-oriented wind directions in accordance with the scores defined in the PAS (Table 4.1).

Level	Parameter	Criterion	Indicator	Relative score
Site	Wind direction	Luff	Low slopes (-1)	0.33
			Middle slopes (0)	0.33
			High slopes (1)	0.07
		Angular	Low slopes (-1)	0.46
			Middle slopes (0)	0.46
			High slopes (1)	0.2
		Parallel	Low slopes (-1)	0.46
			Middle slopes (0)	0.46
			High slopes (1)	0.2
		Lee	Low slopes (-1)	1
			Middle slopes (0)	1
			High slopes (1)	0.74

Table 2.8 Fuzzify function fuzzy values and corresponding scores.

In this model a file designated WindClass was calculated. The procedure consisted initially on obtaining a rastermap from the Aspect Model for an orientation of 315º and aperture angle of 360º. This file was multiplied by a value of eight and reclassified in accordance with the range of wind classes from the PAS. The resulting file, WindClass was also used for the Terrain Morphology - Snow Damage submodel.

The *Pick* tool was the following tool to integrate the workflow of the model. In this tool an output value is assigned using a position raster dealing as allocation basis for the values of the input rastermaps. Aiming to calculate a map where the indicator scores for different types of slopes are appropriately allocated within the existing wind classes, the position rastermap in the *Pick* tool was the WindClass file while the input rastermaps were the output rasters from the *Fuzzify* tool.

The final step was to integrate map algebra tools in order to normalize the output rastermap from the *Pick* tool. The resulting file describes the predisposition to snow damage on a terrain morphology level (Fig 2.20), according to the scores established in the PAS.

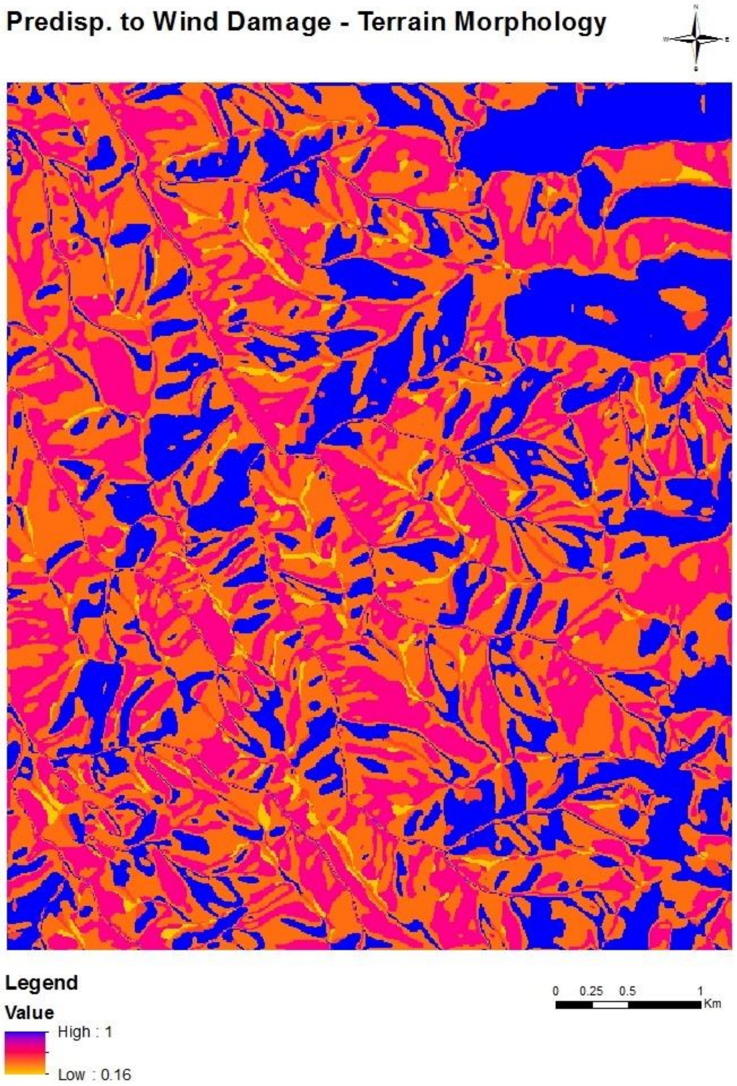


Figure 2.20 Output rastermap from the Terrain Morphology - Wind Damage submodel

2.4 Secondary Models

2.4.1 Stand level damage models

As previously established in the structure of the PAS, for each Predisposition to Bark Beetle final model, a snow and wind damage predisposition must be ascertained for both site and stand level. The stand-related submodels were constructed around the Stand joined shapefile (See section 2.1.5). The procedure for both snow and wind damage on stand level damage modelling was similar. The desired features to be scored according to the PAS were extracted from the shapefile and each represented in a rastermap with the same cell size (10) as all the files used in this model. A *Fuzzify* tool was applied to all the resulting rastermaps with the corresponding scoring fuzzy numbers and all the output rastermaps were summed. The resulting rastermap was then subjected to a calculation step in order to maintain only the study area, and assign a value of 0 to all non-forest areas.

The files that resulted from each submodel, Wind damage stand level and Snow damage stand level, were integrated in the final Predisposition to Bark Beetle Attack Model on stand level.

Snow Damage

The input file for the Snow Damage – Stand level was the Shapefile from the Rosalia Forest that was previously joined with data from the forest inventory conducted by the OBF. Being this model stand-related, neither terrain-based parameters, nor files were used. Furthermore the DEM does not integrate this analysis, nor the WindClass and Convex Points file.

The features that constitute the shapefile (Table 3.1) have different classes of values. Nevertheless all of them are translated into numerical values in the interest of applying the indicator weights from the PAS.

Level	Parameter	Criterion	Indicator	Relative score
Stand	Species Composition	Proportion of pine and spruce (%)	≥ 90	0.75
			70	0.4
			50	0.3
			40	0.2
			0	0.1
	Structure	Age class (years)	≥ 150	0.2
			100	0.3
			30	0.5
			10	0.5
			5	0.1
		Canopy closure	2.0	0.2
			1.5	0.1
			1.0	0.0
			0.5	0.2
			0	0.5
	Vitality	Stem damages	4; 5	0.5
			3	0.3
			1; 2	0.1
			0	0.0

Table 2.9 Indicator list for the Snow damage – Stand level model.

The final raster dataset must have a range of values from 0 to 1 and should only include stand values. Regarding the value of 0 to 1, a sequence of map algebra operations was integrated where the sum operation output file is divided by a rastermap composed by its own maximum value. This procedure leads to a normalized range of values of the original dataset.

In order to identify non stand areas as areas with no predisposition to snow damage, a *Times* tool was integrated. The rastermaps multiplied were the reclassified Forest Area feature map and the rastermap that resulted from the normalized indicator results. The areas that are excluded in the Forest Area rastermap as a result of this operation are areas such as roads, residential areas, construction yards, among others. The final procedure was to convert all NoData values into zero values. This was performed with a *Raster Calculator* tool, using the incorporated IsNull function.

Figure 2.21 Output rastermap from the Snow Damage on stand level model on a monochromatic colour ramp.

Wind Damage

In this model, analogously to the process conducted in the Snow Damage – Site Level model, the input file was the layer with shapefile from the Stands joined with the inventory data. The desired features were extracted from this layer into separate rastermaps and a customized *Fuzzify* tool was applied to each rastermap. Both linear and sinus shaped fuzzify functions were applied in this model.

Level	Parameter	Criterion	Indicator	Relative score
Stand	Species Composition	Proportion of deciduous trees (%)	≥ 30	0.0
			< 30	0.6
		Proportion of larch, pine and fir (%)	≥ 30	0.0
			< 30	0.6
		Proportion of spruce (%)	≥ 90	0.6
			< 90	0.0
	Structure	Canopy closure	2.0	0.27
			1.6	0.00
			1.2	0.27
			0.8	0.53
			0.4	0.80
			0.0	0.00
		Age class	100	1
			80	0.7
			30	0.2
			10	0
			0	0
	Vitality	Stem damages	4	0.4
			3	0.33
			2	0.25
			1	0

Table 2.10 Site level indicators and indicator weights for snow damage.

With all the rastermap output files from the *Fuzzify* tools, a *Weighted Sum* tool was applied. The resulting rastermap was subsequently subjected to a map algebra procedure where it was divided by a constant value rastermap of the maximum value.

Following this normalization operation, the output rastermap was multiplied by the reclassified Forest Area rastermap in order to keep only values relevant for the PAS modelling. The output file was integrated in the Predisposition to Bark Beelte Attacks model on stand level.

Figure 2.22 Output rastermap from the Wind Damage on stand level model on a monochromatic colour ramp.

2.4.2 Site Level Damage Models

Snow damage

In this model the objective was to calculate a raster where the DEM, Shapefile and Terrain Morphology Predisposition to Snow Damage files served as input file and allowed for the predisposition of the site for snow damage to be assessed.

Similarly to the procedure conducted for the Snow Damage on Stand Level model, these three files can be adapted whenever necessary, through the application of *Fuzzify* tools to the target indicator features and afterwards summed. The final steps focused mainly on normalizing results and ensuring that non-relevant areas were assigned a value of zero predisposition to snow damage.

Regarding the DEM, two tools were applied: *Slope* and *Fuzzify.* The *Slope* tool was utilized for an output measurement of percent rise and for a Z-factor of 1. To the output file from the *Slope* tool and to the original DEM, a *Fuzzify* function was applied for the Slope and Altitude Indicators, respectively (Table 4.4). The fuzzify tool was applied for altitude fuzzy numbers established in the PAS. Concerning the Shapefile, three *Feature to Raster* tools were applied. This step allowed to extract the features to be scored according to the PAS and create a Forest Area rastermap used in subsequent procedures.

Level	Parameter	Criterion	Indicator	Relative score
Site	Terrain	Altitude	≥ 1400	0.4
			1100	0.6
			900	0.8
			800	1.0
			400	1.0
			200	0.4
			0	0.4
		Slope	100	0.67
			60	0.33
			40	0
			20	0.33
			5	0.67
	Soil	Water supply	7	0.33
			6	0.27
			4; 5	0.20
			3	0.13
			2	0.07
			1	0.00
			0	0.00
		Bonity	16	0.67
			8	0.33
			1	0

Table 2.11 Site level indicators and indicator weights for wind damage.

As the output rastermap from the Terrain Morphology Predisposition to Snow Damage had been previously normalized there was no need to adjust it before applying the *Weighted Sum* tool. The output rastermap from this tool was subjected to a normalization operation similarly to the procedure conducted in the Snow Damage Stand Level model.

In order to include only relevant areas, the output file from the normalization operation was multiplied by the Forest Area previously prepared from the Stands shapefile. The final step of this model consisted on setting NoData values into values with a predisposition to snow damage of zero.

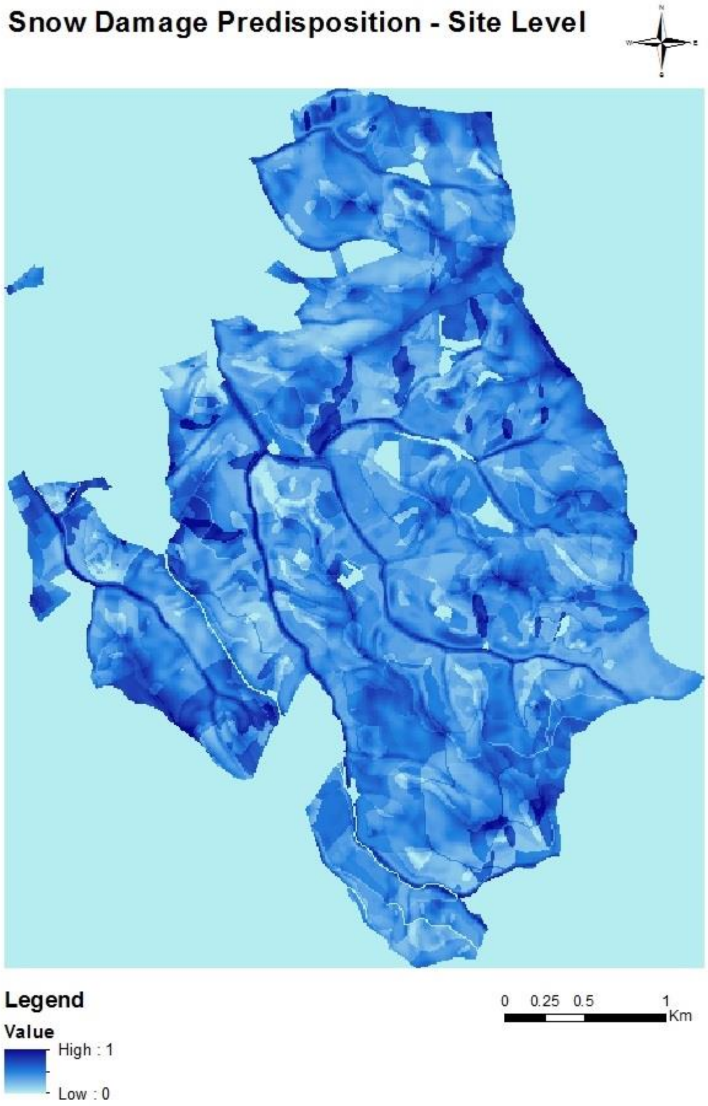


Figure 2.23 Output rastermap from the Snow Damage Predisposition on site level.

The output file from this model integrated the Predisposition to Bark Beetle Attacks on Site Level primary model as one of the indicators to be scored.

Wind Damage

For the Wind Damage model on site level, the previously developed Terrain Morphology model output rastermap, the DEM and the Stands shapefile were utilized. A *Slope* tool was applied to the DEM file in order to score the slopes of the study area according to the PAS. This scoring procedure was conducted through a *Fuzzify* tool for linear trends. To the Stands shapefile, three *Feature to Raster* tools were applied in order to extract the Gleysols, Bonity and Forest Area field values.

To the Gleysols and Bonity fields a *Raster Calculator* tool was applied. Being the field value the same as the scoring value, the raster calculator is not strictly necessary for the Gleysols field in terms of a single analysis but in order to allow for future scoring systems the tool was implemented in this model. The *Raster Calculator* tool applied to the Bonity field scored the field for the fuzzy number values from the PAS in a linear trend.

Level	Parameter	Criterion	Indicator	Relative score
Site	Terrain	Slope	100	0.07
			58	0.13
			36	0.20
			17	0.27
			9	0.33
			3	0.40
	Soil	Gleysols	1	1.0
			0	0.0
		Bonity	16	0.20
			8	0.10
			1	0.0

Table 2.12 Site level indicators and indicator weights for wind damage.

With all necessary files scored, a *Weighted Sum* tool was applied. The consequent output rastermap was subjected to a normalization procedure in order to adjust the range of values to a range of 0 to 1, a transformation needed for the subsequent Primary Model.

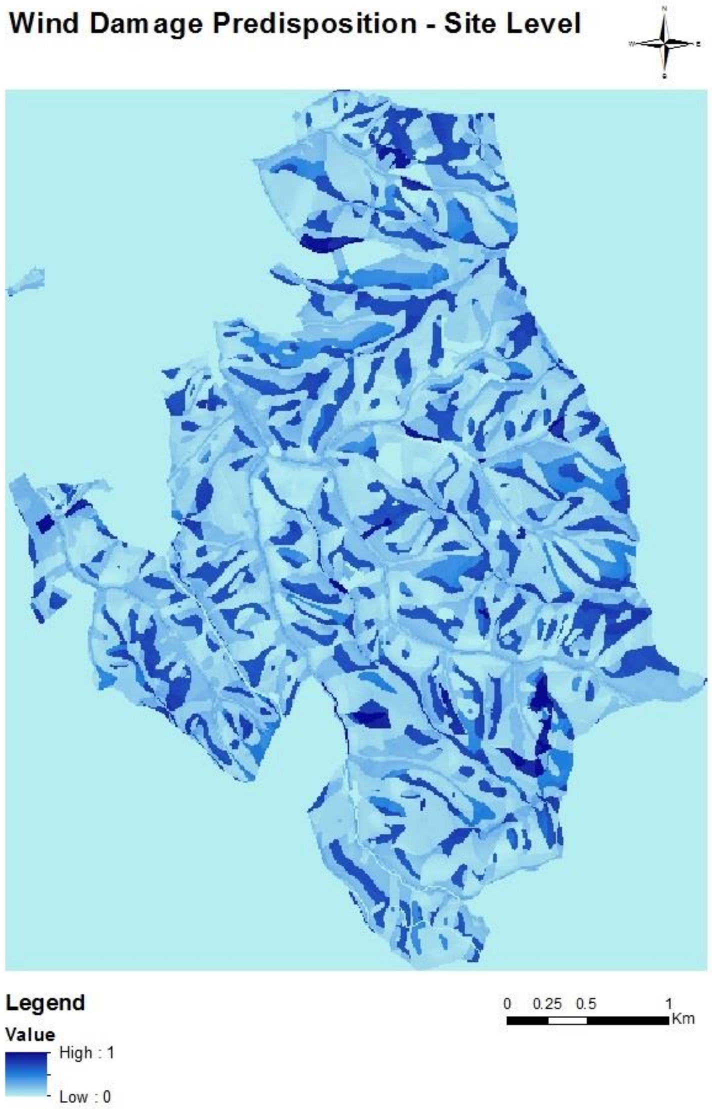


Figure 2.24 Output rastermap from the Wind Damage Predisposition on site level.

The output file from this model was integrated as input for the Predisposition to Bark Beetle attacks on a site level, which would be later also subjected to a *Fuzzify* tool. With the four secondary models complete, the Primary models can be constructed with the respective input files.

2.5 Predisposition Assessment to Bark Beetle Attacks models

After all preparatory and secondary models were constructed, the necessary components for the indicator scoring of the PAS could be developed. Regarding the secondary models, the normalisation steps in the final part of each model, enabled the preparation of the data for the scoring procedure that ensued in these primary models. The preparatory models either assisted in preparing intermediary files, such as the Adjust model, Terrain Morphology models or to prepare files used for the primary models.

2.5.1 Stand Level

In this model the general procedure undertaken was similar to the one conducted for the Predisposition to Bark Beetle Attacks model on Site Level. The input files in this model were the Stands shapefile and the two output rastermaps from the Predisposition to Snow and Wind Damage on Stand Level.

To the Stands shapefile, five *Feature to Raster* tools were applied, as to extract the Proportion of Spruce, Forest Area, Age Class, Canopy Closure and Stand Edges fields. To the remaining four rastermaps, four Fuzzify tools were applied, allowing for the scoring of each field for their respective indicator values (Table 2.13).

Level	Parameter	Criterion	Indicator	Relative score
Stand	Species composition	Proportion of spruce	100%	1.00
			70%	0.83
			50%	0.50
			25%	0.17
			10%	0.08
			0%	0.00
	Structure	Stand Age (years)	≥100	1.00
			90	0.90
			65	0.60
			40	0.20
			< 40	0.00
		Canopy closure	2	0.16
			1.6	0.08
			1.2	0.28
			0.8	0.40
			0	0.40
		Stand edges	High proportion	0.60
			Closed stand	0.00
	Predisposition to	Wind Damage	0%	0.00
			10%	0.20
			30%	0.40
			50%	0.60
			≥ 70%	0.80
		Snow Damage	0%	0.00

		10%	0.05
		30%	0.10
		50%	0.15
		≥ 70%	0.20

Table 2.13 List of parameters, criteria, indicator values and indicator weights for stand level predisposition assessment.

A *Reclassify* tool was applied to the resulting Forest Area rastermap in order to be used on the final procedure of the model where only areas of interest to the study were preserved

Regarding the Stand Edges rastermap, a linear fuzzify function was applied. Even though a straightforward *Reclassify* tool could be here applied, since only two indicator values were considered and field data also falls into two classes, the integration of a *Fuzzify* tool renders possible adjustment of any values, as well as the addition of different trends for other PASs.

To the output files from the secondary models, Snow and Wind damage on stand level, customized *Fuzzify* tools were used. As these rastermaps had been previously subjected to value normalization procedures, they could be directly integrated in the *Fuzzify* tools.

The following step was conducted through the *Weighted Sum* tool where the six rastermaps that were subjected to the *Fuzzify* tools (two from the secondary models and four from the Shapefile) were summed.

With the reclassified Forest Area rastermap and the output rastermap from the *Weighted Sum,* a *Times* tool was utilized. Similarly to the previous procedures conducted in the secondary models and the Primary model for site level, this allows a user to attribute a value of zero predisposition to bark beetle attacks to all areas of the input map that are of no interest to the study.

The final step of this model was to extend the logic practiced during the last calculation made using the *Times* tool, for all the values assigned as NoData.

2.5.2 Site Level

For the predisposition assessment to bark beetle attacks model on site level, six input files were necessary. These files would be processed through intermediate calculation steps and scored for the PAS indicator weights (Table 2.14) or directly scored. The first file was the Low-Middle-High Slopes model output rastermap (See section 2.3.1). In this rastermap the slopes of the terrain were classed as low, middle and high slopes with the values -1, 0 and 1 respectively. These values were reclassified through a *Reclassify* tool, adapting the scale to include values of 1 to 3 values, maintaining the order.

This file, together with the Convex points file obtained in the same Low-Middle-High slopes, which identifies all areas with a convex terrain shape, were scored for the terrain morphology indicator. To the

Convex points file, a *Reclassify* tool was also applied, assigning a value of 4 to the convex areas. The two were joined through a *Cell Statistics* tool where the maximum from both files was calculated. As a result of both reclassification processes, the output file from the *Cell Statistics* tool identified areas with low, middle, high slopes and convex areas with values from 1 to 4, respectively. A *Fuzzify* tool was applied to this rastermap for the PAS fuzzy number values of the Site Morphology indicator**.**

The second input file to be integrated in this model was the Stands shapefile. Four *Feature to Raster* tools were applied to it in order to extract the Bonity, Water Supply, Gleysols and Forest Area fields. To first three rastermaps a customized *Fuzzify* tool with the respective PAS indicator values was assigned. To the Forest Area rastermap a *Reclassify* tool was applied so that Forest Areas were identified with a value of 1 and all others with a value of 0. In the *Fuzzify* function applied to the Water Supply rastermap, a sinus trend function was applied as well as a linear trend so that a smoother and gradual break between values was represented.

The two other input files in this primary models were the rastermaps resulting from the Predisposition to Wind and Snow Damage secondary models. As a result of the normalisation procedures in each of the models, the value ranges of the files were in accordance with the indicator values established in the PAS. As a result, the subsequent tools to be integrated were two *Fuzzify* tools, grading these rastermaps in accordance with the PAS indicator values.

The sixth input file in this model was a file that represented the number of possible bark beetle generations based on thermal characteristics of the site. The number of possible generations was identified, based on studies conducted through the PHENIPS model (Baier, et al., 2007)**,** as 2 and the respective indicator score for that value was 0.6, so that a constant raster was created for that value. The subsequent procedure was to integrate a *Weighted Sum* tool, where the six output rastermaps from the *Fuzzify* tools and the generation number constant raster were summed.

In order to assign a value of zero to all the areas that are excluded from this analysis, a *Times* tool was applied to the rastermap that resulted from the *Weighted Sum* tool and the reclassified Forest Area rastermap. The last step on this model was to also assign a value of zero predisposition to bark beetle attacks to all the NoData values.

Level	Parameter	Criterion	Indicator	Relative score
Site	Generation factor	Temperature	thermal sum allows for 2 generations + 1 sister brood	1.00
			thermal sum allows for 2 generations	0.60
			thermal sum allows for 1 generation + 1 sister brood	0.20
			thermal sum allows for 1 generation	0.10
			thermal sum allows for less than 1 generation	0.00
	Soil	Water supply	Xeric	0.80
			moderately drained	0.64
			moderately moist	0.32
			well supplied	0.00
			very moist	0.32
			wet, saturated	0.48
		Gleysol	Gleysoil or soil with distinct stagnic properties	0.40
			no gleysoil	0.00
		Bonity (Productivity)	Low	0.00
			Medium	0.10
			(very) high	0.20
	Terrain	Morphology	plateau, ridge, hilltop	0.40
			upper and middle slopes	0.28
			lower slopes, valleys, ditches	0.04
	Predisposition to	Wind damage	Maximum (100%)	1.00
			Very high (70%)	1.00
			High (50%)	0.75
			Moderate (30%)	0.50
			Low (10%)	0.25
			None (0%)	0.00
		Snow damage	Maximum (100%)	0.20
			Very high (70%)	0.20
			High (50%)	0.15
			Moderate (30%)	0.10
			Low (10%)	0.05
			None (0%)	0.00

Table 2.14 List of parameters, criteria, indicator values and indicator weights for site level predisposition assessment.

Chapter 3

Results

3.1 Stand Level Results

From the research conducted throughout the modelling sequence, results on the predisposition level of the study site and stand were obtained. Even though the analysis for each level, was based on several different indicator values, the scoring approach was similar. The resulting rastermaps will be presented from each primary model.

The general modelling procedure for stand level assessment was based on the Stands shapefile, where the interest fields were transposed into rastermaps and subsequently scored. The criteria used in this chapter to analyse the level of predisposition was the observation between the final result and the relation with the maximum possible value of predisposition based on the range of values of the PAS.

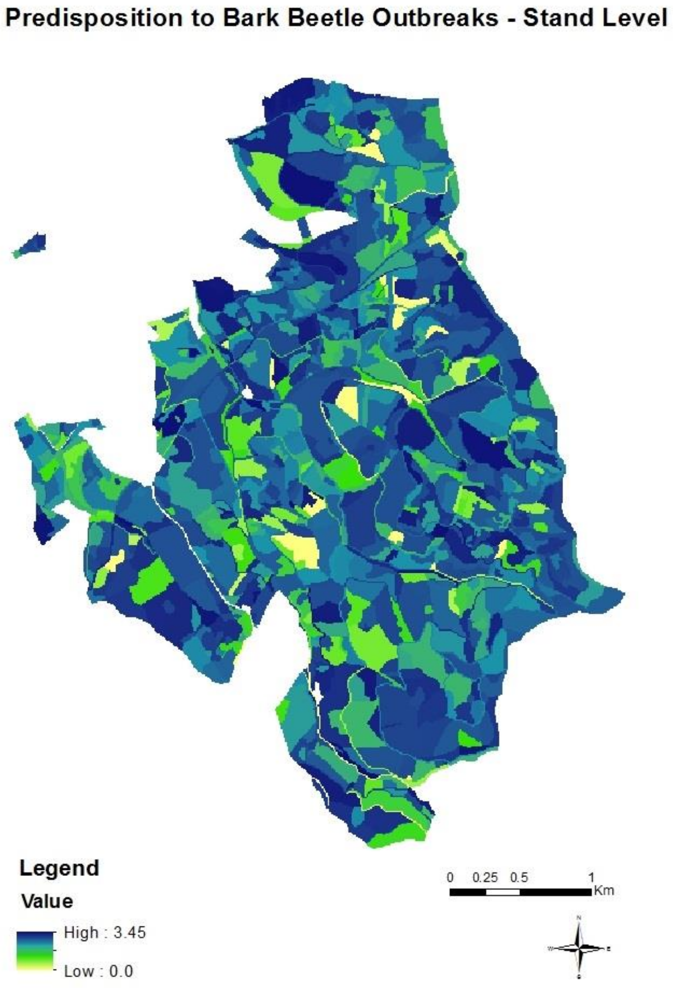


Figure 3.1 Stand Level Predisposition to bark beetle outbreaks.

Based on the indicator values presented in Table 2.13, the maximum possible predisposition on stand level corresponds to a value of 4.00. As a result of the operations conducted with the Forest Area rastermap a value of 0.0 predisposition was attributed to non-forest areas, the only visible area with values higher than 0.0, represent stand or stand edge areas.

Using a sequence of tools, *Times, Int* and *Build Raster Attribute Table*, the values from the resulting rastermap were extracted and later processed with Microsoft Office of MS Office. The *Times* tool is applied in order to prepare the rastermap to the *Int* tool. The data was multiplied by 1000 and after the *Int* tool is applied, the data format was converted to integer by truncation. The subsequent procedure was to build the Attribute Table containing the values from the input rastermap, through the *Build Raster Attribute Table* tool.

The statistical analysis from this data revealed the areas of the stand that have either a higher or a lower level of predisposition to bark beetle outbreaks. Considering the full output rastermap, the results were adapted to a scale of Low, Medium, Medium/Low, Medium/High and High predisposition (Table 7.1).

Rastermap value intervals	Predisposition to *Ips typographus* outbreaks
0.0 – 1.5	Low
1.5 – 2.0	Medium/Low
2.0 – 2.5	Medium
2.5 - 3.0	Medium/High
3.0 – 4.0	High

Table 3.1 Predisposition class distribution considering the original range of value for both site and stand results.

As a result of this value reclassification, graphs were constructed with the relative frequency of each class of predisposition. These relative frequencies were analysed and represented for the entire map. Therefore, all areas with no interest to the study within stand areas or outside of the stand area are not visually represented in the map. In terms of range of values in the legend of the rastermap, these areas were all assigned a value of 0.0 (Fig. 3.2).

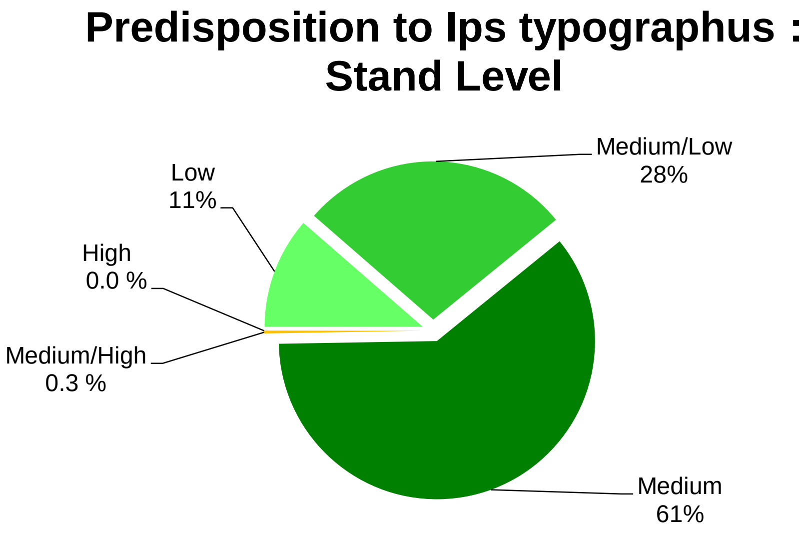


Figure 3.2 Predisposition results for the entire map area based on the range of classes established in Table 6.1 for stand level.

From the analysis conducted for the results gathered for predisposition to bark beetle outbreaks, the main statistical parameters were studied (Table 3.2). These results were obtained by applying the sequence of tools previously described, preserving 4 decimal points from the output data.

Statistic	Value
Maximum	3.454
Minimum	0.0
Mean	1.963
Standard Deviation	0.382

Table 3.2 Statistics results for stand level predisposition to bark beetle outbreaks.

3.2 Site Level Results

The modelling approach for site level predisposition assessment was similar to the one constructed for stand level. Primary data and output rastermaps from secondary models were adapted when necessary and scored for the values established in the PAS. In the interest of analysing the data statistically, a duplicate sequence of tools as for the stand level predisposition assessment was applied. As a result of the output rastermap data were in Float form and in order to produce an Attribute Table, these must be in Integer format, the first tool was the *Times*. Here the rastermap was multiplied by a value of 1000, and subjected to an *Int* tool where the Float to Integer transformation was performed. The final tool applied was the *Build Raster Attribute Table.*

With the data from the table that was obtained through this sequence of tools, a statistical analysis of the data was conducted. A graph was constructed for stand level predisposition assessment, the first graph refers to a statistical analysis where the entire rastermap was considered, and the second one includes only non-null predisposition values.

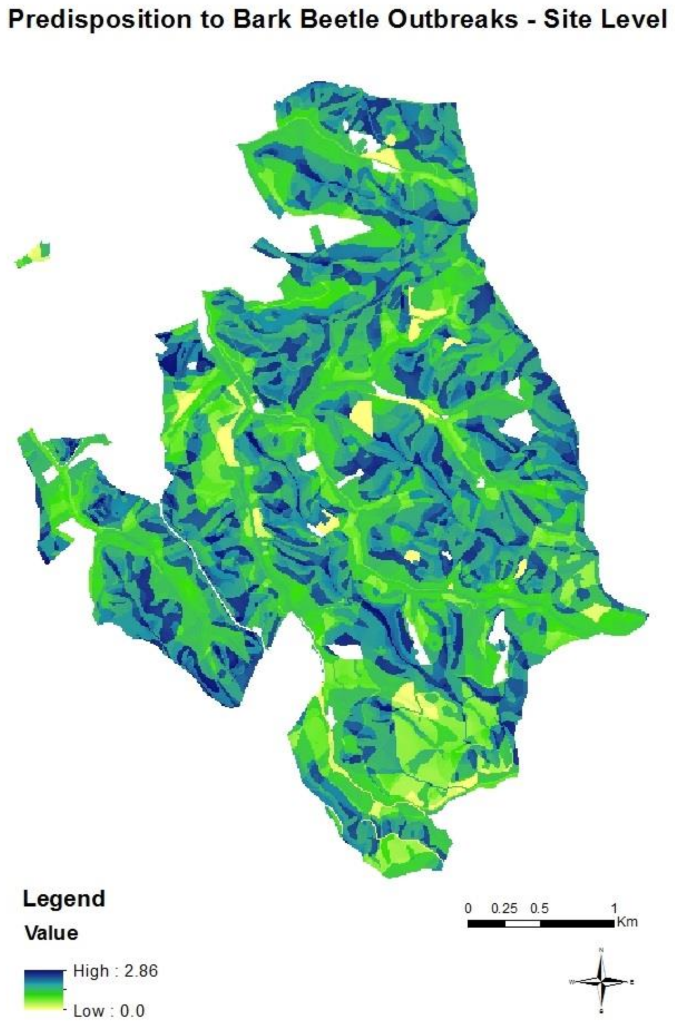


Figure 3.3 Site Level Predisposition to bark beetle outbreaks.

The predisposition classes for site level assessment were identical to those considered for stand level, having a maximum value of predisposition 4.0 as well (Table 3.1). Therefore the graphs concerning the relative frequency of each predisposition class were developed in the same format as for stand level.

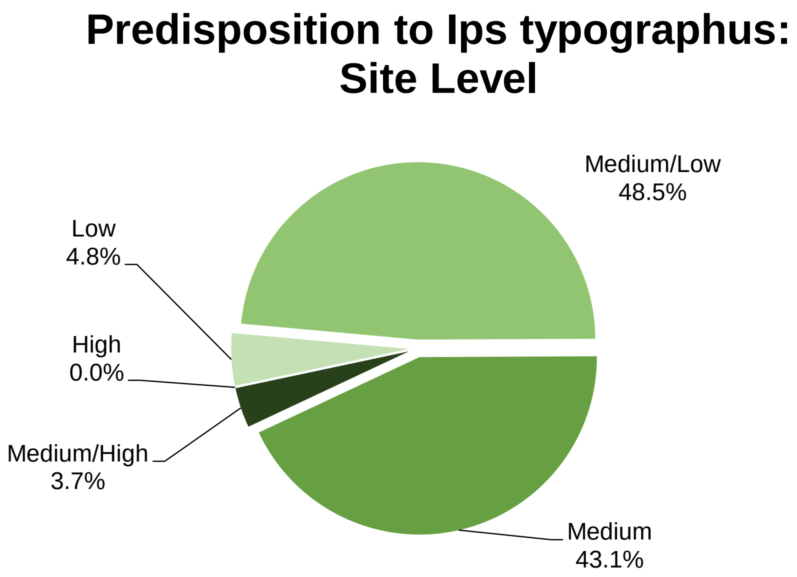


Figure 3.4 Predisposition classes results for site level.

As performed for predisposition on stand level, the output data were subjected to the sequence of tools previously described preserving 4 decimal points. This data was studied for the statistical parameters presented in Table 3.3.

Statistic	Value
Maximum	2.864
Minimum	0.0
Mean	1.965
Standard Deviation	0.363

Table 3.3 Statistics results for site level predisposition to bark beetle outbreaks.

3.3 Overall Predisposition Results

With both site and stand level rastermaps regarding the predisposition to bark beetle outbreaks, a joint study between the two files was conducted (Fig. 3.5). One of the objectives of this study was to observe on a theoretical range of 0.0 to 8.0 predisposition level, what was the distribution of predisposition classes for the Rosalia Lehrforst. Another objective was to estimate the statistical correlations between the features from the Stands shapefile and the final predisposition rastermap.

In this process the aim was to identify the most and least relevant features influencing the final predisposition result. This process was executed by resorting to the *Band Collection Statistics* tool from ArcGIS. With this tool a user can produce a table containing information on the statistical parameters for an individual layer, as well as covariance and correlation matrices between two layers.

The process of joining both rastermaps was executed through the *Sum* tool of ArcGIS. Here the values of each layer were added on a cell-by-cell basis. Just as applied for the site and stand predisposition results, the sequence of *Times*, *Int* and *Build Raster Attribute Table* tools was applied to the previously summed rastermap. As in the two previous sections, this process allowed to extract the attribute table from which a user can edit and study the values from the rastermap.

Rastermap value intervals	Predisposition to *Ips typographus* outbreaks
≤ 3.0	Low
3.0 – 3.5	Medium/Low
3.5 – 4.5	Medium
4.5 - 6.0	Medium/High
6.0 – 8.0	High

Table 3.4 Predisposition classes distribution considering the original range of value for both site and stand results.

Based on the theoretical range of values, the predisposition classes were adapted from the ones chosen for site and stand level. Three of the classes focus on the values between 3.0 and 4.5 since most of the values were concentrated within that interval. Therefore by extending the number of classes for the same interval, a more accurate perception of the results can be achieved.

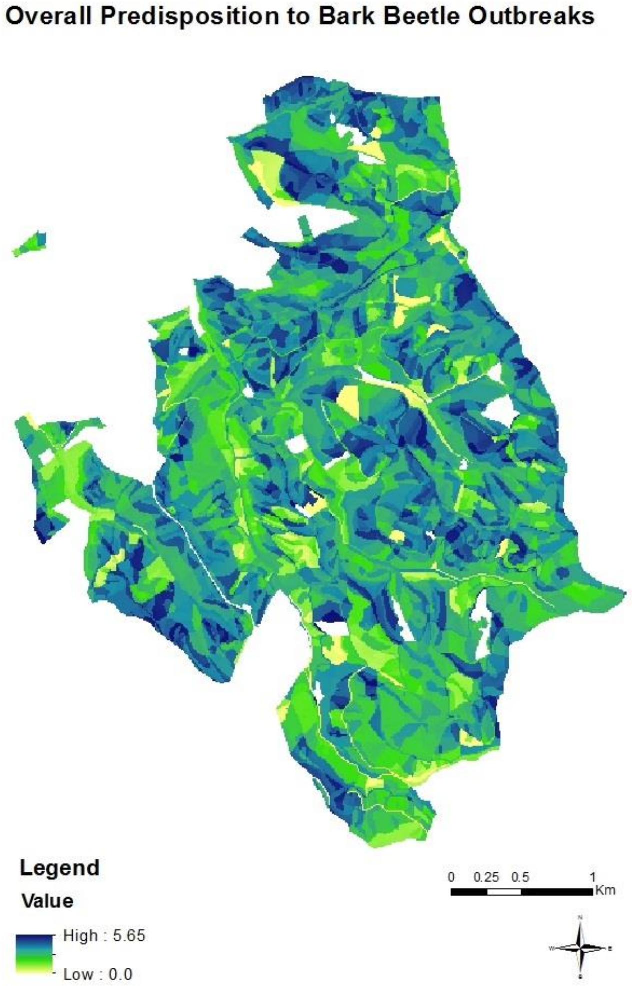


Figure 3.5 Overall predisposition results from the sum between site and stand results.

The statistical study based on the values associated with the joined rastermap was executed through MS Excel. The results of the relative frequency of each predisposition class are depicted in graph form (Fig. 3.6).

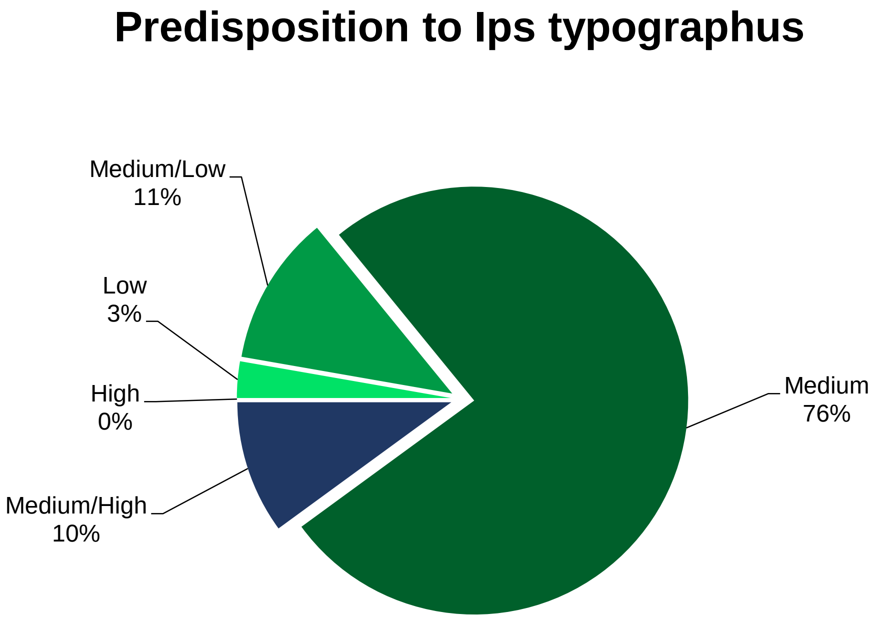


Figure 3.6 Relative frequency of the predisposition classes for the rastermap obtained by the sum of results at site and stand level.

Concerning overall predisposition to bark beetle outbreaks, a statistical analysis of the results was conducted (Table 3.5).

Statistics	Value
Maximum	5.651
Minimum	0.0
Mean	3.935
Standard Deviation	0.615

Table 3.5 Statistics results for overall predisposition to bark beetle outbreaks.

Chapter 4

Discussion and Conclusions

4.1 Predisposition model

Predisposition estimates of abiotic and biotic disturbances in forest environments represent a valuable process in assessing and managing risk. Disturbances such as storms and insect infestations pose great threats to forests causing damages which can only be controlled through informed and experienced management. Spruce bark beetles outbreaks pose a considerable hazard to European forests, with different magnitudes depending on climatic, topographic and ecological aspects of the area in question. In the last two decades (1992-2012) salvage from bark beetle damages in Austria have varied between 0.6 and 3.0 million m^3 making it the most destructive biotic threat to Norway spruce in Europe (Pasztor, et al., 2014).

In order to plan efficient management measures such as salvage logging and sanitation felling, it is essential to assess the risk of infestation using phenology models and dynamic simulation models (Stadelmann, et al., 2013). The Predisposition Model developed in this thesis allows for the calculation of this risk on a simulation basis since the characteristics of the model grant the possibility to adapt the initial conditions to different predisposition systems.

The first objective established for this project aimed at ensuring assessment flexibility, as well as at the integration of data from the PAS as indicator weights and construction of customizable fuzzify functions. The key aspects concerning the flexibility of the model resided in using input data and other constant input values as model parameters and a mask-like work flow. This methodology allows the user to conduct the data analysis by performing iterative processes or to apply the same study to different maps.

An additional property that supported the flexibility side of the model was the fact that through the work flow of the model, the pixel values were preserved as Float. By maintaining this property, input data can have both Integer point and Float point pixel types without interfering with the results obtained from the model. The fact that the rastermaps obtained from the secondary and primary models have float type values provides the evidence that this property is preserved. Furthermore, the extraction of the raster attributes table from the data in order to carry out further studies is a straightforward process following the sequence of tools described in Chapter 3.

The second objective of the work consisted in building a Predisposition Assessment Model that would integrate the data from the PAS as indicator weights. The procedure chosen to integrate the data consisted in implementing different tools that allowed for the extraction from the primary data of the target features to be evaluated and subsequently reclassify them for the PAS indicator weights. The tools implemented were *Reclassify*, *Raster Calculator*, *Fuzzy Membership* and the hybrid *Fuzzify* tool. The choice of the tool to apply was based on the set of indicator weight values and type of trend of each set of weight values.

Based on the final results obtained, these tools and consequently the weights for each range of values were successfully implemented in the models. Furthermore, in line with the first objective established for the assessment model, these tools were implemented as customizable as possible. Both the *Reclassify* and *Fuzzy Membership* tools of ArcGIS allow for simple inquiry and editing of the break values in use. For the *Raster Calculator* and *Fuzzify* tool, the only knowledge necessary to edit the break values for each trend is basic ArcGIS map algebra.

Concerning the *Fuzzify* function constructed, the behaviour of the function that will result from the indicator weights provided must be first assessed. Only then should a trend type be chosen, as a sinus trend should be used to smoothen simetric changes for the trend slope signal (Fig. 2.12). As for linear trends a user should only input the break values and the respective indicator weights. The function will then assign all intermediate indicator values in a continuous manner. All functions and respective graph representations are presented in the Annex B section.

As the full results of the project will be obtained in October of 2014, only then can a full validation of the model be conducted. By using simultaneously the PHENIPS, the Water Deficit model and the Predisposition Model the most sensitive areas or more exposed to risk can be pinpointed and risk management measures implemented according to the exposure level verified.

As demonstrated by the results of each submodel and by the primary models, these tools allowed for a complete integration of the principles of the PAS. Similar to the spatial analysis approach developed in MapModels, the workflows of each model are clear and appropriately ready to be run on a node-to-node basis. Being ModelBuilder a more recent and extensively developed and improved, certain capabilities of the Predisposition Model produced in this thesis make it considerably more user friendly and efficient than MapModels.

As all models are connected through the output files that serve as input for other models, running the primary models is the only necessary action to produce predisposition results on both levels. The “Results” command from ArcGIS enables a user to view the error report from a specific session and pinpoint the cause of a possible error. Furthermore each tool in ArcGIS has an extensive description and examples which renders any desired adjustments easier to perform.

The choice between trends, concerning fuzzy membership indicator value attribution, in MapModels is less arduous as the software was developed with direct editing access to the code of the tools. As mentioned previously, the process of construction a function in the present Predisposition Model can be carried out by resorting to the fuzzify function and inserting the range of values of the indicator according to ArcGIS’s map algebra. The use of the sinus trend was reduced as it was found that in MapModels for certain indicators its use represented an irregular function which would have the same limit of values but awarded indicator weights in incorrect fashion.

Bark beetle outbreak predisposition on site and stand level can be assessed separately in a powerful and widely used software, ArcMap of ArcGIS. Moreover this assessment is based on comprehensive dynamic work flows and user friendly tools that can be edited according to the desired analysis parameters and objectives.

4.2 Rosalia Forest predisposition results

The results of the statistical analysis performed indicate the level of predisposition and relative frequency of each predisposition class to bark beetle outbreaks, on site and stand level (Section 3.1 and 3.2). In Section 3.3 the two final rastermaps were summed in order to conduct an identical study on the overall predisposition of the Rosalia Forest.

Concerning the results on stand level, the maximum level of predisposition was 3.45 out of a maximum value of a 4.0 according to the PAS. The majority of the results fell on the Medium/Low (28%) and Medium (61%) predisposition classes. This data suggests that a considerable area of the Rosalia forest has a moderate level of predisposition to bark beetle outbreaks.

Among the features of the forest inventory that were implemented in the shapefile, the Proportion of Spruce showed the highest correlation with stand predisposition, attaining a value of 0.59. Being *I. typographus* a bark beetle species that breeds in mature Norway spruce on windfelled trees or cut trees (Hedgren & Schroeder, 2004), this correlation value reflects an increase of the predisposition in parallel with the percentage of potential host trees available.

Concerning site level results, the maximum value estimated for predisposition was 2.85 in a scale of 0.0 - 4.0. However, for this level of analysis, a higher dispersion of the values was observed, a fact that results from the assessment procedure conducted in the submodels that precede the primary model from which this file originates as well as the primary data used. The primary data consisted on both the shapefile and DEM, where the second one has a higher cell resolution than the shapefile as its information is divided through larger polygons.

For predisposition assessment on site level, both the DEM and the data joined with the shapefile were used throughout the model work flow, contrary to the assessment led for stand level where only the shapefile was used. A higher resolution was thus obtained in each of the rastermaps produced and consequently a larger dispersion of values, when compared with the results for stand level predisposition.

Regarding the rastermap produced by summing the predisposition to bark beetle outbreaks on site and stand level, the mean value obtained was 3.94 (range 0.0 – 8.0). Should the two constituent predisposition values obtained from the site and stand rastermaps be added, the maximum value possible for the Rosalia forest would be 6.32. Yet the maximum value encountered was 5.65, thus indicating that the forest area has a medium level of predisposition regarding bark beetle outbreaks. However, a considerable share of the overall results (10%) fell into the medium/high category, contrary to the results obtained separately for site and stand level.

Opposite to the scope of the analysis conducted in the SAMBIA model (Fahse & Heurich, 2011) in the Bavarian Forest National Park, no antagonists for the bark beetle were considered in the model. The SAMBIA model aimed to generate agent–based simulations, leading to the understanding temporal and spatial aspects of infestations effects and to the identification of possible management measures. By contrast, in the Predisposition Model an assessment of the outbreak exposure level assessment is provided focusing on wind and snow damage influences, thus contributing to an upstream perspective these agents.

The two main factors that contributed to the registered level of predisposition were the considerable heterogeneity of the stand regarding the number of tree species and its diversified age structure. The average proportion of spruce was 20% and age 61 years. These results are in agreement with the findings of Wermelinger (2004) who conducted a review finding that forests with highly diverse tree composition and age structure are more resistant to wind throw and consequently bark beetle attacks.

Since the model has a deterministic character and depends on the PAS used and on the parameters chosen for processing of the DEM, as well as on the predicted thermal conditions that will determine the number of bark beetle generations, possible stochastic influences must be considered for decision-making processes. Such influences may increase predisposition to wind and snow events, thus increasing overall predisposition to bark beetle outbreaks. As a result it is essential that planned mitigation measures are implemented, especially in areas having a predisposition higher than medium, in order to minimize potential damage.

The predisposition model developed in the present thesis is an essential component for the management of bark beetle outbreaks. However, considering both abiotic and biotic damages, field data are an indispensable requisite for the successful implementation of programmes such as the prevention and control of bark beetle outbreaks. This data should include parameters on climate, soil and tree physiology, as well as phenological information concerning the beetles.

By integrating the different sets of data considered into spatial and temporal simulation of seasonal development of *I. typographus*, such as PHENIPS (Baier, et al., 2007), water deficit models and predisposition assessment models, swarming and infestation events can be constructed. These models can also provide a deeper insight of the site and stand if retrospective and prospective analyses of bark beetle development are performed. Another important condition in order to assure the applicability of models such as the one developed in this thesis is file compatibility and the ability to change parameters if one wishes to do so within the chosen software. With this aspect ensured, software, mathematical models, protocols and other management tools can be shared within different organisations, disseminating knowledge on bark beetle outbreak predisposition assessment.

It is imperative that mechanisms such as models are integrated in widely used softwares that follow the global trend of increasing information transmission such as ArcGIS. Management organisations will be able to reach more balanced and profitable decisions if an holistic perspective of the underlying environment is constructed and compared with other scenarios and study cases. Ultimately, developments of the information technology, as well a higher spatial resolution and general capability of GIS-based modelling increase, coupled with the expanding knowledge on bark beetle infestations, will lead simultaneously to higher standards and achievements in ecosystem fostering and conservation and to a deeper understanding of the services provided.

4.3 Future Work

- The Rosalia Roof Project is expected to be concluded in October of 2014 with the full model establishment. By then, results on bark beetle attacks, climatic and tree physiology will have been analysed, enabling the validation of the Water Deficit, PHENIPS and PAS models for the parameters that were initially considered.
- The model developed in this thesis constitutes a tool for predisposition assessment of bark beetle infestations. Considering the nature of the software and objectives under which it was built, the model can be used and edited for different conditions. This aspect opens the possibility for future improvements and adaptations to new findings in the bark beetle risk assessment field of study.

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Annex – A

Model Work Flows

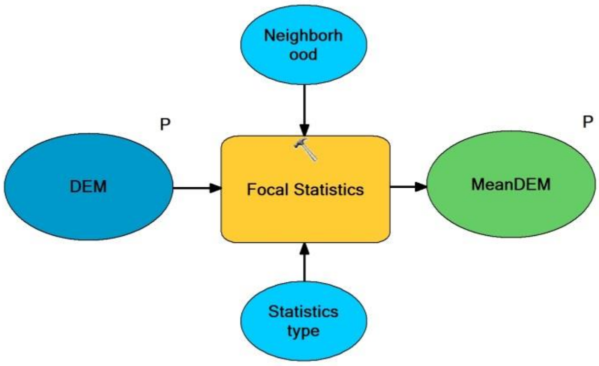

Fig. A-1 Smooth Model

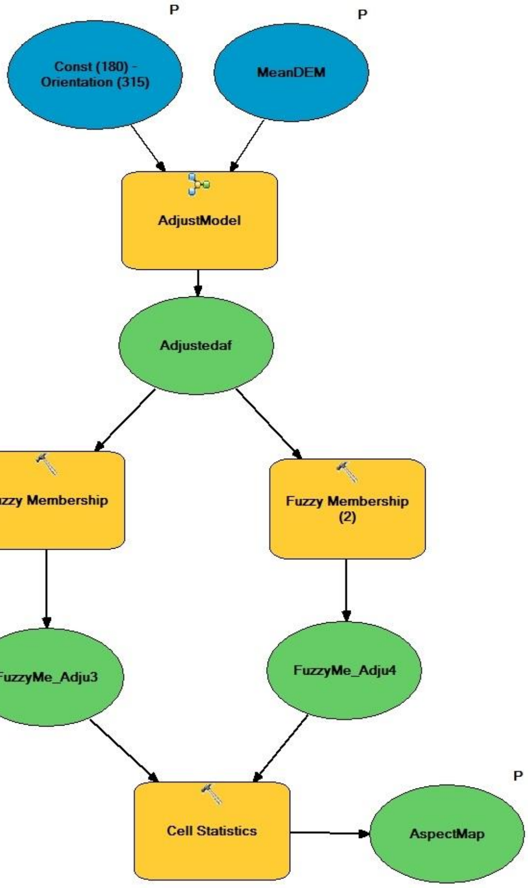

Fig. A-2 Aspect Model

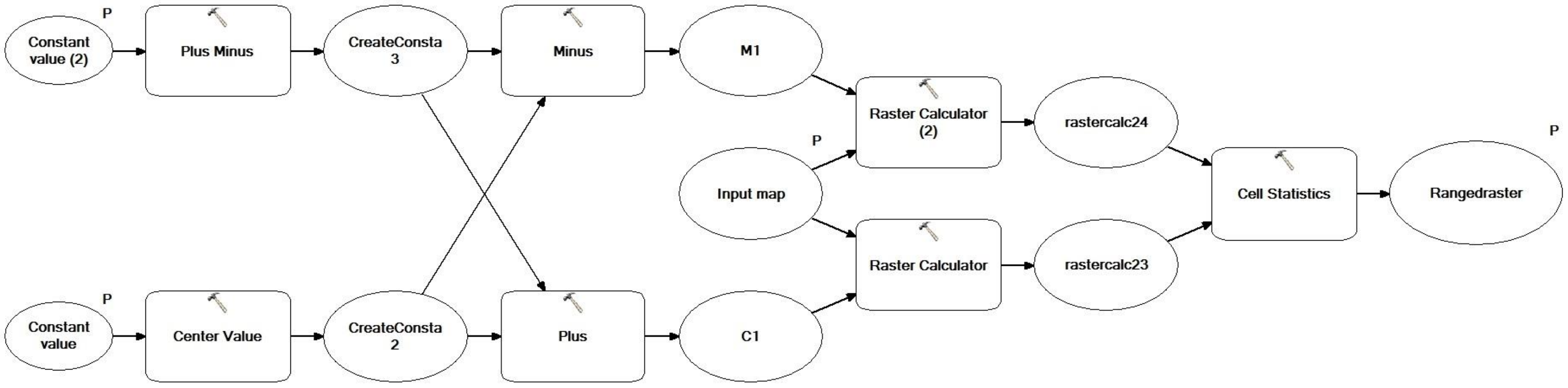

Fig. A-3 Range submodel

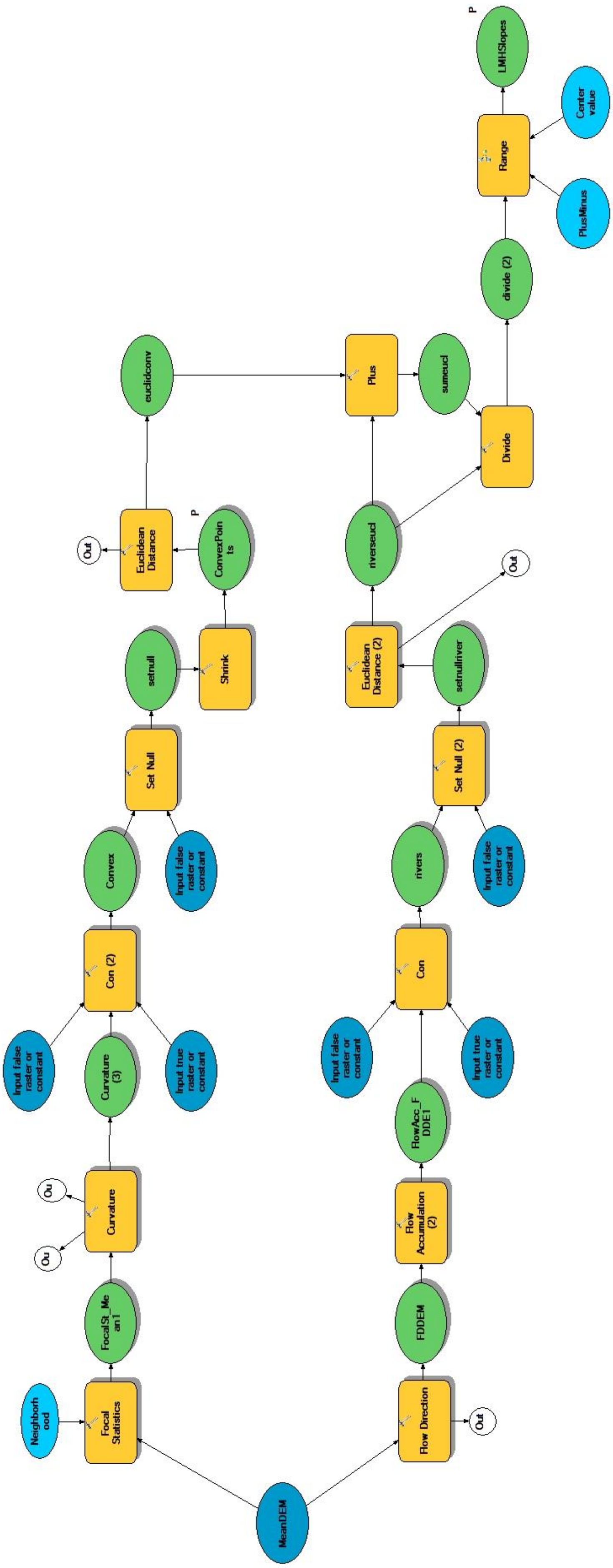

Fig. A-4 Low Middle High Slopes Model

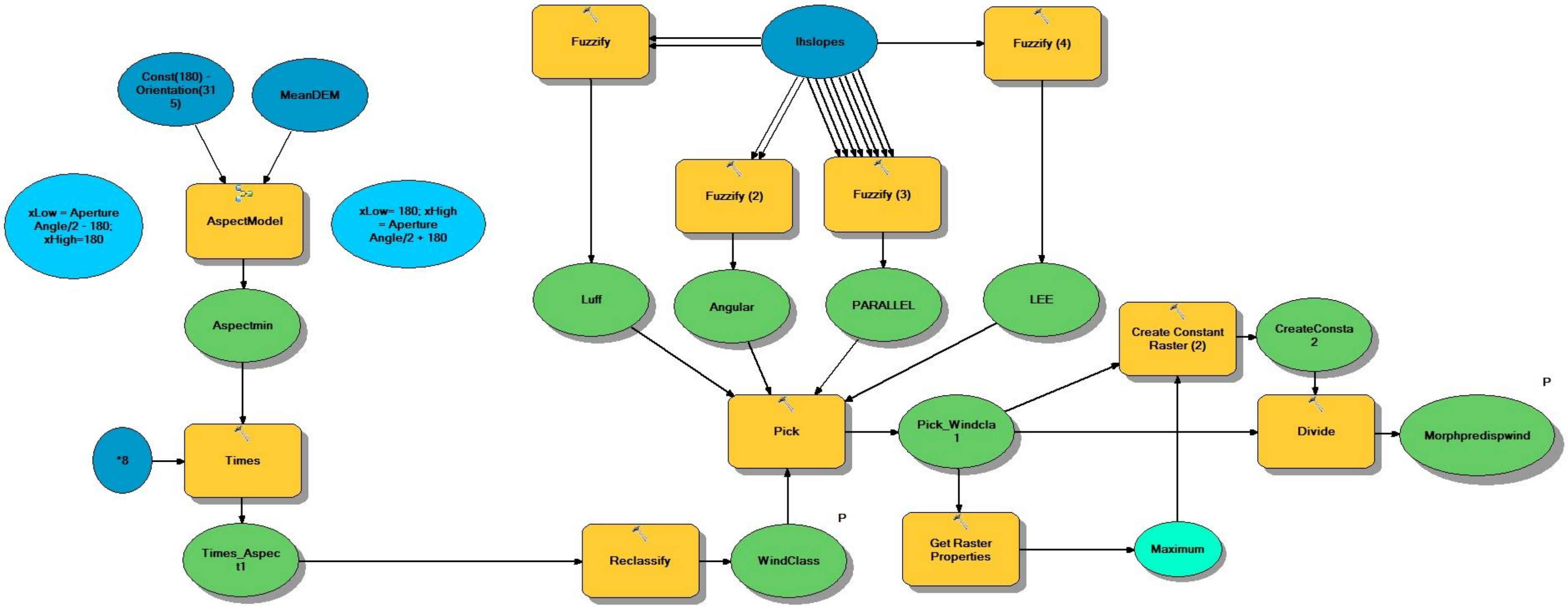

Fig. A-5 Terrain Morphology – Wind Damage Model

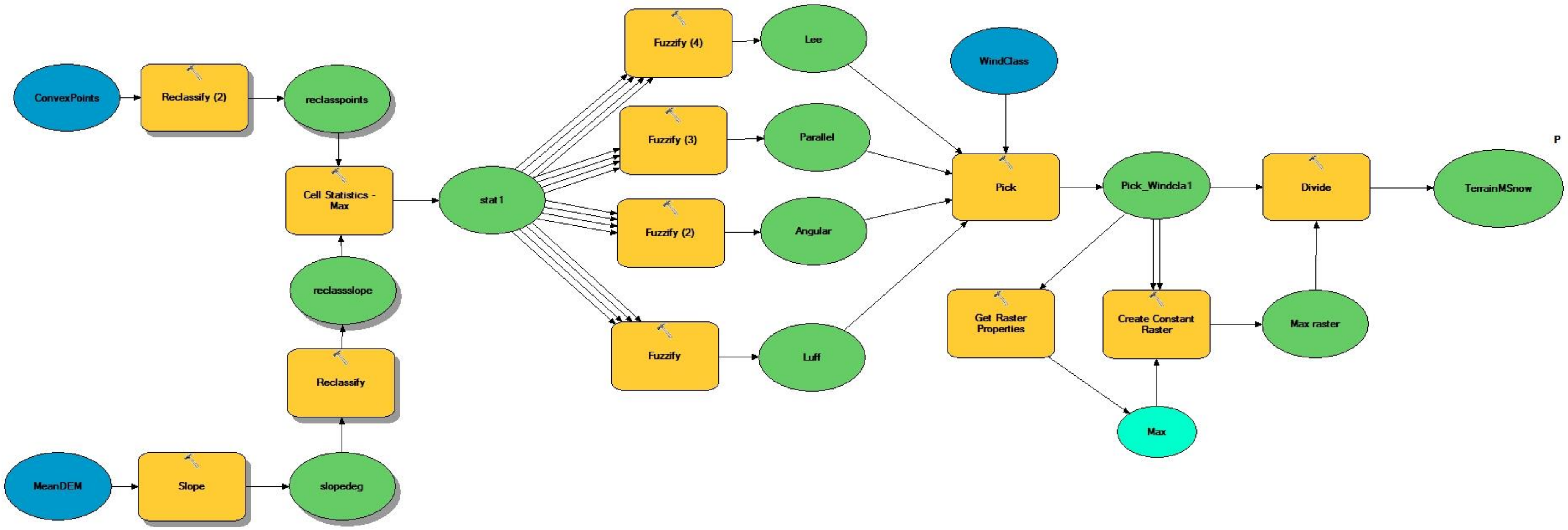

Fig. A-6 Terrain Morphology - Snow Damage Model

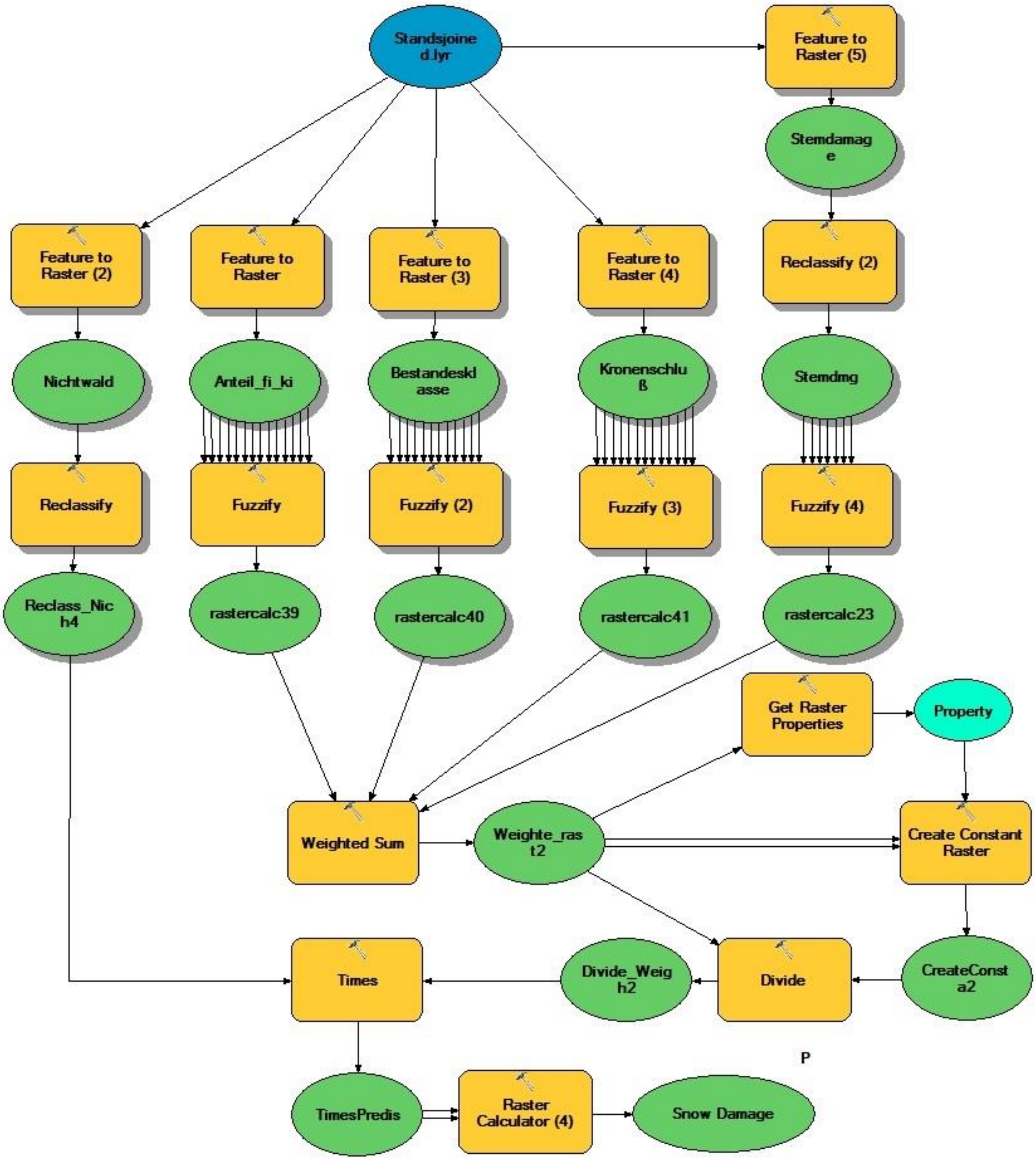

Fig. A-7 Stand Level Damage – Snow Damage Model

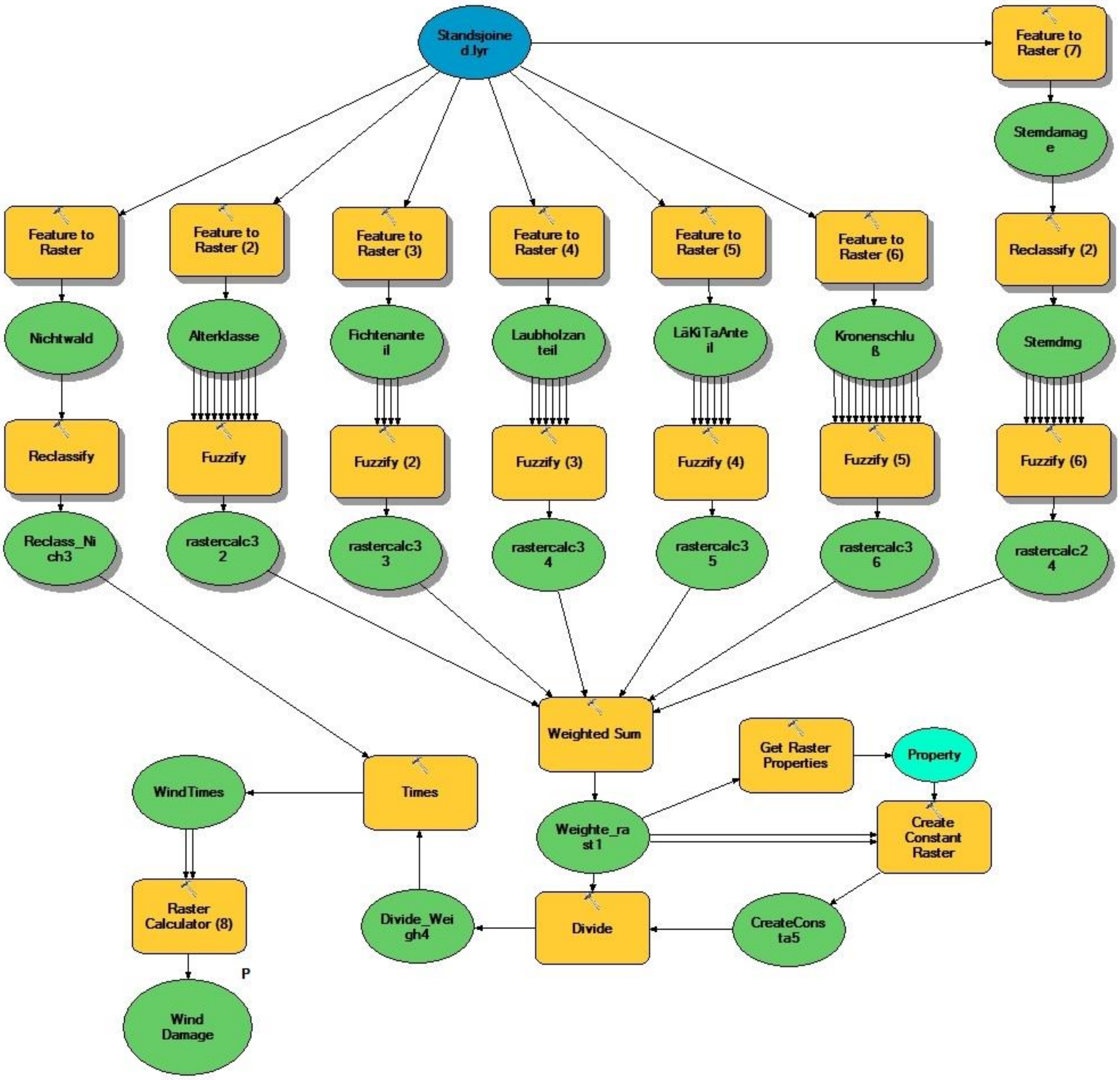

Fig. A-8 Stand Level Damage – Wind Damage Model

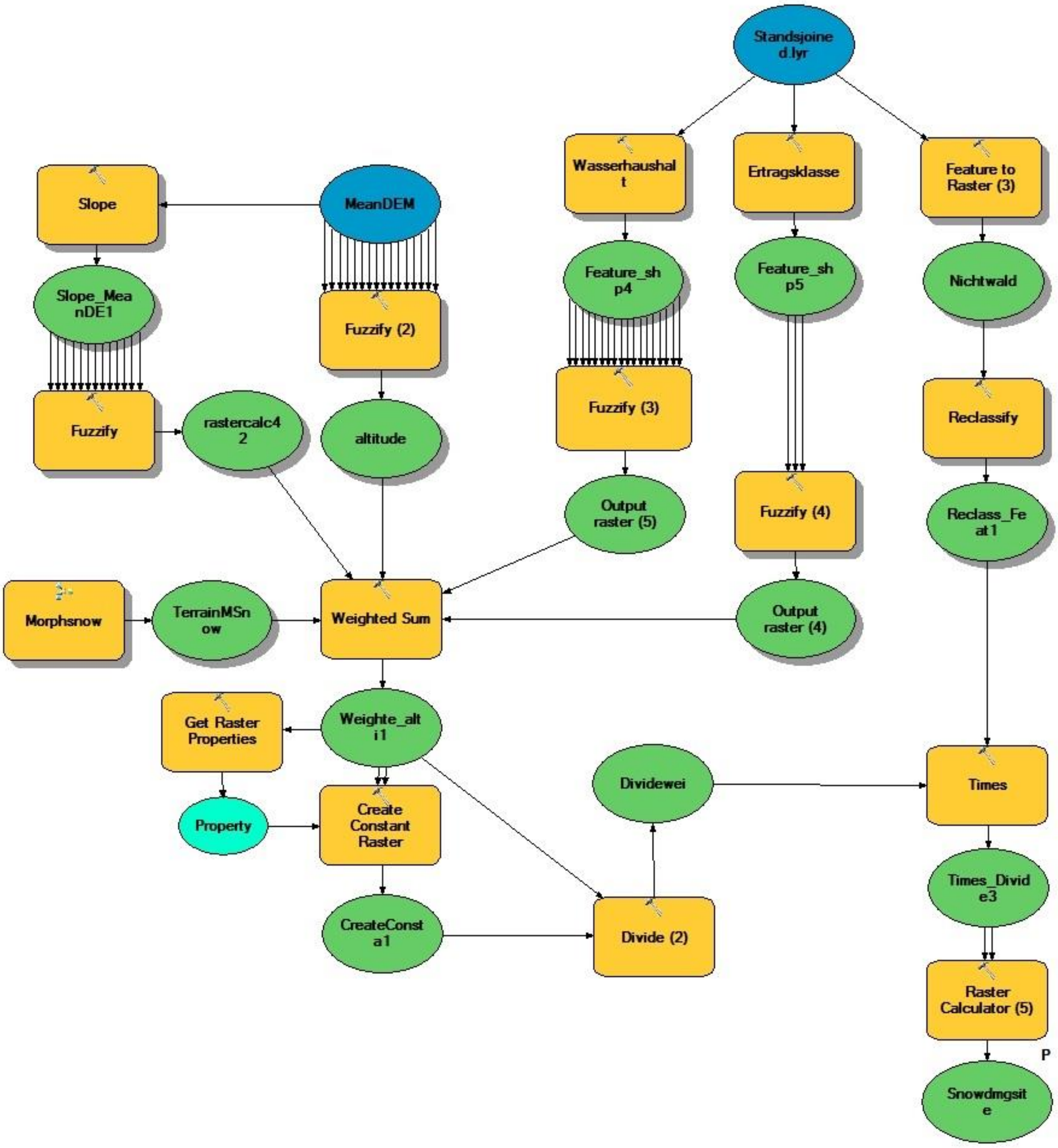

Fig. A-9 Site Level Damage – Snow Damage Model

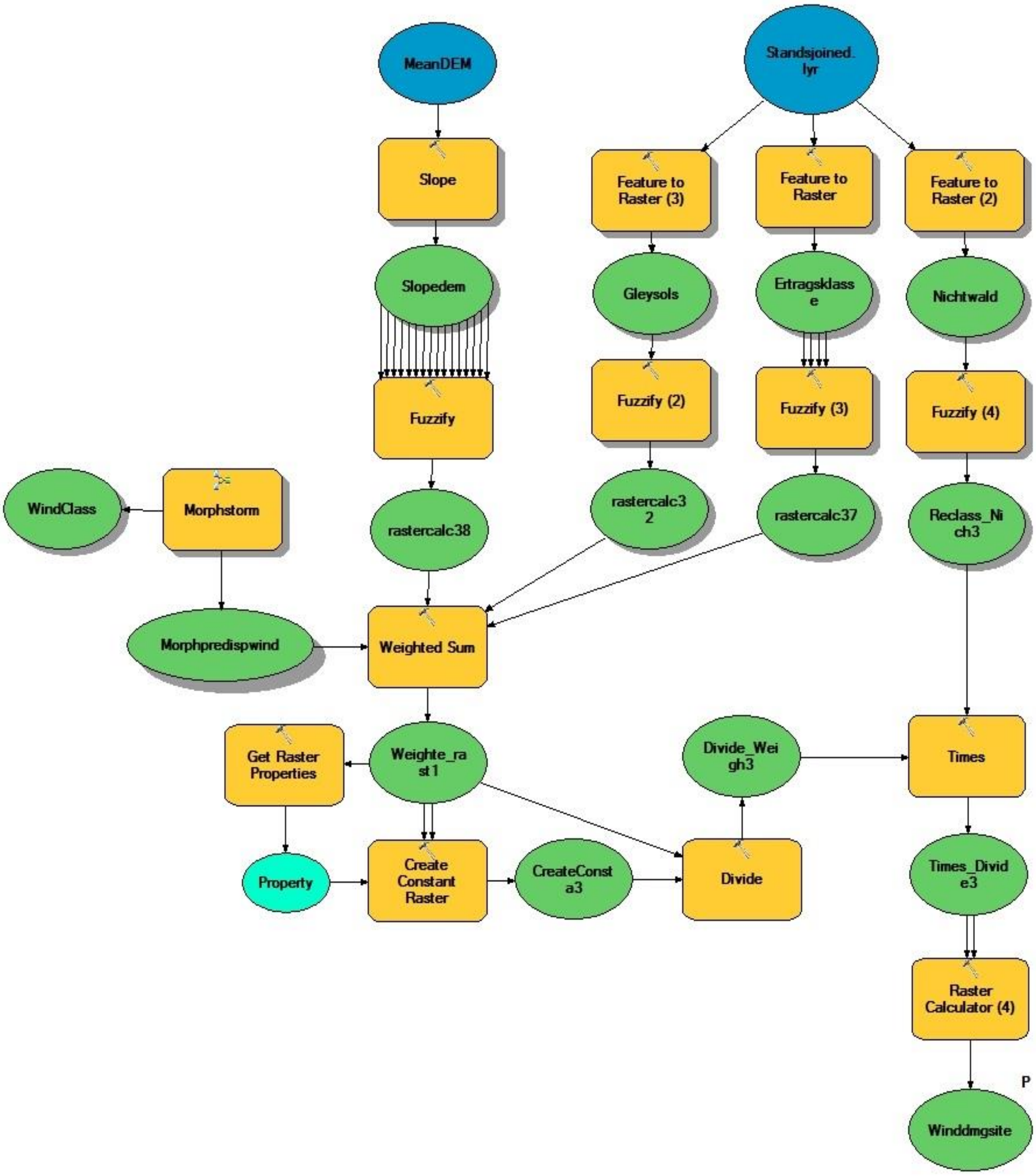

Fig. A-10 Site Level Damage – Wind Damage Model

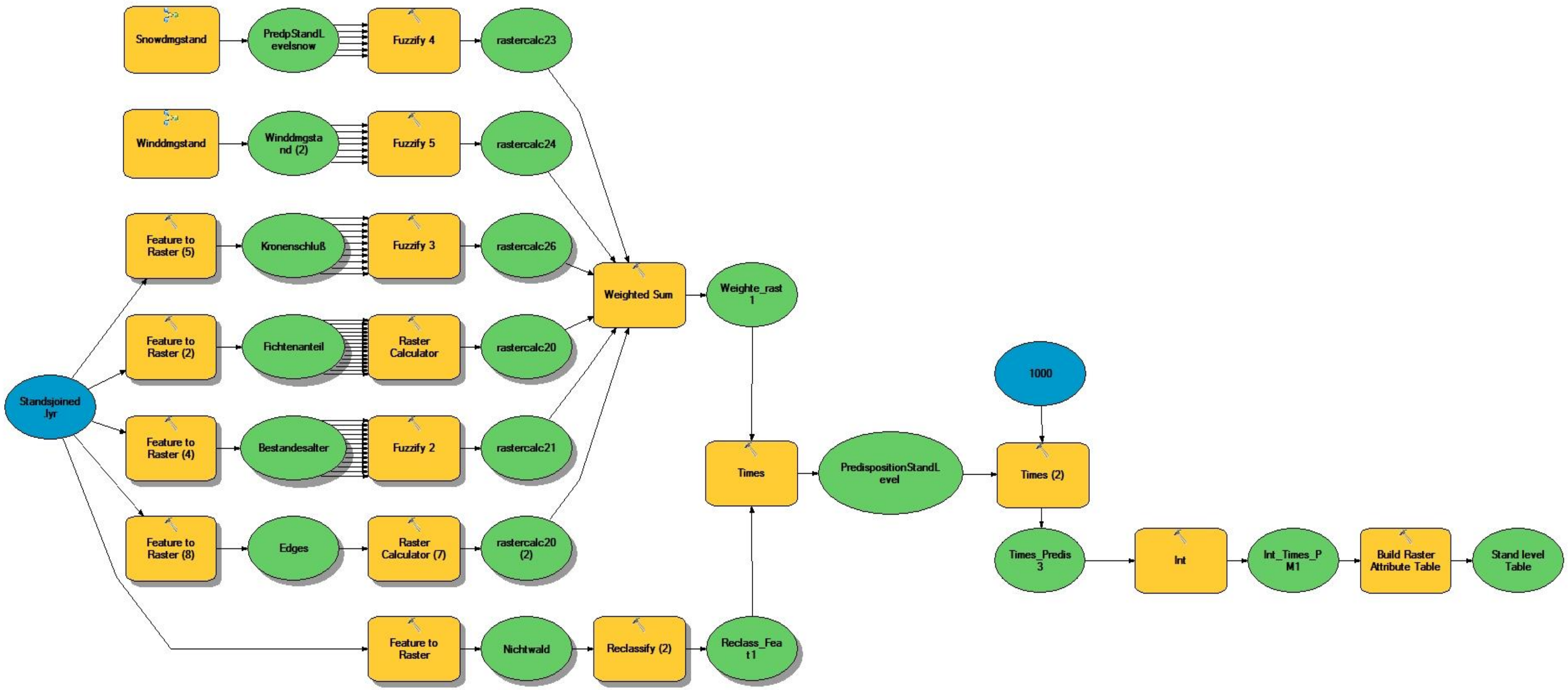

Fig. A-11 Stand Level Predisposition Model

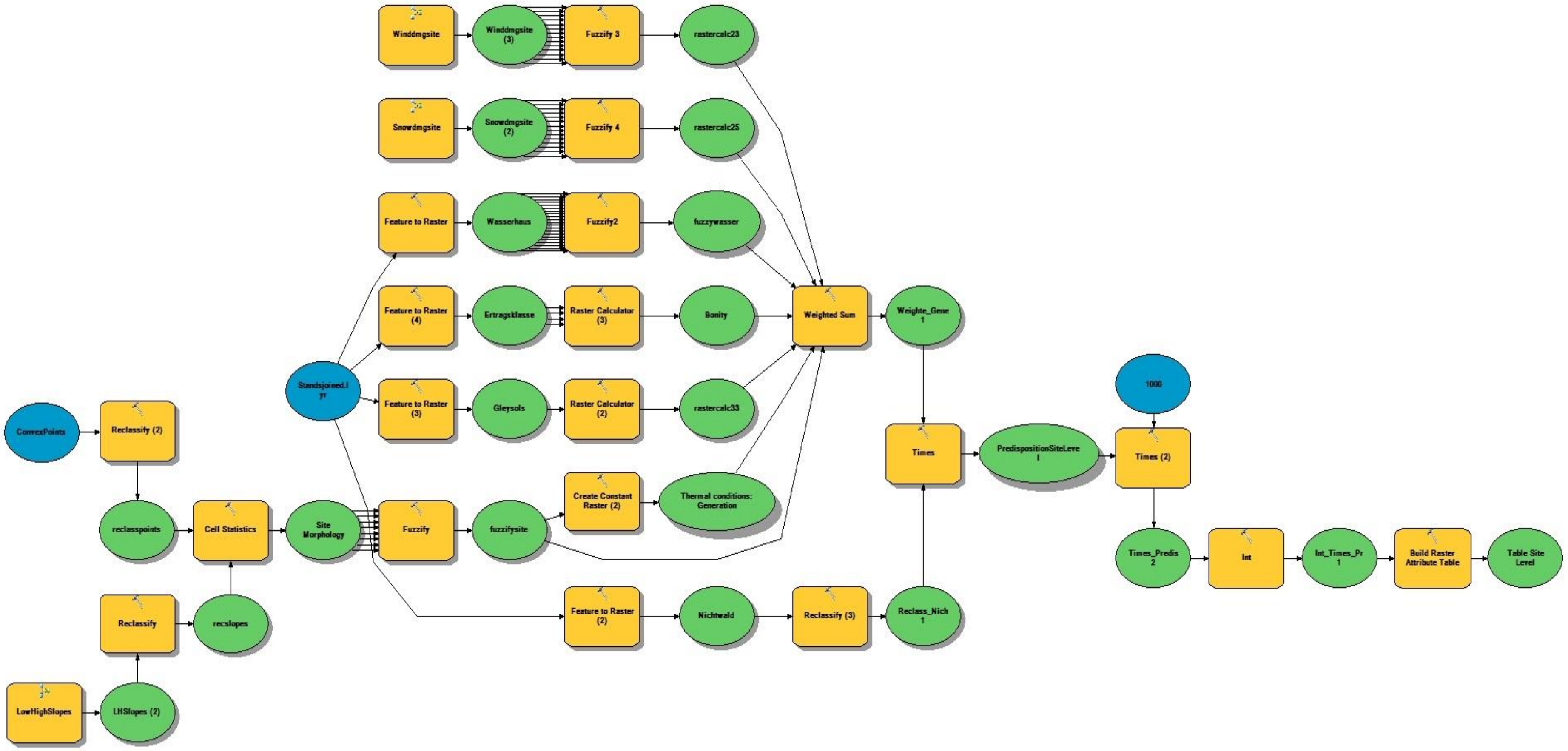

Fig. A-12 Site Level Predisposition Model

Annex - B

Fuzzify Tool Functions

A - 2.1 **Snow Damage – Stand Level**

- Proportion of spruce and pine

$$r(v)=\begin{cases}-v, & v\le 0.4\\ v-0.3, & 0.4<v\le 0.5\\ 0.5*v-0.05, & 0.5<v\le 0.9\\ 3.5*v-2.75, & v>0.9\end{cases}$$

- Age Class

$$r(v)=\begin{cases}0.1, & v<5\\ 0.08*v-0.3, & 5\le v<10\\ 0.5, & 10\le v<30\\ -0.0029*v+0.59, & 30\le v<100\\ -0.002*v+0.5, & 100\le v<150\end{cases}$$

- Canopy Closure

$$r(v)=\begin{cases}-0.6*v+0.5, & v<0.5\\ -0.4*v+0.4, & 0.5\le v<1.0\\ 0.2*v-0.2, & 1\le v\le 2\end{cases}$$

- Stem Damage

$$r(v)=\begin{cases}0, & 0.0\le v<1.0\\ 0.1*v-0.1, & 1.0\le v<2.0\\ 0.2*v-0.3, & 2.0\le v\le 3.0\end{cases}$$

A - 2.2 **Wind Damage – Stand Level**

- Age Class

$$r(v) = \begin{cases} 0, & v \leq 10 \\ 0.01 * v - 0.1, & 10 < v \leq 80 \\ 0.015 * v - 0.5, & 80 < v \leq 100 \\ 1.0, & 100 < v \end{cases}$$

- Proportion of spruce

$$r(v) = \begin{cases} 0.0, & v < 0.9 \\ 0.6, & 0.9 \leq v \end{cases}$$

- Proportion of other deciduous trees

$$r(v) = \begin{cases} 0.0, & v < 0.9 \\ 0.6, & 0.9 \leq v \end{cases}$$

- Proportion of larch, pine and fir

$$r(v) = \begin{cases} 0.6, & v < 0.3 \\ 0.0, & 0.3 \leq v \end{cases}$$

- Canopy Closure

$$r(v) = \begin{cases} 0.8, & v \leq 0.4 \\ -1.35 * v + 1.61, & 0.4 < v \leq 0.8 \\ -0.65 * v + 1.05, & 0.8 < v \leq 1.2 \\ 0.27 * \sin\left(\left(\frac{\pi}{0.8}\right) * (v - 0.4)\right) + 0.27\,, & 1.2 < v \end{cases}$$

- Stem Damage

$$r(v) = \begin{cases} 0, & v = 0 \\ 0.25 * v - 0.25, & 0 < v \leq 2 \\ 0.08 * v + 0.09, & v = 3 \\ 0.07 * v + 0.12, & 3 < v \leq 5 \end{cases}$$

A – 2.3 **Snow Damage – Site Level**

- Slope

$$r(v) = \begin{cases} 0.67, & v \leq 5 \\ 0.023 * v - 0.783, & 5 < v \leq 20 \\ 0.33 * \sin\left(\left(\frac{\pi}{40}\right) * (v + 20)\right), & 20 < v \leq 60 \\ 0.0085 * v - 0.18, & 60 < v \leq 100 \end{cases}$$

- Bonity

$$r(v) = 0.0446 * v - 0.038, \qquad v \leq 16$$

- Altitude

$$r(v) = \begin{cases} 0.4, & v < 200 \\ 333.3 * v + 66.7, & 200 \leq v < 400 \\ 1.0, & 400 \leq v < 800 \\ -500 * v + 1300, & 800 \leq v < 900 \\ -1000 * v + 1700, & 900 \leq v < 1100 \\ -1500 * v + 2000, & 1100 \leq v < 1400 \end{cases}$$

- Water Supply

$$r(v) = \begin{cases} 0.0, & v < 1.0 \\ 0.07 * v - 0.07, & 1 \leq v < 2 \\ 0.06 * v - 0.05, & 2 \leq v < 3 \\ 0.07 * v - 0.08, & 3 \leq v < 4 \\ 0.2, & 4 \leq v < 5 \\ 0.07 * v - 0.15, & 5 \leq v < 6 \\ 0.06 * v - 0.09, & 5 \leq v < 7 \end{cases}$$

A - 2.5 **Wind Damage – Site Level**

- Slope

$$r(v) = \begin{cases} 0.4, & v < 3 \\ -0.012 * v - 0.435, & 3 \leq v < 9 \\ -0.008 * v - 0.398, & 9 \leq v < 17 \\ -0.004 * v - 0.333, & 17 \leq v < 36 \\ -0.003 * v + 0.315, & 36 \leq v < 58 \\ -0.001 * v - 0.213, & 58 \leq v < 100 \end{cases}$$

- Bonity

$$r(v) = \begin{cases} 0, & v < 1 \\ 0.014 * v - 0.014, & 1 \leq v < 8 \\ 0.013 * v, & 8 \leq v \leq 16 \end{cases}$$

A – 2.6 **Primary Models – Stand Level**

- Proportion of Spruce

$$r(v) = \begin{cases} 0.8 * v, & 0.0 \leq v < 0.1 \\ 0.6 * v + 0.02, & 0.1 \leq v < 0.25 \\ 1.32 * v - 0.16, & 0.25 \leq v < 0.5 \\ 1.65 * v - 0.325, & 0.5 \leq v < 0.7 \\ 0.567 * v + 0.433, & 0.7 \leq v < 1.0 \end{cases}$$

- Age Class

$$r(v) = \begin{cases} 0.005 * v, & v < 0.4 \\ 0.016 * v - 0.44, & 0.4 \leq v < 0.65 \\ 0.012 * v - 0.18, & 0.65 \leq v < 0.9 \\ 0.01 * v, & 0.9 \leq v < 100 \\ 1.0, & 100 \leq v \end{cases}$$

- Canopy Closure

$$r(v) = \begin{cases} 0.4, & v < 0.8 \\ -0.3 * v + 0.64, & 0.8 \leq v < 1.2 \\ 0.012 * v - 0.18, & 1.2 \leq v < 1.6 \\ 0.2 * v - 0.24, & 1.6 \leq v < 2.0 \end{cases}$$

- Predisposition to Storm Damage

$$r(v) = \begin{cases} 0, & v = 0.0 \\ 0.02 * v, & 0.0 \leq v < 0.1 \\ v + 0.1, & 0.1 \leq v \leq 0.7 \\ 0.8, & 0.7 < v \end{cases}$$

- Predisposition to Snow Damage

$$r(v) = \begin{cases} 0.5 * v, & 0.0 \leq v < 0.1 \\ 0.25 * v + 0.025, & 0.1 \leq v < 0.7 \\ 0.2, & 0.7 \leq v \end{cases}$$

A – 2.7 **Primary Models – Site Level**

- Water supply

$$r(v) = \begin{cases} -0.16 * v + 0.96, & 1 \leq v < 2 \\ -0.32 * v + 1.28, & 2 \leq v < 3 \\ 0.32 * \sin\left(\left(\frac{\pi}{2}\right) * (v - 1)\right) + 0.32, & 3 \leq v < 5 \\ -0.32 * v + 1.28, & 2 \leq v < 3 \end{cases}$$

- Bonity

$$r(v) = 0.013 * v - 0.011$$

- Terrain Morphology

$$r(v) = \begin{cases} 0.24 * v - 0.2, & 1 \leq v < 2 \\ 1.28, & 2 \leq v < 3 \\ 0.12 * v - 0.08, & 3 \leq v \leq 4 \end{cases}$$

- Predisposition to Wind Damage

$$r(v) = \begin{cases} 2.5 * v, & 0.0 \leq v < 0.1 \\ 1.25 * v + 0.125, & 0.1 \leq v < 0.7 \\ 1.0, & 0.7 \leq v < 1.0 \end{cases}$$

- Predisposition to Snow Damage

$$r(v) = \begin{cases} 0.5 * v, & 0.0 \leq v < 0.1 \\ 0.25 * v + 0.025, & 0.1 \leq v < 0.7 \\ 0.2, & 0.7 \leq v < 1.0 \end{cases}$$