Cartography M.Sc.

Master thesis

Precision Mapping for Pest Identification in Mediterranean Pine Forest. Case study: Pine Processionary

Alexandros Theofanidis

2022

Precision Mapping for Pest Identification in Mediterranean Pine Forest. Case study: Pine Processionary

submitted for the academic degree of Master of Science (M.Sc.)
conducted at the Department of Aerospace and Geodesy
Technical University of Munich

Author:	Alexandros Theofanidis
Study course:	Cartography M.Sc.
1st Supervisor:	Dr.-Ing. Holger Kumke (TUM)
2nd Supervisor:	Dr. Mejia Aguilar Abraham (Eurac Research)
Reviewer:	Dr. Paulo Raposo (UT-ITC)

Chair of the Thesis
Assessment Board: Prof. Dr.-Ing. Liqiu Meng

Date of submission: 10.12.2022

Statement of Authorship

Herewith I declare that I am the sole author of the submitted Master's thesis entitled:

"Precision Mapping for Pest Identification in Mediterranean Pine Forest. Case study: Pine Processionary"

I have fully referenced the ideas and work of others, whether published or unpublished. Literal or analogous citations are clearly marked as such.

Munich, 10.12.2022 Alexandros Theofanidis

Acknowledgments

I would like to express my deepest gratitude and appreciation to my supervisor and the coordinator of this Master Program, Holger Kumke for his support.

I would also like to thank my external supervisor dr. Mejia Aguilar Abraham for the valuable feedback and remarks through the research process of this master thesis. Thank you for your extraordinary support, encouragement, understanding, valuable comments, and frequent meetings, which made the completion of this thesis possible. Thank you for always being available and willing to solve my problems, answer my questions and provide me the necessary data for this research.

Furthermore, I want to express my gratitude to my reviewer Paulo Raposo Ph.D for his understanding, his useful comments and recommendations after my mid-term presentation that helped me to keep my thesis in the track of seeking cartographic questions.

I would also like to extend my thanks to all the 10 forestry expert professional participants for taking the time to participate in my user study. Their knowledge and their opinion have been a great asset for my thesis.

I want to thank all the lecturers for this academic experience as they gave me the chance to meet different aspects of cartography and realize that maps are valuable tools of vital necessity that help humanity go further.

In advance, I want to express my respect for my three best friends and cartographers I met during those two years of my studies, Majk Shkurti, Syed Miftah Zeyah, and Enock Seth Nyamador for the amazing moments we had together and all the knowledge we exchanged during every project.

Last but not least, I want to express my respect to my family for being always supportive with my choices and my struggle to complete this Master's Program.

Abstract

As forestry is a spatial-related science, maps are tools that are used for efficient management and protection of important natural resources such as biomass, wood, and livestock. One of the most valuable function of the maps in forestry is to visualize areas that are prone to threats that can cause a degradation to the ecosystem. More specifically the threat that this thesis is investigating is related to pest populations' breakouts that can extinguish large areas covered by forests.

In this thesis, the threat that we examine is the insect *Thaumetopoea pityocampa* known as Pine processionary moth. A latitudinal and altitudinal expansion of the pine processionary moth has been observed due to climate variability, creating high accuracy maps for monitoring the pest population purposes and further protection of the pine forests seems to be quite promising for reducing the cost of forest management and make the whole planning of the Forestry Departments more efficient when they have to combat a threat like this. Decisions in forestry are influenced by many different aspects and are complex as forest ecosystems are dynamic and are characterized by continuous changes based on the environmental conditions.

This master thesis contributes by identifying and optimizing the visualization of some of the factors that forest scientists need to have a close look at on a map before they make decisions after collecting field data with the use of Unmanned Aerial Vehicles (UAV) and create maps that will be valuable tools in forestry for management and decision-making.

A user test was conducted in order to evaluate which elements are the most important to be presented on a map for pest control and protection purposes and what are the optimal visualization methods for presenting pest outbreaks. While the user study with 10 experienced participants that are specialized in forestry and mapping produced predominantly positive results, the conducted user test gave us a holistic idea on how to improve the proposed visualization of the necessary map elements in order to make user's decisions easier to be made by just looking on maps included into a software platform that may support decision making.

Table of contents

List of Figures

List of Tables

List of Abbreviations

DEM Digital Elevation Model

UAV	Unmanned Aerial Vehicle
PPM	Pine Processionary Moth
NIR	Near Infra-Red
IR	Infra-Red
UV	Ultra-Violet
Px	Pixels
WMS	Web Map System
SAR	Synthetic Aperture Radar
LIDAR	LIght Detection And Ranging
VI	Vegetation Indices
NDVI	Normalized Difference Vegetation Index
EVI	Enhanced Vegetation Index
MSAVI	Modified Soil Adjusted Vegetation Index
NDRE	Normalized Difference Red Edge

1. Introduction

1.1 Motivation and problem statement

Forests are undisputed one of the most important ecosystems that offer great benefits, services and protection for the humankind. Their efficient management and their protection are of paramount significance, especially under the imminent threat of the climate change our planet is facing. “Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss” describes the 15th goal of the Sustainable Development Goals (SDGs) of the United Nations.

The world's most extensively spread pine species, the conifer *Pinus sylvestris* (Scots pine) can be found all the way across Eurasia (Durrant et al., 2016), and as Scots pine is one of the most commercially important species (Praciak et al., 2013). Any threat against the Scots pine forests must be mitigated and any damage that has already been caused has to be located, assessed and finally restored.

Forest pest is one of the most common factors affecting forests’ health (Yuan & Hu, 2016) and although, according to Hódar, Castro and Zamora in 2013, Scots pine populations are isolated in *high* mountains, which tend to protect them from the attack of a severe defoliating Mediterranean pest, the Pine Processionary Moth *Thaumetopoea pityocampa* is increasingly present in different regions of European forests and cities as well including the *high* elevation Alps Forest. Its presence in north latitudes as well high elevation forests is a clear sign of global warming and pest adaptation. This pest is one of the most destructive species to pines and cedars worldwide. The caterpillars can completely defoliate trees in few months. If the forest is in steep slopes, it can produce instability of the terrain resulting in erosion and degradation.

Forest rangers identify the nests and possible distribution. It is a high time consuming and men power activity. Therefore, it urges a quick monitoring tool to identify, localize, manage, and predict its distribution, to anticipate its propagation and reducing its impact as very steep slopes make it hard or even impossible.

Cartography tools support the environmental efficient monitoring, management, protection, and conservation. In recent decades, the civil use of light platforms (UAVs), miniaturized sensors, new satellite missions, are providing us with high resolution imagery in very short time. With the use of UAVs, we expect to increase the accuracy of the nest locations and create maps that illustrate pest breakouts so that the user has the ability to have a quick access to important information related to the behavior and the preferences of the Pine Processionary.

Increased accuracy of the nests' locations will enable forest scientist to have a better overview of the Pine processionary impact not only on tree level but also on forest level and monitor the expansion that leads to biodiversity loss.

1.2 Research Objective and Research Questions

The current study aims to set the minimum requirements for a Decision Support System applied in pest forestry applications to identify, visualize and finally evaluate decision-relevant maps.

It integrates the ecological aspects (habitat, living conditions and adaptation) and the data driven solutions (high precision digital thematic maps) for the identification, distribution, and extension of the pest at the level of the tree (pine), forests, and areas, for forest protection and management purposes.

To better understand the goals of this research, Research Objectives (Table 1) and Research Questions (Table 2) are set in advance.

RO.1: To develop a method that identifies infested trees with the use of multiband aerial imagery obtained by UAVs.
RO.2: To explore and test different visualization aspects of the pests' location, behaviour and the size of the threat that causes their outnumber existence.

RO.3: To evaluate and finally establish a visualization pattern for the use and benefit of forestry applications (Mapping technique to produce precision maps)

Table 1: Research Objectives (ROs)

The research questions are formulated like so to answer the above stated objectives

RQ1: In what degree and in what manner can cartography improve the management and protection of forests that are threatened by the existence of malicious pests when outnumbered?
RQ2: How can UAV imagery data contribute in monitoring pests?
RQ3: Are 3D maps more suitable for the specific case study compared to 2D maps?
RQ4: What colours should be used to emphasize to the user an imminent threat?

Table 2: Research Questions (RQs)

The result of this project is expected to be a web-based map for that will indicate regions where the risk of a population outbreak is high and can cause damages to the ecosystem.

1.3 Innovations intended

The goal of this thesis is to combine already existing cartographic methods of visualizing decision-relevant information in an innovative and optimal way to indicate natural and artificial elements that are necessary for locating pest's nests. By having the precise location of the nests, forest scientists can also have access in valuable information regarding the position, the elevation, the orientation and the climate conditions of the environment that the pest is present. The data sources are high resolution multispectral imagery obtained with the use of UAVs.

So far, other researchers have conducted research in Spain where they managed to develop a method for monitoring the Pine processionary moth in pine forests with the use of RGB camera attached to a UAV. According to (Adrián Cardil et al., 2017) RGB imagery allowed the percentage of defoliation to be assessed at tree-level and they had the chance to differentiate healthy from infested and completely defoliated trees with high accuracy.

In this thesis we explore the possibility of using UAV imagery obtained by multispectral camera in order to have the ability to apply through image processing, a remote sensing index that will make the identification of the exact number of nests per tree more effective.

1.4 Thesis Outline

The thesis is divided into six chapters. In the first chapter, motivation and the problem statement are presented, research objectives and questions are defined. The second chapter provides information about the life cycle of the pest, the damages it can cause to the trees and the devastating impact of a massive population breakout. Furthermore, the main cartographic design principles for web maps are reviewed in this chapter.

In the third chapter of the thesis the methodology on how the trees are mapped with high accuracy using high resolution imagery obtained by UAVs, how the nests of the Pine processionary moth are indicated and how the layers of the web application for a decision support system for forest ecosystem protection purposes might look. The main stages of the methodology consist of the data collection session, the imagery analysis for tree identification, the questionnaire for the users.

The fourth chapter presents the implementation and evaluation of the visualization techniques based on the user research and the results of the survey are discussed in chapter number five.

In the last chapter the results are concluded and a further research potential is referenced.

2. State of the Art

This chapter includes an overview of general information regarding the Pine processionary life cycle, its preferences based on environmental factors and the reasons why its population has to be sustained in low levels. These information help the reader to better understand why precision in mapping is required and how it affects the management of the pests' population.

A review of cartographic design principles for web maps is also included. Moreover, this chapter gives the reader the opportunity to explore the most common visualization methods that are combined in this research. Afterward, a review of the most dominant and already existing main visualization that forestry experts use is provided.

2.1 Thaumetopoea pityocampa - Pine processionary moth – Processionary caterpillar

2.1.1 Distribution of the pest.

According to Régolini, the pine processionary moth (PPM, *Thaumetopoea pityocampa*) is the main defoliation factor of pines in the Mediterranean area (Figure 1), necessitating constant surveillance and regular pest management (Régolini et al., 2014). And as PPM it in terms of temporal occurrence, geographic extent, and economical effect, is by far the most important insect defoliator of pine forests in Southern Europe and North Africa (Jactel et al., 2015).

It is found in all the countries of the Western Mediterranean (Huchon & Demolin, 1970) and is currently spreading to higher latitudes, probably in response to climate change, with increasing winter temperatures (Battisti et al., 2005; Robinet & Roques, 2010).

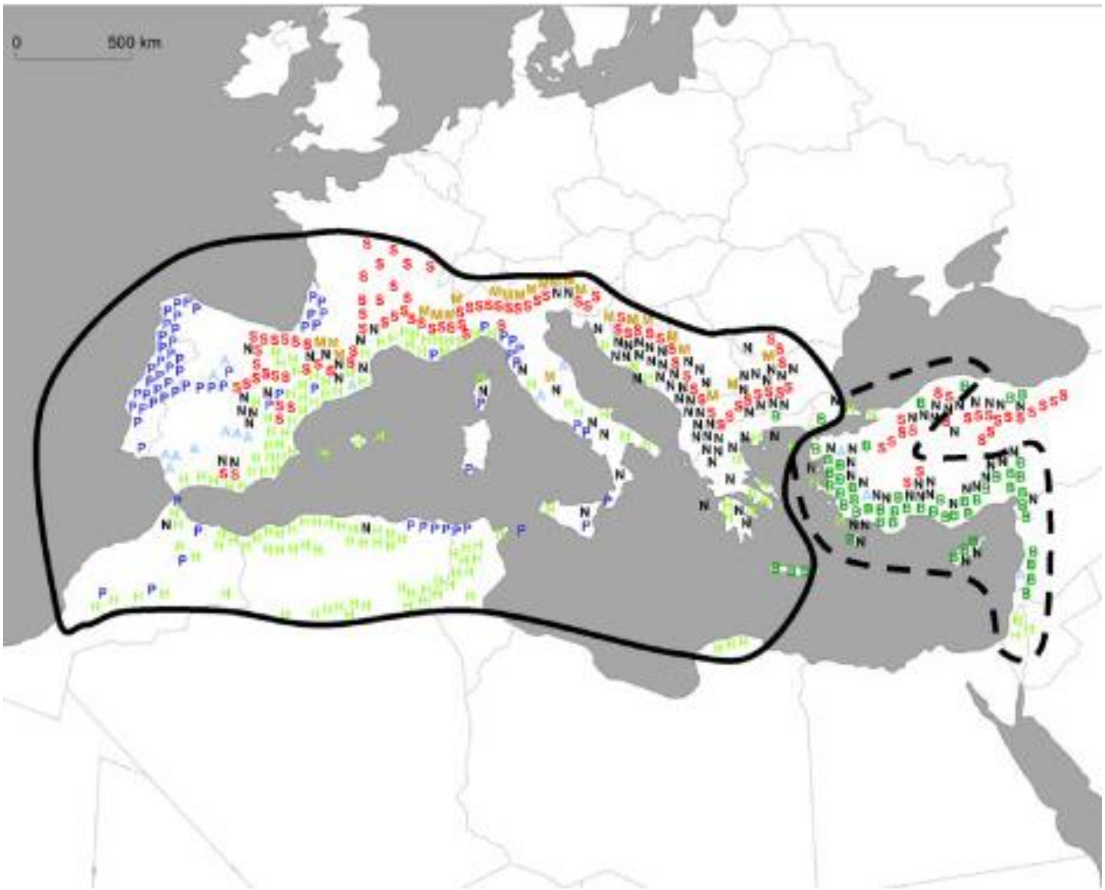


Figure 1: Ranges of the pine processionary moths indicating the occurrence of native Pinus. Thaumetopoea pityocampa, solid line; Thaumetopoea wilkinsoni, dashed line; A = Pinus pinea, B = P. brutia, H = P. halepensis, M = P. mugo, N = P. nigra, P = P. pinaster, S = P. sylvestris. (Kerdelhué et al., 2009)

2.1.2 The threat of PPM

Forests and woodlands cover nearly 40 percent of the Earth's land surface, and they are the most biologically diverse ecosystems in most parts of the world (World Resources Institute, 1992). They are ecosystems that are vulnerable in many natural threats and they are continuously facing risks that jeopardize their sustainability.

One the most serious risks that these ecosystems are dealing with can be fragmentation. As Dale and Pearson address, habitat fragmentation is the process that occurs when a habitat or land cover type is subdivided either by a natural disturbance" (e.g. fire or storm) or by human activities (e.g. roads or cultivation) (Dale & Pearson, 1997). In addition, outnumbered populations of insects can cause the extinction of great forest vegetation as they defoliate trees for their survival and expansion.

Nowadays, the progress in the field of science and technology of remote sensing GIS and cartography the past decades provide us an opportunity to better understand, monitor and finally take measures about the unwanted and harmful, for the environment, changes taking place on the Earth’s surface.

2.1.3 Life Cycle of PPM

Adult moths live for about one day in summer, and during this time they mate and lay their eggs on pine tree branches. The larvae, or caterpillars, emerge in autumn from the eggs laid in the summer, and begin feeding on the trees’ needles in autumn (Forest Research, 2022). About January the caterpillars build distinctive white nests of silken, webbing on the branches and foliage of pine trees where several nests can be found in a single tree (Forest Research, 2022).

The caterpillars spend the rest of the winter in these nests high in the trees (Figure 4), spending the days in these nests, and leaving them at night to be fed on the trees’ needles (Forest Research, 2022). In early spring they establish processions on the ground before pupating in the soil until summer (Fig. 2 and 3), when they emerge as adult moths (Fig. 5). This pupal stage, on the other hand, might remain inactive for another year, or perhaps two, extending the life cycle to two or three years. (Forest Research, 2022) as presented in Figure 6.

Figure 2: Caterpillars moving as in a procession and so called processionary (Ricciardi et al., 2021)

Figure 3: Processionary caterpillar covered with hair-like bristles called setae responsible for reactions (Ricciardi et al., 2021)

Figure 4: Processionary caterpillars' nest covered with larvae (Ricciardi et al., 2021)

Figure 5: Adult Processionary caterpillar (Watts, 2008)

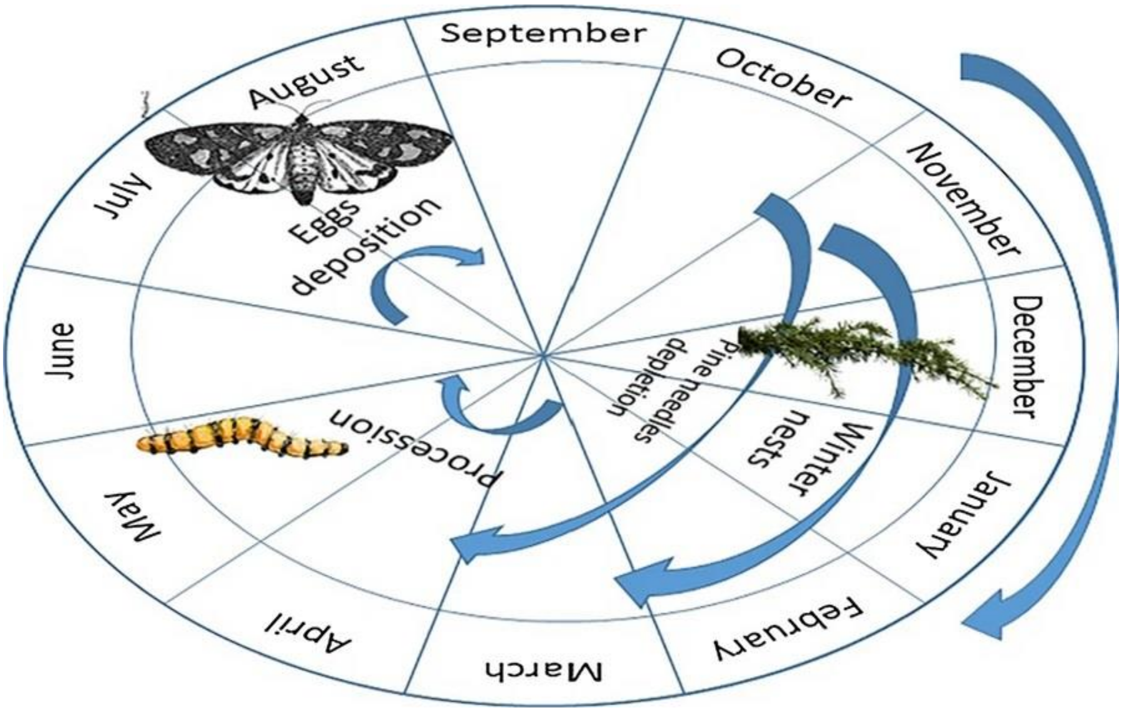


Figure 6: Pine processionary life cycle (Ricciardi et al., 2021)

2.1.4 Environmental Conditions that foster a PPM population increase

Thaumetopoea pityocampa has a very peculiar one-year development cycle as described on the previous section, which is reversed compared to the other species of the genus and to most of other defoliating insects, because the larvae feed across the winter (Battisti et al., 2015). That means that the survival of PPM is strongly affected by the temperature of the environment. When the temperature conditions allow it, a population outbreak is expected under the condition that trees are available.

Temperature conditions are highly related with the amount of sunlight that an area is exposed to it. As the mean temperature rises, Battisti emphasizes that global warming is predicted to cause distributional changes in organisms whose geographic ranges are temperature-controlled (Battisti et al., 2005). A latitudinal and altitudinal expansion is reported lately of the pine processionary moth, *Thaumetopoea pityocampa*, whose larvae build silk nests and feed on pine foliage in the winter (Battisti et al., 2005).

Larvae of *Thaumetopoea pityocampa* develop throughout the winter, although their feeding activity and survival can be impaired by adverse climatic factors. Survival at low temperature of larvae originating from a population with range expansion in an alpine valley in Northern Italy (Hoch et al., 2009).

In Figure 7, according to European Environmental Agency, an overall increase of the annual temperature is observed, making the conditions for the PPM larvae even more beneficial. A characteristic example of an overall air temperature in the province of Bolzano is also presented in Figure 8.

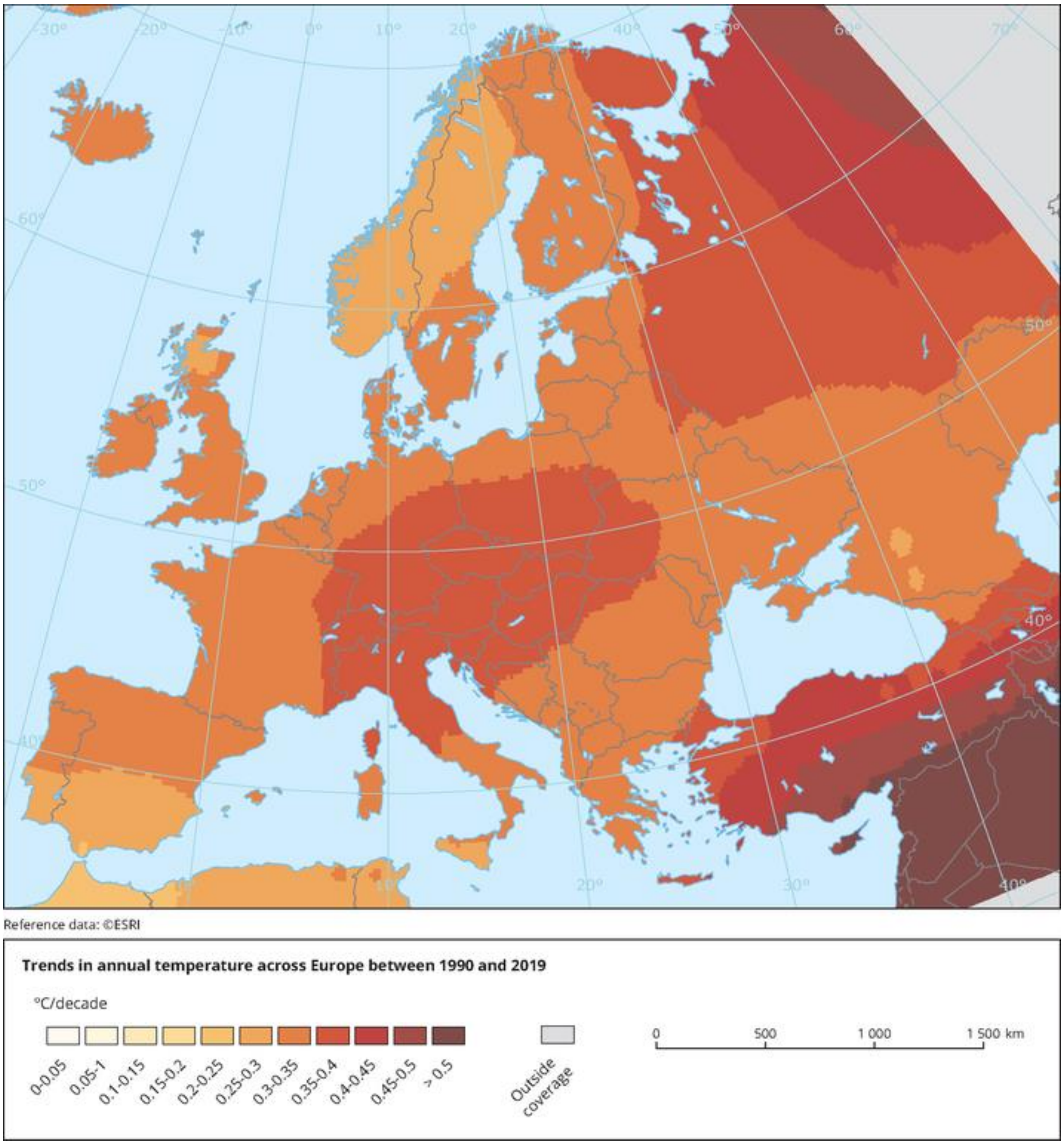


Figure 7: Trends in annual temperature across Europe between 1990 and 2019 (European Environment Agency, 2020)

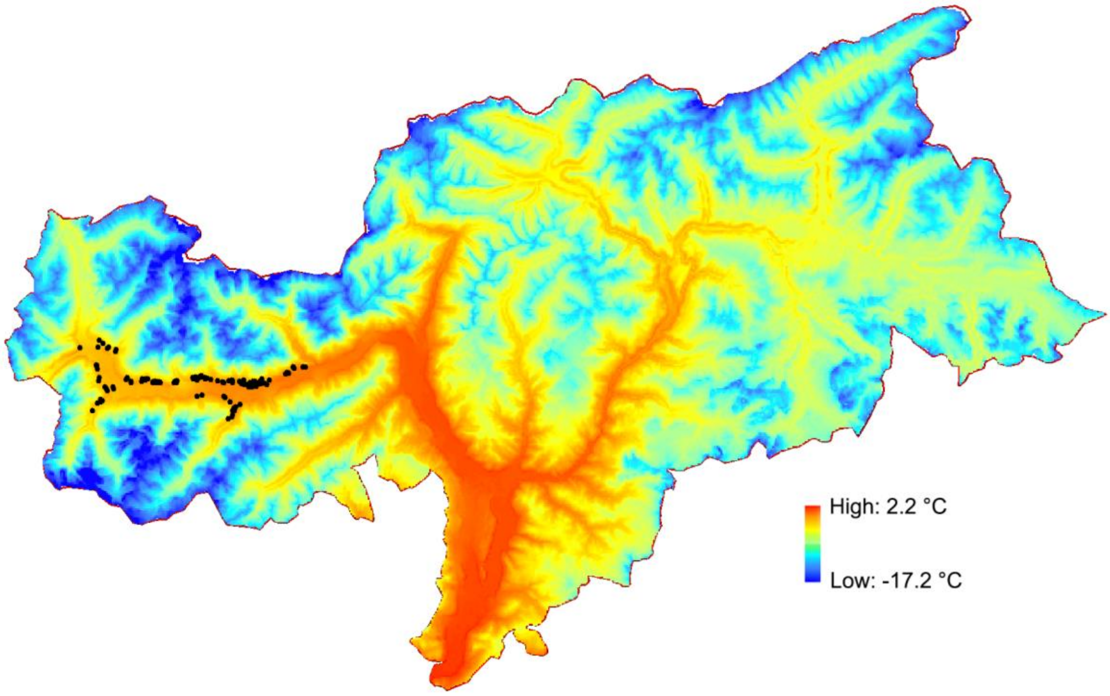


Figure 8: Monthly mean temperature 1981 - 2010 (Crespi et al., 2020) Black dots on the western part of the map represent the spatial distribution where PPM is present. PPM Locations were provided by the Forest Service of Bolzano.

2.1.5 Cartography's role in PPM management and control

Visualization through mapping has long been treated as a fundamental geographic method (MacEachren & Taylor, 2013). According to the International Cartographic Association, cartography is the art, science and technology of making maps (ICA, 2003).

A map is a symbolic depiction of geographical reality that represents selected features or characteristics, resulting from the creative effort of its author's execution of choices, and is designed for use when spatial linkages are of major relevance (ICA, 2003). Maps are powerful tools to illustrate spatial information and in the case of pest control, maps can reduce the financial cost of forest protection.

Maps can contribute to forest agencies by making monitoring of the PPM more efficient. Another useful role of precision maps where the nests are visualized is the reduction of the time required for all the necessary activities, when a population increase of the PPM is observed. Route planning can be significantly improved by locating the areas that are endangered due to a dominant presence of the PPM.

Especially with the use of UAVs, wide areas of land can be easily monitored, observed and also changes can be detected in short amount of time and with relatively low cost. UAVs provide us the opportunity to visit remote areas that are hard, risky and dangerous to be reached. Steep slopes and terrain, dense vegetation, and unstable soil are some of the main reasons why some of the areas of interest are hard be approached.

Cartography's role in monitoring natural phenomena like a pest population breakout is to find ways for optimal visualization of information that supports and encourages the decision making by scientists and workers. Information related to an area that is relevant to PPM's survival such as slope percentage, elevation, orientation, vegetation type coverage, nest distribution, aspect, and solar radiation, need to be visually accessible on maps in a way, that an experienced eye with academic background in forest science can quickly have an idea about the parts of the represented area that are in a high risk, or are potentially in danger.

2.2 Remote Sensing and Spectral Signatures

2.2.1 Remote Sensing – Definition and applications

In recent years, there has been a surge in the use of remotely-sensed data in natural resources mapping and as source of input data for environmental processes modeling (Melesse et al., 2007). Acquiring information from distance is remote sensing (Earth Science Data Systems, 2019). The United States Geological Survey defines remote sensing as the process of detecting and monitoring the features and the characteristics of an area from a distance by measuring its reflected and emitted radiation, most commonly from satellite or aircraft (USGS, 2022).

Many definitions have been given for the field of remote sensing and the definition that better ascribes it for the needs of our case study and describes properly the reasons why we used multispectral imagery is the one given by

Campbell & Wynne. They described the scientific field of remote sensing as "*the practice of deriving information about the Earth's land and water surfaces using images acquired from an overhead perspective, using electromagnetic radiation in one or more regions of the electromagnetic spectrum, reflected or emitted from the Earth's surface*" (Campbell & Wynne, 2011).

It is an undisputed fact that remote sensing methods and techniques are used for environmental monitoring and protection purposes. Some examples of remote sensing applications are:

- Large forest wildfires mapping from space that allows forest rangers to see a much larger area than the one they see from the ground (USGS, 2022).
- Tracking clouds to predict the weather or watching erupting volcanoes, and dust storms (USGS, 2022).
- Tracking the growth of cities and changes in farmland or forests over several years or even decades (USGS, 2022).
- Within forest ecology, cover and vegetation structure measurements, vegetation chemistry and moisture, biodiversity, and information about soil properties (Lechner et al., 2020) can be derived as for forest ecosystem management and protection purposes.
- Water resources management and research such as mapping of watersheds and features, indirect and direct hydrological parameter and hydrological variables estimation (Melesse et al., 2007).
- Flood monitoring and watershed management.

2.2.2 Electromagnetic spectrum

An optical imaging system, which is similar in form and use to a normal digital camera except that it can record data beyond visible wavelengths such as infrared across the electromagnetic spectrum (Fig. 9), is the most often used type of sensor used in remote sensing.

In Table 3 the principal divisions of the Electromagnetic Spectrum are presented but two significant categories are not shown in the table. The optical spectrum (0.30-15 μm) and the reflective spectrum (0.38-3.0 μm). The first defines the wavelengths that are reflected and also refracted with mirrors and lenses (Campbell & Wynne, 2011). The second defines that portion of the solar spectrum used directly for remote sensing (Campbell & Wynne, 2011).

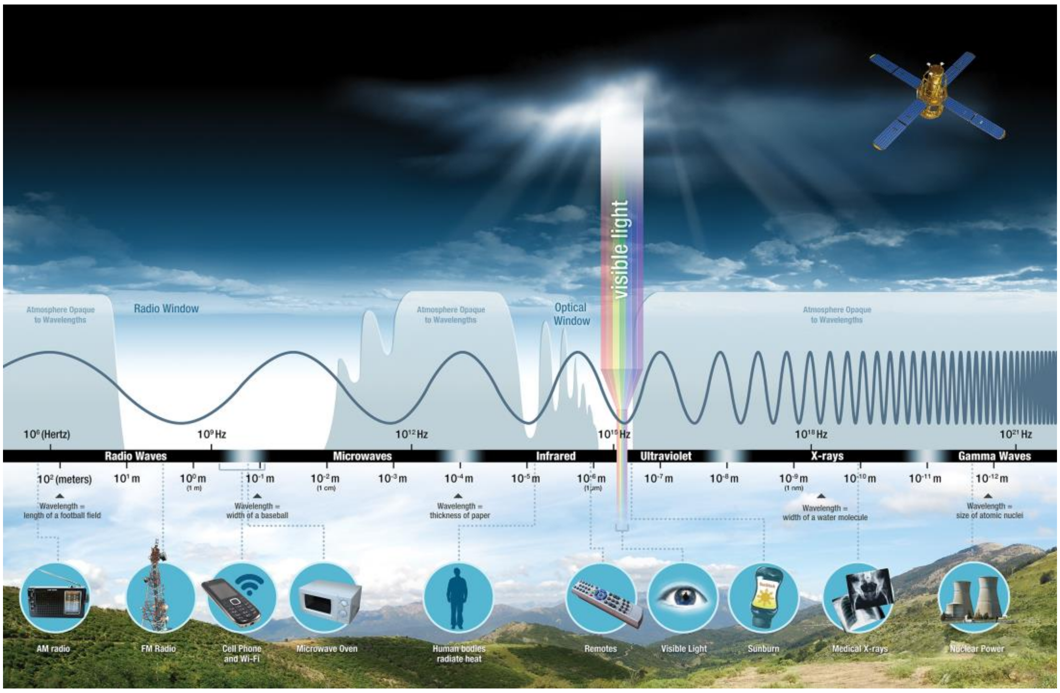


Figure 9: Diagram of the Electromagnetic Spectrum (NASA Science, 2019)

Division	***Limits***
Gamma rays	<0.03 nm
X-rays	0.03-300 nm
Ultraviolet radiation	0.30-0.38 μm
Visible light	0.38-0.72 μm
Infrared radiation	
Near infrared	0.72-1.30 μm
Mid infrared	1.30-3.00 μm
Far infrared	7.0 – 1000 μm (1mm)
Microwave radiation	1mm – 30 cm
Radio	≥ 30 cm

Table 3: Divisions of the Electromagnetic Spectrum (Campbell & Wynne, 2011)

2.2.3 Data Acquisition for Remote Sensing applications

Remote Sensing requires imagery data. To accomplish data collection for remote sensing usage, different types of sensors are used mounted on airborne, spaceborne platforms (Fig. 10). Nowadays an upcoming and promising type of platform that can successfully carry sensors for image acquisition are the UAVs.

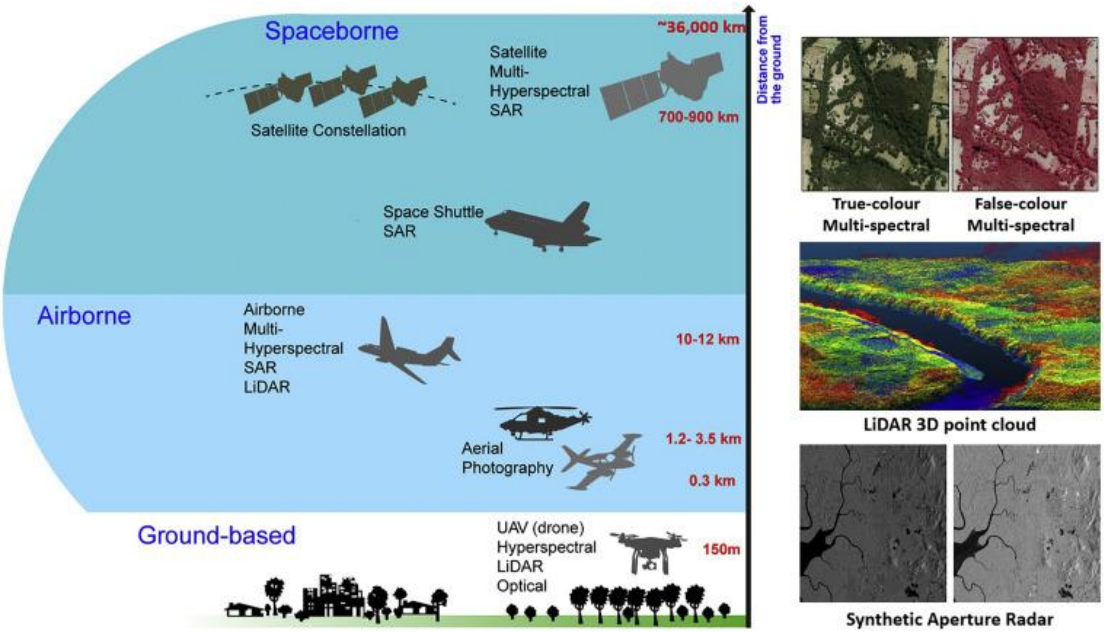


Figure 10: Common Remote-Sensing Platform and Sensor Combinations and Remote-Sensing Data (Lechner et al., 2020)

Imaging sensors

Imaging sensors are the most fundamental component of every remote sensing system, and they are available in a wide range of spatial, temporal and spectral resolutions (Toth & Jóźków, 2016). Remote sensors are conventionally divided into two types: passive sensors and active sensors (Rustamov et al., 2018). The main difference between the two types of sensors is the source of light or energy that they receive. An illustration of the manner that both passive and active sensors receive signals is provided in Figure 11.

Materials reflect and absorb at different wavelengths, and because of these differences among objects, differences in land cover (i.e., forest and canopy cover) can be identified (Lechner et al., 2020) by using sensors that can capture these differences in reflectance of the objects. In general, remote sensing offers unique insights into current environmental issues and is an important tool for driving solutions (Lechner et al., 2020). However the upon given definition is not applicable in any study case as remote sensing has multiple applications and covers different necessities of different scientific fields. Other applications of remote sensing than environmental monitoring are agricultural production efficiency, vessel tracking, homeland security, military and law enforcement purposes etc.

Optical systems are passive sensors, based on reflected sunlight or emitted thermal energy respectively, and as a consequence cannot penetrate clouds and smoke, and are not applicable and during the night (Lechner et al., 2020).

On the other hand, active sensors have their own light or illumination source and they specifically emit an active pulse and detects the backscatter reflected to the sensor (GISGeography, 2015).

The advantages of active sensors is that there is no limit in the time framework of operation as sunlight is not necessary and bad weather conditions (clouds) do not affect the quality of the data (Gikunda, 2021). Another advantage of using active sensors is that the emitted pulse by the sensor allows a greater penetration through vegetation, soil, and water bodies (Gikunda, 2021).

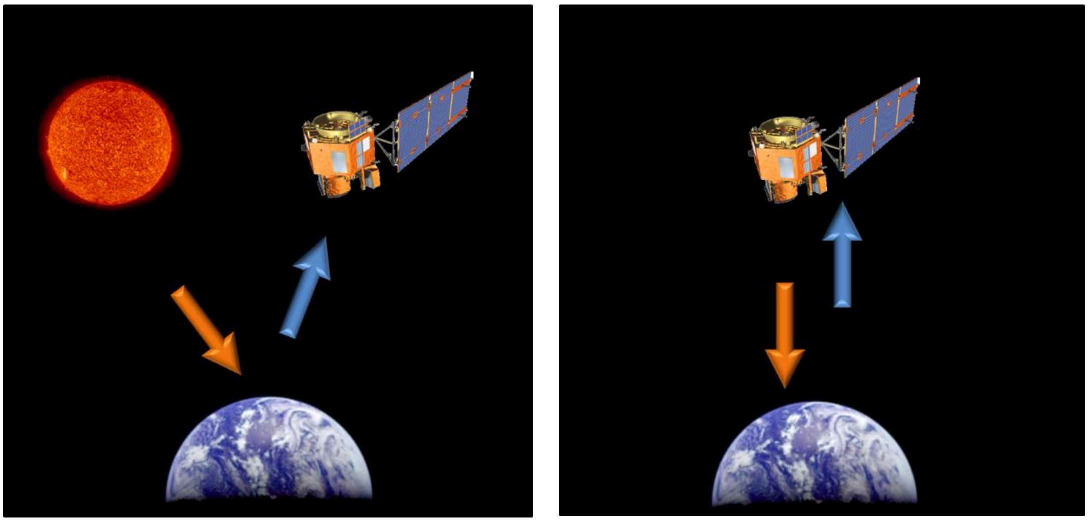


Figure 11: Passive Sensor (left). Active Sensor (right) (Mai, 2015)

2.2.4 Spectral Signatures

The fluctuation of a material's reflectance or emittance with regard to wavelengths is referred to as its spectral signature. Spectral signatures or spectral fingerprints characterize materials based on electromagnetic radiation absorption, reflectance, and transmission (Padma & Sanjeevi, 2014).

Signature of any item and/or its condition comprises a set of observable features that, lead to the identification of an object and/or its condition, either directly or indirectly (Navalgund et al., 2007). The spectral signature is an important tool in the interpretation of digital imaging data since it serves as the foundation for identifying and distinguishing diverse things on Earth. (Kachhwaha, 1983).

Specifically in the domain of vegetation analysis, the function that is described by the ratio of the intensity of the reflected light to the illuminated light for each wavelength forms the leaf/canopy spectral signature (Carter & Knapp, 2001; Jones et al., 2003; West et al., 2003).

The impact on the spectral signature is determined by the strength of physiological changes and the severity of the symptoms (Malthus & Madeira, 1993) and spectral analysis allows scientists to detect changes in the physiological properties of plants and trees and thus, the detection of plant diseases is possible through remote sensing and image processing techniques. Spectral analysis actually measures the intensity of a signal's periodic (sinusoidal) components at different frequencies (Burg, 1975).

In Figure 12 the spectral signature of different features such as water, dry and wet soil is presented whereas in Figure 13 the way that spectral signature of vegetation in different health condition of vegetation is being is formed are illustrated.

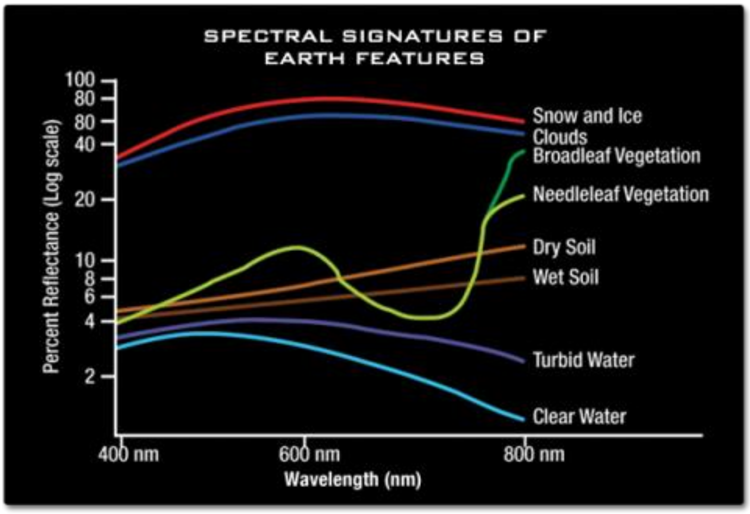


Figure 12: Spectral signatures of different Earth features within the visible light spectrum. Credit: Jeannie Allen (NASA Science, 2019)

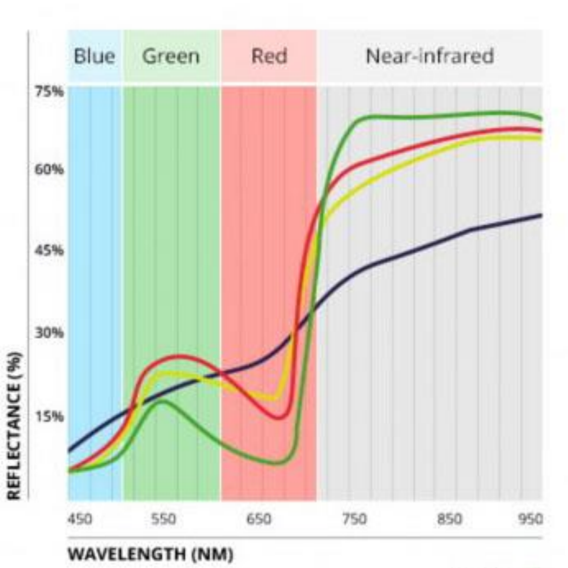


Figure 13: Spectral signature showing behavior of healthy (green), stressed (red), nitrogen deficient (yellow), and necrotic (purple) plant (SARE, 2018)

2.2.5 Image Segmentation

Spectral matching approaches enable efficient usage of information from spectral signatures (Homayouni & Roux, 2004). Image segmentation is a component of digital picture processing that is used to divide an image into various segments and discrete areas (Nadipally, 2019), therefore spectral signatures can provide both qualitative and quantitative information for image classification, making the spectral signature the fundamental basis for image processing (Chen et al., 2016).

In remote sensing, classification entails grouping pixels in an image into a (relatively limited) collection of classes, so that pixels in the same class have comparable features (Mohd et al., 2009). Classifying remotely sensed data into thematic maps remains difficult because various factors, such as the landscape complexity in a study region, chosen remotely sensed data, image processing and classification methodologies, can all impact classification success. (Lu & Weng, 2007). Generally, image classification techniques can be grouped as supervised and unsupervised (Lu & Weng, 2007).

2.2.5.1 Supervised classification

In supervised classification, representative samples are chosen for each land cover class and then the software applies these "training cites" to the entire image (GISGeography, 2014). A sufficient number of training samples and their representativeness are critical for image classifications (Hubert-Moy et al., 2001; Chen & Stow, 2002; Landgrebe, 2003; Mather & Koch, 2004). The nature of the training samples, the number of bands employed, the number of classes to be recognized compared to the spatial resolution of the picture, and the characteristics of the classifier are the most critical aspects influencing classification accuracy. (Pal & Mather, 2006).

2.2.5.2 Unsupervised classification

Unsupervised classification involves selecting an algorithm that will take a remotely sensed dataset and locate a certain number of statistical clusters in multispectral or hyperspectral space (Mohd et al., 2009). Although these clusters are not always equivalent to actual classes of land cover, this method can be used without having prior knowledge of the ground cover in the study site (Nie et al., 2001). In general, unsupervised classification is the most fundamental approach to segment and comprehend a picture because no training samples are required.

2.2.6 Vegetation Indices

Vegetation indices are a remote sensing tool for identifying vegetation and measuring its health and vitality (Buczkowski, 2015) and are results of spectral imaging modification of two or more image bands that is intended to improve the contribution of vegetation attributes. Vegetation indices give us the ability to compare geographical and temporal terrestrial photosynthetic activity and changes in canopy's structure. Vegetation tends to alter its reflectance properties according to its health condition and this allows to have an overview of the vegetation's health condition after applying the arithmetic calculations of the vegetation indices among the different spectral bands (Fig. 14 and Fig. 15).

Scientists have created vegetation indices (VI) for subjectively and quantitatively analyzing vegetative coverings using spectral data in the domain of remote sensing applications (Bannari et al., 1995) and are intended to enhance sensitivity to vegetation properties while reducing confounding variables such soil background reflectance, directional effects, and atmospheric influences (Fang & Liang, 2014).

The vegetation indices created by combining reflectance in the red and NIR bands are maybe the most often utilized data in vegetation mapping (Weng, 2011) and play a significant role in monitoring variations in vegetation (Matsushita et al., 2007).

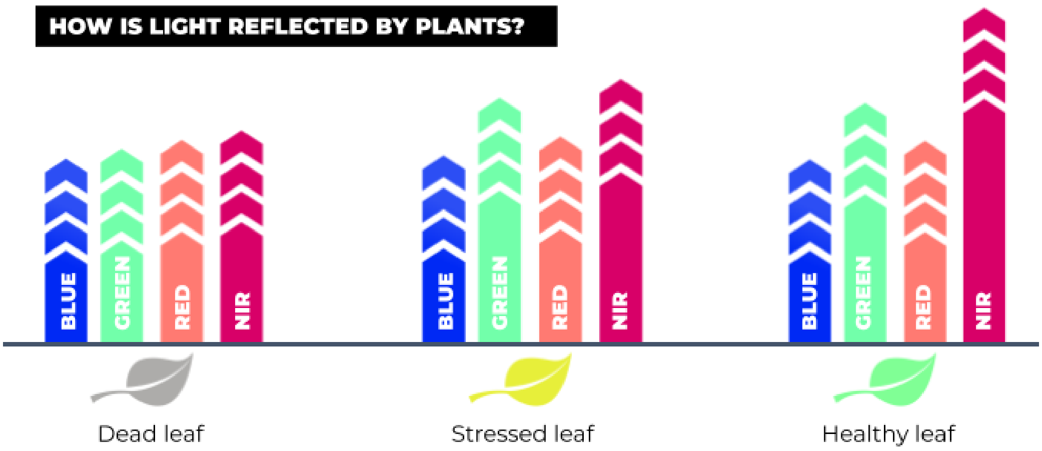


Figure 14: Differences in light reflectance by plants based on their health condition (Buczkowski, 2015)

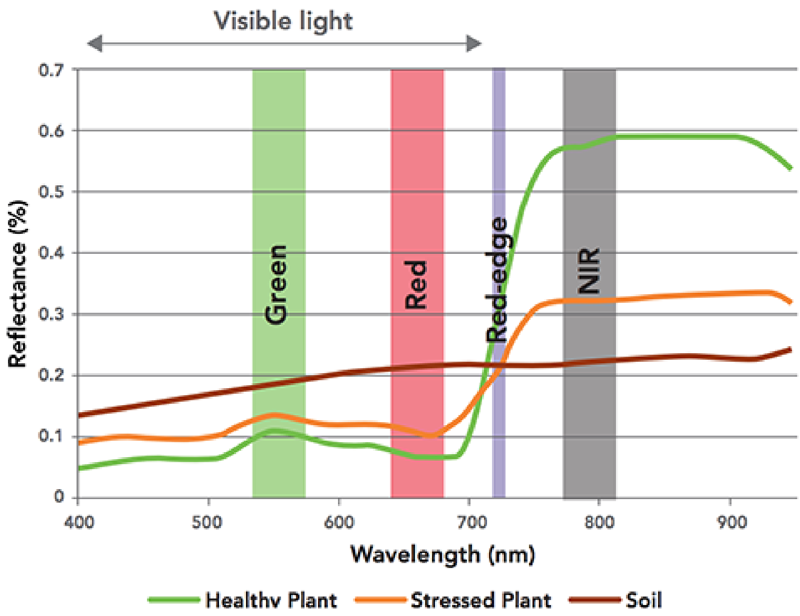


Figure 15: The spectral reflectance characteristics of healthy versus stressed vegetation (SARE, 2018)

NDVI

The most common vegetation index used in agriculture and forestry is the NDVI. Healthy vegetation (chlorophyll) reflects more near-infrared (NIR) and green light compared to other wavelengths but absorbs more red and blue light (GISGeography, 2017).

$$NDVI = \frac{(NIR-RED)}{(NIR+RED)}$$

NDVI values range from +1.0 to -1.0 where areas of barren rock, sand, or snow show very low NDVI values (0.1 or less). Sparse vegetation such as shrubs and grasslands or senescing crops may result in moderate NDVI values (approximately 0.2 to 0.5) whereas high values (above 0.6) correspond to dense vegetation (USGS, 2018).

2.3 Visualization and map making principles

2.3.1 Visual Variables

The graphic dimensions across which a map or other visualization can be varied to encode information are referred as visual variables (Roth, 2017). In Figure 16 examples of point symbols are provided for each of the visual variables. Visual variables are used to encode information about line, point and area features.

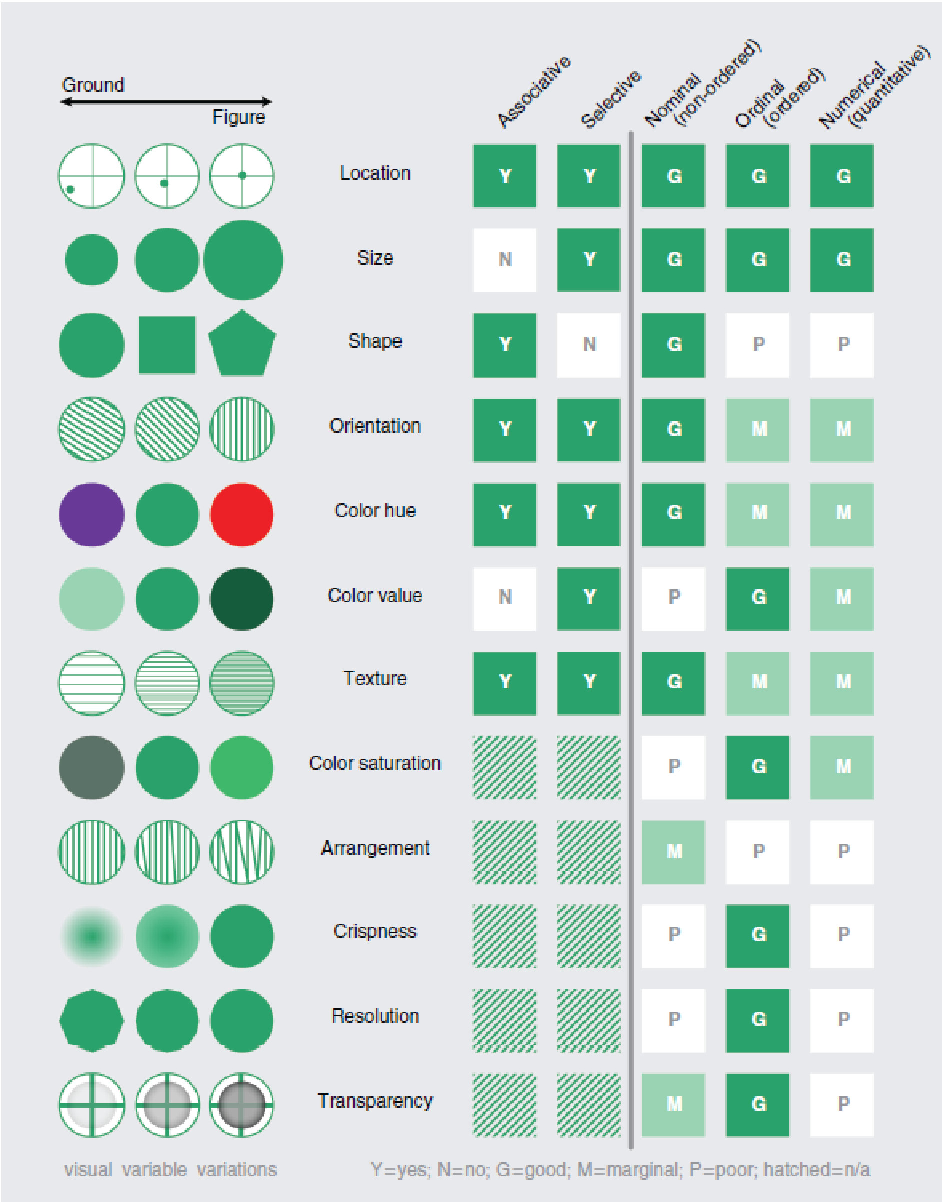


Figure 16: The visual variables and their syntactics. Figure derived from Bertin (1967/1983), MacEachren (1995), and MacEachren et. al. (2012)

Bertin (1967/1983), a French cartographer originally identified seven visual variables that can be manipulated to encode information.

1. Location describes the position of map symbols relative to a coordinate frame. Location in cartography often refers to the position of a map symbol in relation to a projected spatial coordinate system, implying that location is primarily used to depict the spatial component of information in cartographic design. However, the usage of perspective height in prism maps is one example of how location may be utilized to express attribute information (Roth, 2017).

2. Size describes the amount of space occupied by the map symbol (Roth, 2017). The fundamental visual variable adjusted in proportional symbol maps and value-by-area cartograms is size. Flow maps that scale the thickness of the flow lines to an attribute value also adjust the line size to describe an attribute value.

3. Orientation describes the direction or rotation of the map symbol from "normal" (Roth, 2017) and is frequently used in multivariate glyph symbols to distinguish between the represented properties. Orientation is also adjusted in flow maps to illustrate flow directionality.

4. Color hue describes the dominant wavelength of the map symbol on the visible portion of the electromagnetic spectrum (e.g., red, green, blue) and is one of three visual variables linked with the perception of "color" (Roth, 2017). According to Brewer, color theory occupies a substantial space in the cartographic canon (Brewer, 2005) and is particularly relevant for choropleth mapping as well as other types of reference and thematic maps that colors are used in order to designate different categories or classes. A qualitative or spectral color scheme manipulates the hue of a color while controlling the other components of the color; such color schemes are only suited for choropleth maps (Roth, 2017).

5. Color value describes the relative amount of energy emitted or reflected by the map symbol (Roth, 2017). Color value variation causes the perception of shading, or areas of relative brightness (high emission or reflectance of energy) and darkness (low emission or reflectance of energy). Manipulating color values is important for choropleth maps that illustrate ordinal or numerical information.

To promote discriminability, a sequential color scheme alters color value in one direction, occasionally spanning across two or three separate color hues. A diverging color scheme shifts color value away from a key midpoint in two ways, with each direction signified by color value shifts within a separate color hue.

6. Texture describes the coarseness of the fill pattern within the map symbol. It was once common to modify texture in choropleth maps using halftone or dithering techniques in order to simulate the appearance of shading. Caivano gave a description in 1990 for texture as a higher-order visual dimension with three fundamental components: the directionality of the texture units (related to the visual variable orientation), the size of the texture units (related to the visual variable size), and the density of the texture units (approaching the perceptual effect of shading associated with the visual variable color value). Regarding the latter component, map symbols with a denser texture tend to rise to figure. Bertin’s set of visual variables was extended by Morrison (1974) to include two extra variables used in cartographic design.

7. Color saturation describes the spectral peakedness of the map symbol across the visible spectrum. Colors which are bold or saturated emit or reflect energy in a concentrated band of the visible spectrum, whilst colors that seem to be pastel or desaturated emit or reflect light equally over the visible spectrum. Color value may therefore be conceived of as the amount of black in a map symbol, whilst color saturation can be conceived of as the amount of grey in a map symbol. Map symbols that are bold and saturated tend to rise to the figure, whereas pastel and desaturated map symbols appear to recede to the ground.

8. Arrangement refers to the graphic marks layout comprising a map symbol. The visual variable arrangement varies from regular (i.e., graphic marks are perfectly aligned in a grid-like structure) to irregular (i.e., graphic marks are randomly placed or coalesce into clusters). Arrangement varies from visual variable texture in that all textures are supposed to be ordered in a regular pattern, regardless of the texture's original orientation, size, or density of the texture. Dot density maps differ in terms of both arrangement and texture density, a higher-order visual feature characterized by Nelsen as "numerousness" (2000).

Lastly, MacEachren (1995) defined three more visual characteristics that are simpler to manipulate thanks to digital production methods. In the context of uncertainty visualization, MacEachren (1992) first grouped these three visual variables under a single approach named "focus," but eventually recognized each component as a visual variable given the possible application to other types of cartographic representation.

9. Crispness describes how sharp the boundary of the map symbol is. Crispness also is referred to as “depth-of-field” and “fuzziness” in information visualization (Roth, 2017). MacEachren et al. (2012) came to the conclusion that crispness was the most efficacious visual variable for depicting uncertainty in the context of point symbolization.

10. Resolution describes the spatial precision at which the map symbol is displayed. The visual variable resolution is related to the concept of generalization in cartographic design, which discusses the meaningful reduction of information in map design when the complexity of the real world is abstracted to match the smaller size of the map. Rather than the conventional aim of generalization, resolution as a visual variable uses distinct degrees of abstraction to convey information. Resolution in a raster representation refers to the coarseness of the grid size whereas resolution in a vector representation refers to the level of detail (in terms of nodes and edges) in the linework (Roth, 2017).

11. Transparency describes the amount of graphic blending between a map symbol and the background or underlying map symbols. MacEachren (1992) made a reference to transparency as “fog” to propose a partially opaque barrier impacting the clarity of the underlying symbols of the map.

Each of these visual dimensions also can be manipulated as design embellishments to improve the aesthetic quality of the map or visualization. Understanding visual variables is critical for understanding how different forms of maps function and how symbol selection implies or does not indicate patterns, groups, order, and quantity. The right use of visual variables is critical for thematic data transmission and producing an effective and intelligible map (Ioseliani, 2021).

2.3.2 Cartographic Symbols

To make maps comprehensible for a particular usage situation symbols are used. Symbols are one of the most fundamental communication elements between the cartographer and the user. They are used in order to match the user's situation better and therefore help finding a link between the map and the current surrounding of the user (Nivala & Sarjakoski, 2005).

According to Buckley and Field, familiar, intuitive, or good explanations for symbols that are not familiar or intuitive (Buckley & Field, 2011) make a map understandable and give the reader or the user the opportunity to completely understand the illustrated information of the map without difficulties. Symbology of map's elements is of paramount significance and in order to be successful, the symbols that are selected to represent linear entities (e.g. contour lines, roads, rivers etc.), areas (e.g. type of land cover, lakes etc.) or points (e.g. points of interest) have to match the type of the data.

Data can be either qualitative or quantitative. Buckley and Field (2011) address that color hue (e.g., red, green, blue) and shape (e.g., points, lines) are the best choices when qualitative data have to be represented (Fig. 17) whereas for quantitative data, size or color lightness and/or saturation (i.e., the intensity of the hue) consist a much better choice for visualizing them (Fig. 18). They finally come to the conclusion that the eye perceives larger or darker symbols as more important (Buckley & Field, 2011), more critical and in greater amounts.

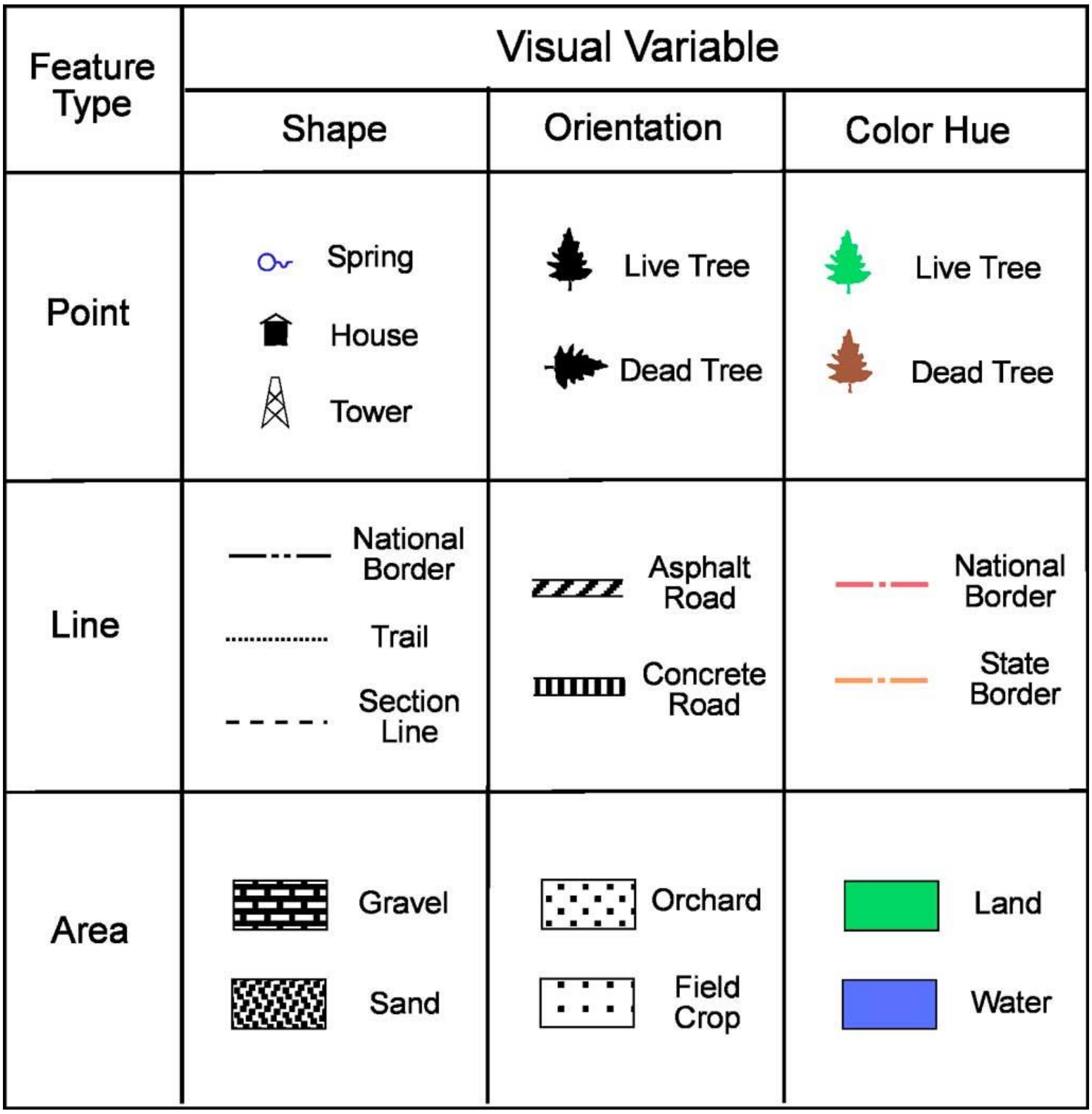


Figure 17: Color hue and shape, and to a lesser extent orientation, naturally evoke qualitative differences among features. (Buckley & Field, 2011)

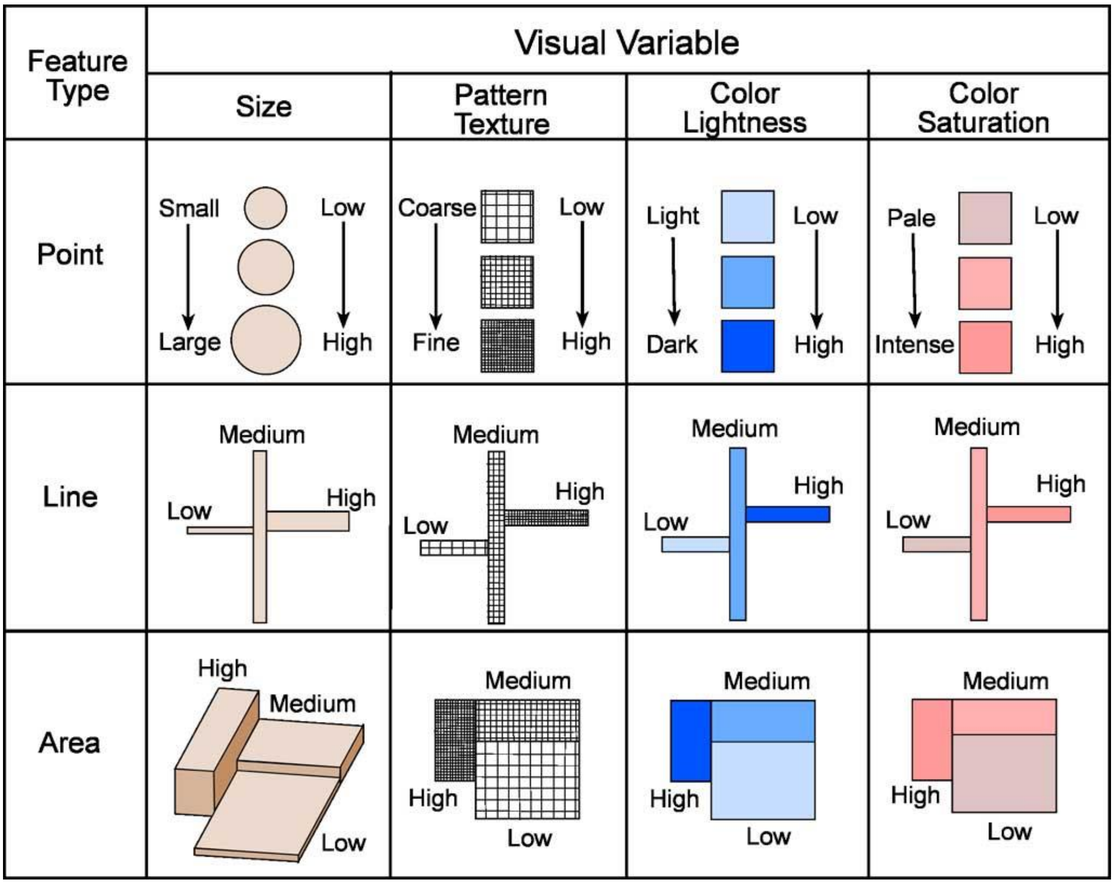


Figure 18: Shape and color value and/or saturation naturally evoke quantitative differences among features. (Buckley & Field, 2011)

2.3.3 Visual Hierarchy

The division of map layers into information planes is referred to as visual hierarchy and according to Kraak describes the order that map elements that are visually perceived (Kraak et al., 2021). Maps are not meant to be read from top to bottom like text, and strong cartographic design leads the focus to the most significant information on the map. The visual variables (see section 2.3.1) correspond to a symbol's visual weight to attribute data, with differences in each visual variable resulting in a data-driven visual hierarchy within the map (Buckley & Field, 2011).

This provides the foundation for differentiating traits and determining their relative value. In cartography and especially in the case of monochromatic maps, Extracting form from background has great significance, so that through the use of appropriate visual hierarchy the area units or symbols on the map are clearly distinguished from each other (Fig. 19) (Kraak & Ormeling, 1998).

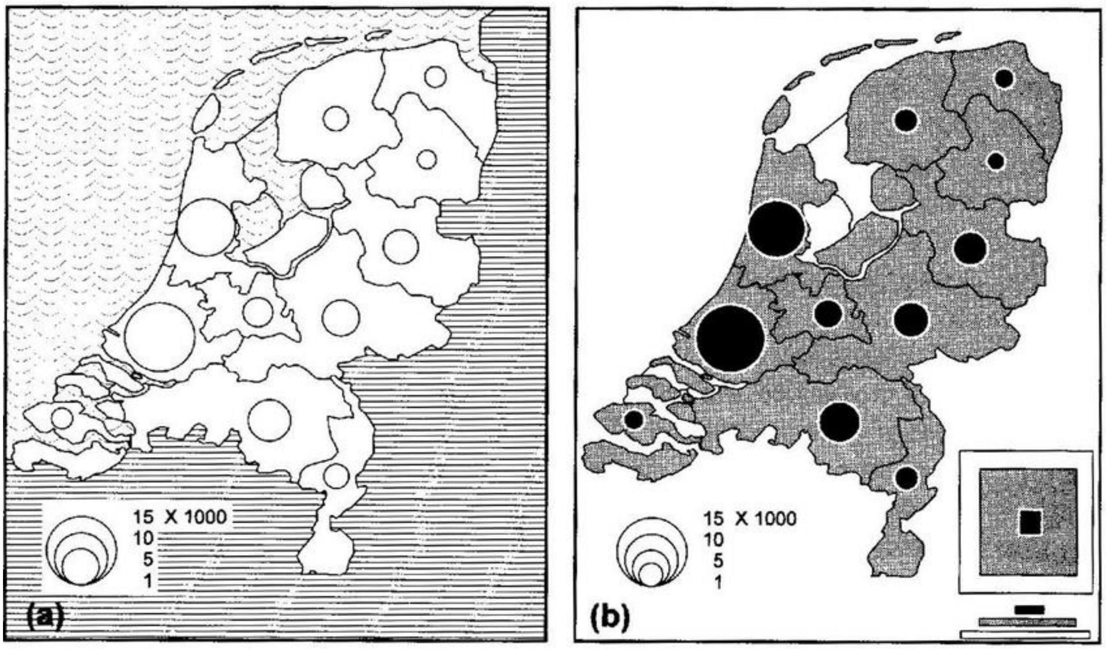


Figure 19: The use of symbols that stand out against the background improves the map's visual hierarchy (source M.-J. Kraak, F. Ormeling 1998)

In general, visual art of map making has to take into consideration visualization properties for an optimal visual result that makes a map easily readable and understandable. Creating or using the appropriate symbols and visual hierarchy can make a map attractive for users and provide them with information in very short amount of time. To conclude, one of the cartographer's duties when makes maps, is to attract users' eyes to the info that they need or needs to be emphasized.

3. Methodology

In this chapter, the methods of data collection, the data analysis and the proposed visualization are covered. The purpose of this session is to present thoroughly the means, the equipment, the software and ways we used to extract the results regarding the ways that a natural phenomenon that threatens forest ecosystems, can be visualized and illustrated in order to raise the awareness in experienced users, related to forestry, of a digital map. A workflow representation of the methodology can be found on Figure 20.

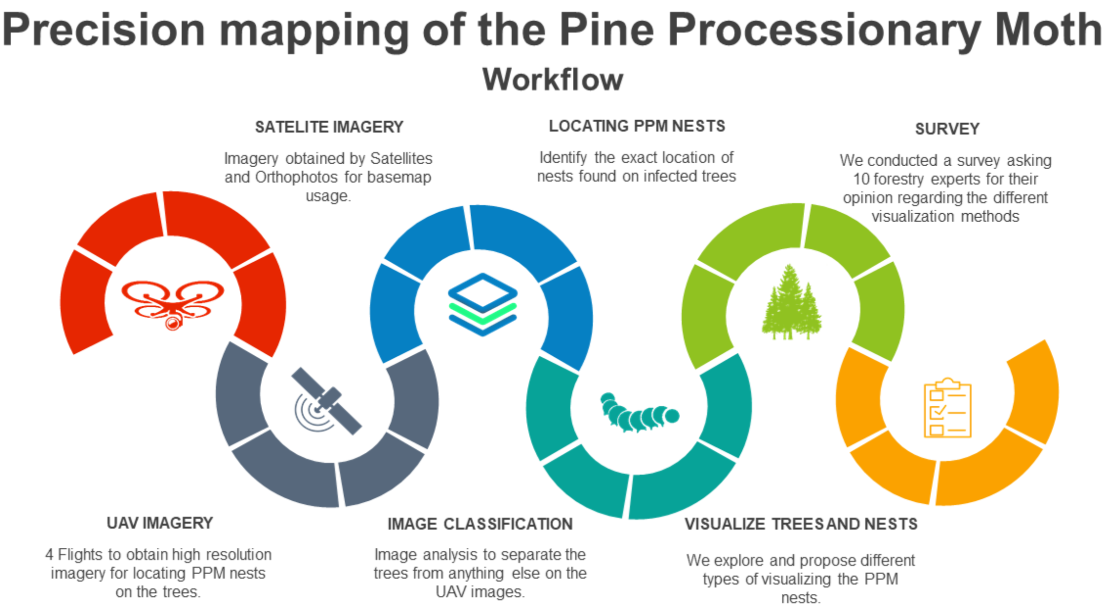


Figure 20: Overview workflow of the methodology

3.1 Study area

To collect data regarding the expansion of the PPM, we visited three areas covered by pine forests in the Autonomous Province of Bolzano. To be precise the coordinates of the cites we conducted the UAV flights were 46.644155°N 11.194233°E and approximately 700 meters of elevation. Two more cites were selected for ground observation and validation of the PPM presence. The coordinates of the two cites we chose for ground control are 46.350459°N 11.338367°E, and 46.502639°N 11.45758°E and around 1270 and 358 meters of elevation respectively (Fig. 21-23).

According to Tappeiner, the prevailing moderate, continental climate in South Tyrol the annual average temperature is of 12.4°C in Bolzano (266 m) (Tappeiner et al., 2020) with temperature differences of even up to 20°C between day and night (McLeod, 2021). Recent research (Bartkowiak et al., 2022) has shown that at level of single vegetation groups, temperature RMSE (Root-Mean-Square Error) values ranged from +1.84 °C in forest to +2.67 °C for permanent crops.

In general, seasons in South Tyrol are characterized by cool to cold winters and warm to hot summers with little precipitation (McLeod, 2021). The average annual precipitation is between 500 mm in Schlanders in the Vinschgau, northwest of Meran, and 1100 mm in the area between Passeier and Brenner. The maximum precipitation is reached during July and August (McLeod, 2021). In addition, South Tyrol has a high number of hours of sunshine (McLeod, 2021), creating favorable PPM expansion conditions even in higher altitudes that exceed 1000 m above sea level.

Figure 21: Study area. Autonomous Province of Bolzano marked in red polygon and cite locations in red dots. Base-map: Topographic by ESRI

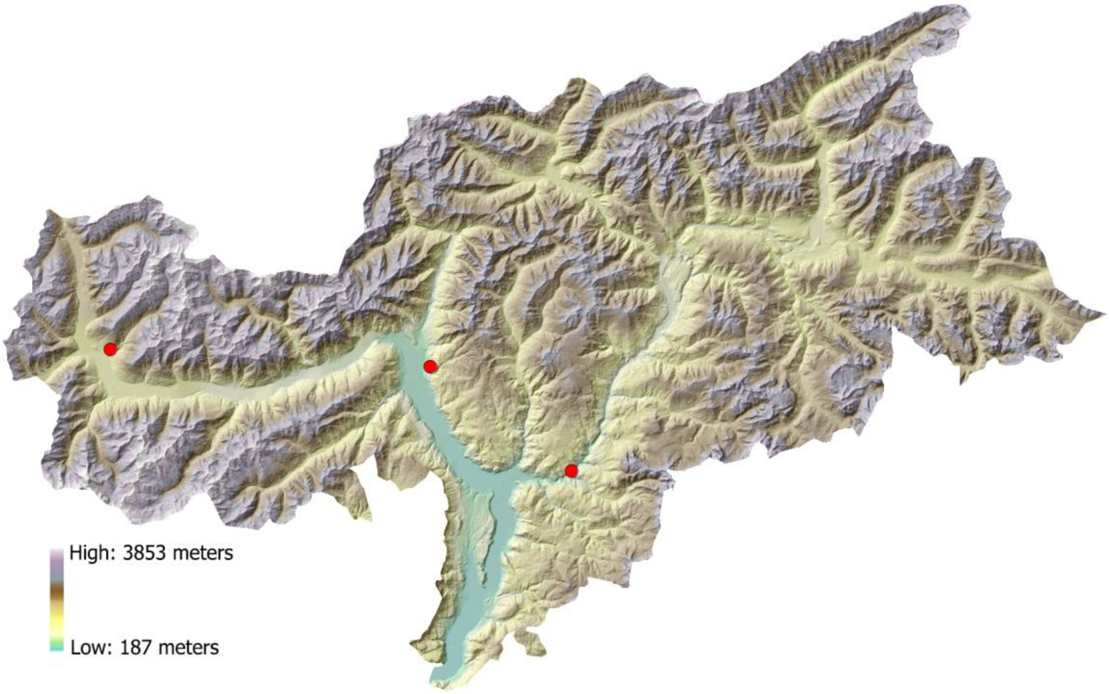


Figure 22: Observation cites (red dots). Terrain map generated by combining DEM and Hillshade effect for a better understanding of the area

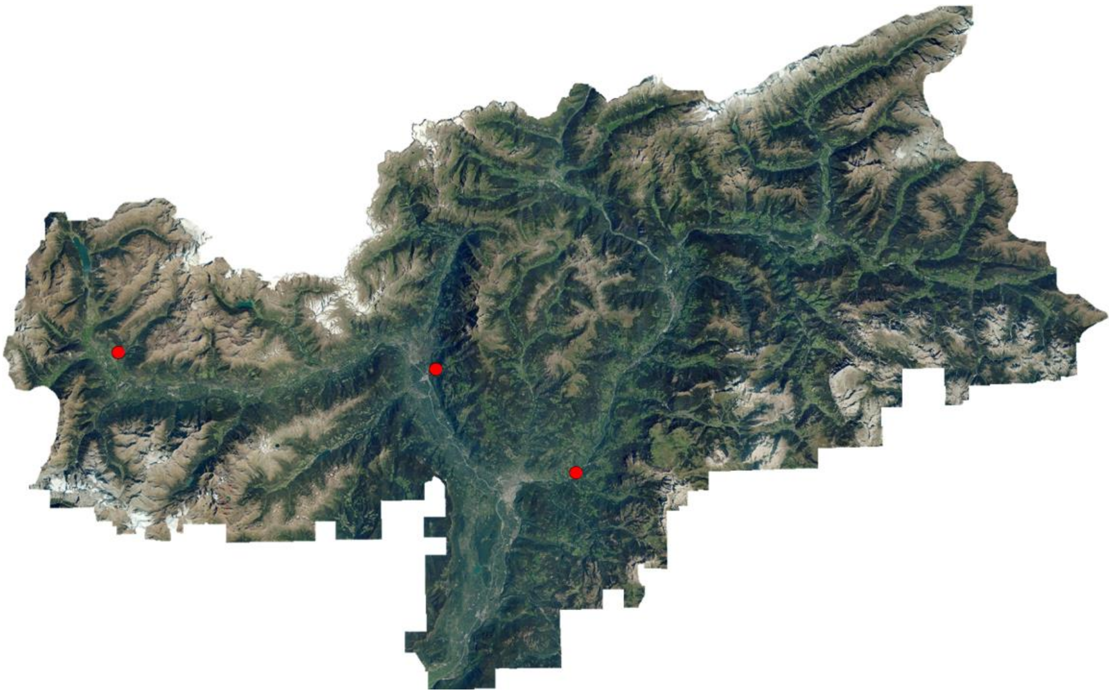


Figure 23: Airborne imagery of the Autonomous Province of Bolzano. Red dots indicate the study areas

3.2 Data collection

Data are the necessary elements of a research that through their analysis, patterns or relationships can be observed and results can be derived. Data are important because with the use of proper visualization, they can be interpreted and help us make decisions, exclude or confirm scenarios and hypotheses. On-site observations were required in order to justify the presence of the pest. Afterwards, a flight was conducted and aerial images were taken for further analysis.

3.2.1 Aerial Imagery

The data that we initially collected and used for this research were mainly highly resolution aerial imagery obtained with UAV and orthophoto maps by airborne photos.

We conducted afterwards a plethora of UAV flights in areas that the presence of the PPM seemed to be alarming. The flights were conducted in different periods of the year in order to have a holistic view of the different PPM's life stages and expansion of the PPM.

3.2.2 Forest agencies

Forest agencies are the public departments that it's their responsibility and their duty to monitor and combat pests that threaten the forest ecosystems. We firstly contacted the Forest Service of Autonomous Province of Bolzano to provide us with shapefiles and coordinates of areas that nests of the PPM can be located on the trees (Fig. 24). The personnel of the forest department, consists usually of technical and scientific staff. The goal of this research is to understand how trees and nests can be illustrated in a way that the user's eye can easily focus on the problem of a PPM population breakout.

People who work for forest agencies either as scientific or technical staff are the people who we are interested for as they are the ones that understand the ecosystem better than anyone else and they are the ones that have to wander and work inside the forest, make decisions and take measures in an optimal way based on their available equipment and resources. Constant contact is required for gathering information regarding specific environmental characteristics of an area. Another reason why constant communication is important is because they will share their opinions about the ways that we propose to visualize population breakouts.

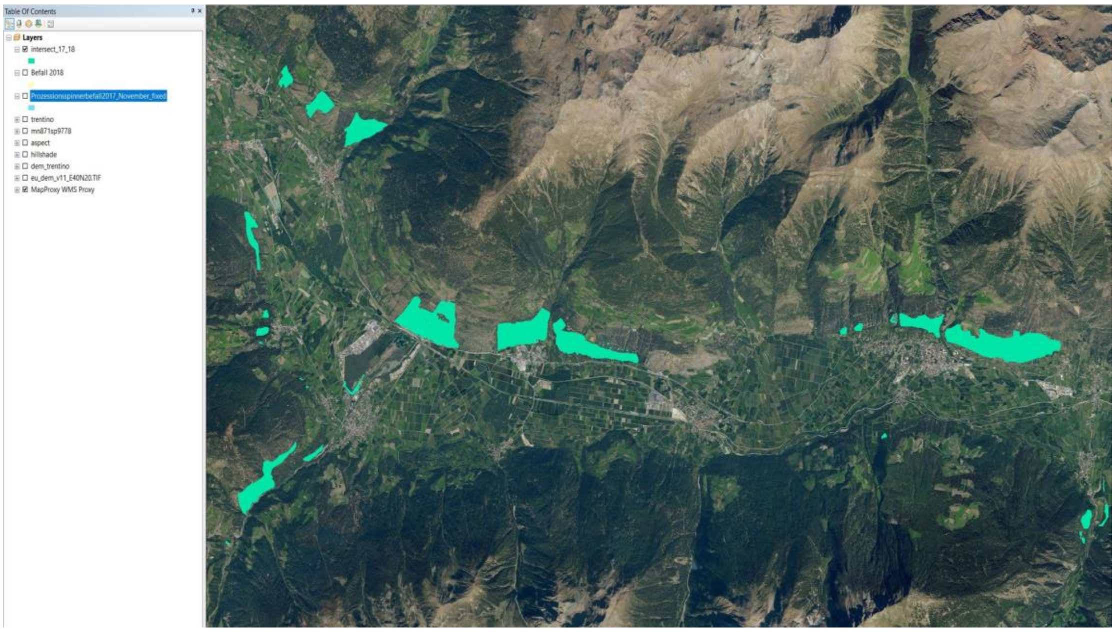


Figure 24: Shapefiles that indicate the presence of the PPM provided by the Forest Service of Autonomous Province of Bolzano

3.2.3 Unmanned Aerial Vehicles (UAVs)

The use of UAVs for this research is considered very important as imagery of high resolution can be acquired in a short amount of time, with low coast, easy handling and distant areas can be approached during a flight. Nowadays, UAVs have the ability to conduct longer flights and cover larger areas.

One more asset that UAVs can be equipped with multispectral and thermal cameras and/or lenses. That gives us the potential to further analyze the imagery and see beyond the visible wavelengths (e.g. near Infrared (NIR), infrared (IR) ultra violet (UV)). For collecting areal imagery we used a Soleon Octocopter UAV (Fig.25) and the lenses that it carries can be found on table 3.

Figure 25: Soleon Octacopter. Source: https://www.soleon.it

We acquired image datasets on December 2021 and June 2022. The flights took place at around 14:00 p.m. to reduce the shadow effect on images. A multispectral camera suitable for capturing the required for basic crop health indexes. MicaSense RedEdge-M was attached under the UAV and the technical characteristics of its imaging sensors can be found on Appendix B.

3.2.4 Airborne Imagery - Orthophotos and Raster Data

In order to assess a visualization method that will help forest workers to better explore forest and potential PPM threats on a map, airborne imagery and orthophoto maps are being used as a base-map.

3.2.4.1 Südtiroler Bürgernetz

Südtiroler Bürgernetz (Fig. 26) is a portal that provides users the ability to have access to spatial open data such related to land coverage, environmental characteristics like air temperature, precipitation, etc. for the district of South Tyrol. A WMS is also available and orthophotos can also be linked as a WMS to GIS software. Orthophoto provided by Südtiroler Bürgernetz is used as the primary background display for our research.

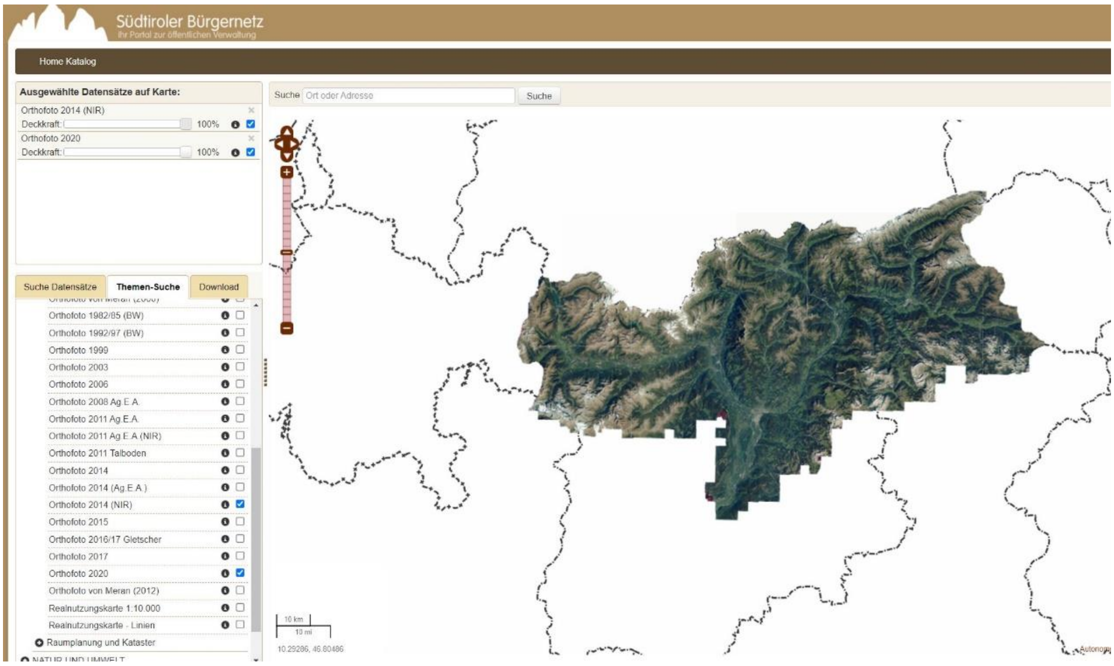


Figure 26: The interface of Südtiroler Bürgernetz

3.2.4.2 Copernicus

Copernicus (Fig. 27) is a European earth observation program that provides information services based on in-situ (non-space) data and satellite Earth observation. Data that can be offered by Copernicus can be Digital Elevation Models (DEM), or land cover raster files.

A DEM is a raster file that each pixel's value corresponds to the elevation at the specific area that a pixel is spatially describing and is a valuable dataset as further analysis can be succeeded by using it. In our case, we used DEM raster files to create aspect, hillshade raster files, and in order to extract values from the DEM to points that indicate the locations of the PPM nests.

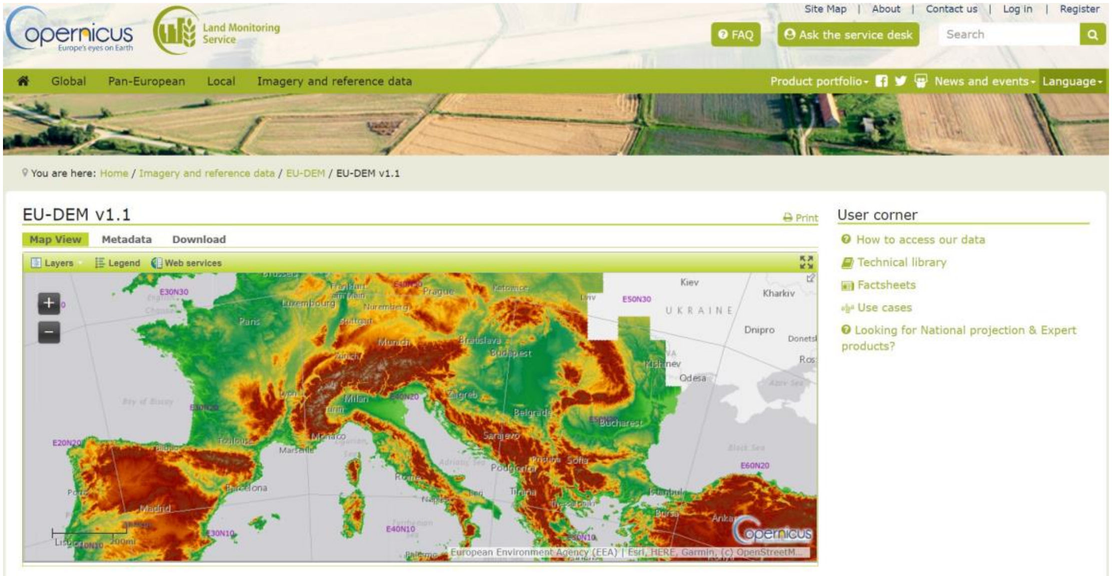


Figure 27: The search interface of Copernicus DEM data (Copernicus, 2022)

3.3 Image Processing for nest identification

Every aerial image that we acquired during a flight consists of different bands. The most useful bands in our case in order to locate white larvae on the trees was the bands that better describe the RED and the NIR values that occur from the reflectance the vegetation. With the use of these two multispectral bands we applied the Normalized Difference Vegetation Index (NDVI).

3.3.1 Semantic segmentation

The goal of semantic segmentation is to assign a categorical label to each pixel in an image that plays a significant role in understanding (Wang et al., 2018). In our case, semantic segmentation is to differentiate the pine trees of an area and access the presence of PPM nests on them. To succeed that, we applied semantic segmentation method by filtering the NDVI raster files that we produced by locating pixels with values greater than 0.7 that indicate healthy vegetation and the trees' canopy could be easily visually detected. A workflow of the process can be found in Figure 28.

NDVI for all the images, was calculated in ArcMap 10.4 by ESRI with the use of "Raster Calculator" tool.

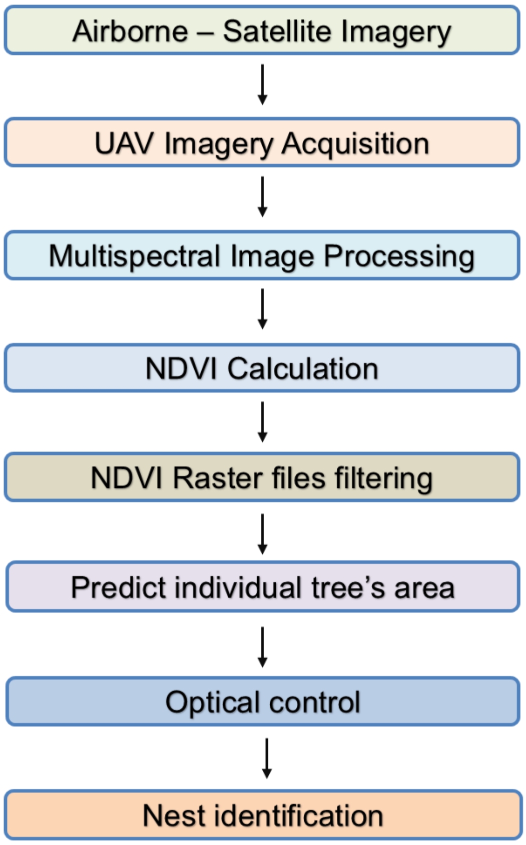


Figure 28: Workflow of the individual tree and PPM nests detection process

3.4 User study

After the completion of the digitization of the trees we designed a questionnaire where we propose visualization methods for a web map application. Ten experts with experience in forest mapping and protection participated and shared their opinions regarding the methods we propose to visualize population breakouts. Through their answers we were able to understand their preferences and insights for the web map application for forestry purposes.

4. Visualizing Decision-Relevant Map Layers to Support Forest Management and Protection against pest population breakouts.

In order to be able to evaluate the concepts and methods presented in the previous chapter, a prototype of different visualization styles for the trees and the nests were implemented and presented to experienced users. In this chapter the development and the design of the user study are described.

4.1 Visualization Implementation

Maps are the perfect tools to present natural phenomena. In our case study we want to establish a visualization pattern that can better express a natural phenomenon that threatens forests and need to be monitored.

In the science of forestry the question regarding “where and why” are often asked thus proper visualization of the available data can boost user’s ability to make faster and more efficient decisions.

4.1.1 Datasets

Our goal for this research was to visualize the PPM nests and the trees of two different areas. We made on-site visits to confirm the presence of the PPM and then evaluate the ecosystem’s condition based on the intensity of the presence of the PPM. We collected aerial imagery with the use of UAV and gave us the ability to precisely digitize trees and nests and integrate them afterwards in a GIS system for producing high precision maps.

Difficulties in data collection

However, collecting data can be challenging as weather conditions are not always suitable for field data collection. Wind and rain are two factors that need to pay attention before scheduling a flight or a visit for observation in the field. Other difficulties that we had to conform were the flight restriction above private properties. To overcome this problem, we chose not to conduct any flights nearby as taking permission from the authorities is a long time procedure and in most cases the requests are rejected for privacy protection reasons.

Digital Elevation Model (DEM)

In addition, as elevation and slope percentage plays an important role in forest management, we used a Digital Elevation Model of 25 m resolution obtained by the European Earth Observation Program named Copernicus. With the use of Digital Elevation Models (Fig. 29), we created different visualization styles that help the user to have a better understanding of the terrain (Fig. 30). In cases where map users are not familiar with an area's terrain, when just looking at an orthophoto map (Fig. 31) it might be confusing. The reason why this happens is because in some parts of the map it is not clear if the user is looking at a stream or ridge. Shadow effect or dark vegetation can confuse the user's eye. To mitigate this problem for our users, we produced a Hillshade layer and proposed the users to use it as a top layer but with a transparency of 60% (Fig. 32).

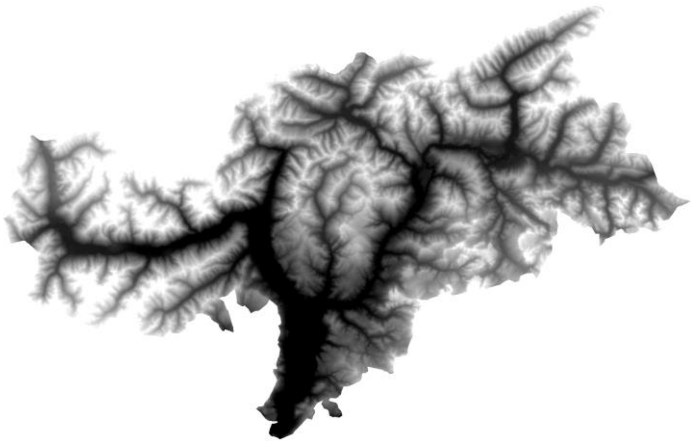


Figure 29: Digital Elevation Model obtained by Copernicus

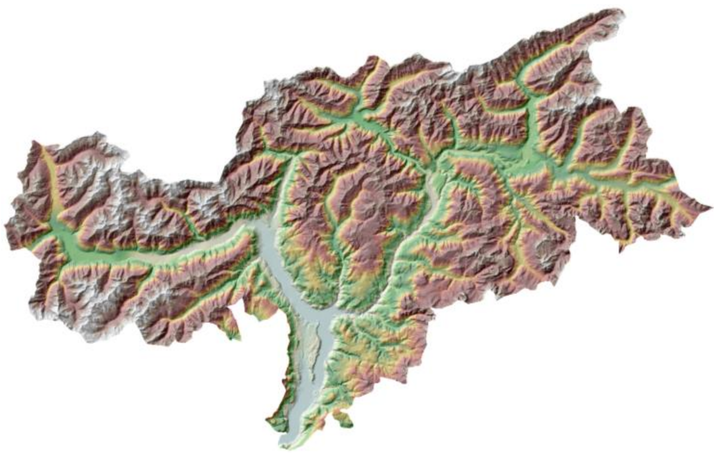


Figure 30: Digital Elevation model. Hillshade layer is on top with 60% transparency

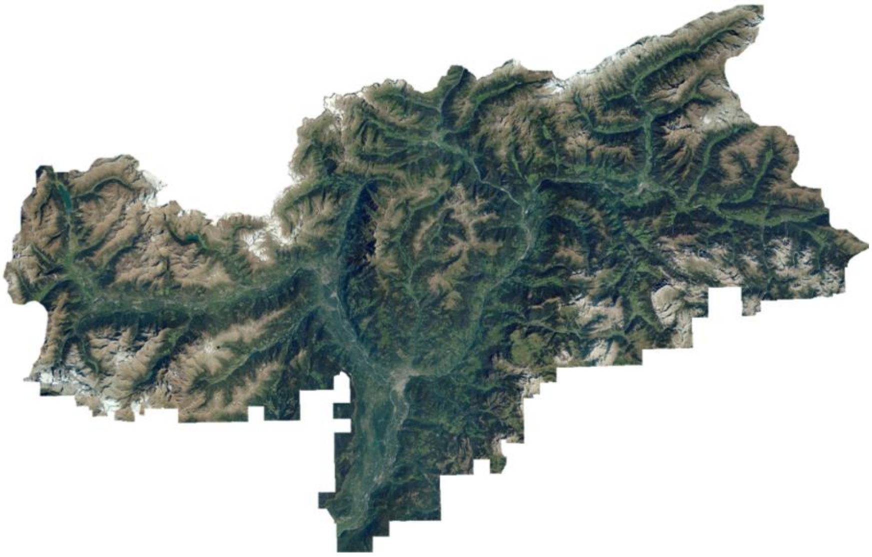


Figure 31: Orthophoto Basemap of the province of Bolzano. Streams and Ridges are not clear

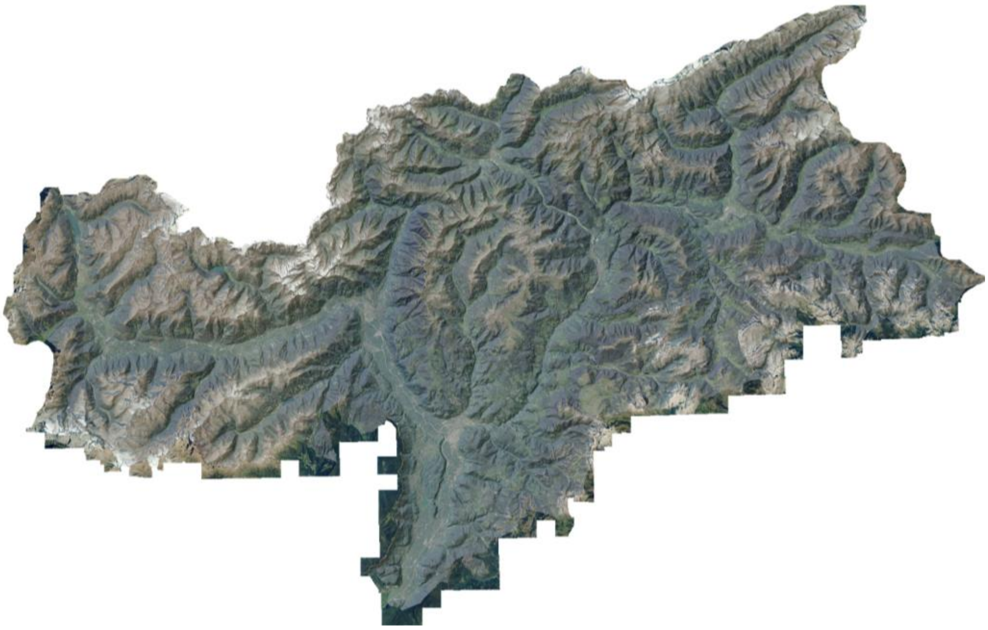


Figure 32: Orthophoto Basemap of the province of Bolzano. Hillshade layer is on top with a 60% transparency giving a better overview of the terrain

Province boundaries

As DEM files acquired by Copernicus are not provided in district level, we had to mask the file in the margin of the district of Bolzano. A shapefile for Italy’s districts was adopted from the European Environment Agency (EEA) as shown in Figure 33.

Figure 33: Dataset of Italy's districts used for masking raster files (European Environment Agency, 2022)

Forest Service

Another useful dataset to visualize for our research was the shapefiles that we adopted from the Forest Service of Autonomous Province of Bolzano. We were provided with polygon shapefiles that indicate the infested areas from years 2017 and 2018. However, in order to have a better understanding of the PPM expansion, we did some spatial analysis were we identified the areas that are in infested for both 2017 and 2018. Consequently we converted the intersected polygons into points and we applied some different visualization methods using pseudo-3D (Fig. 34) and 3D (Fig.35) illustrations of infested areas and asked users to share their impression about them.

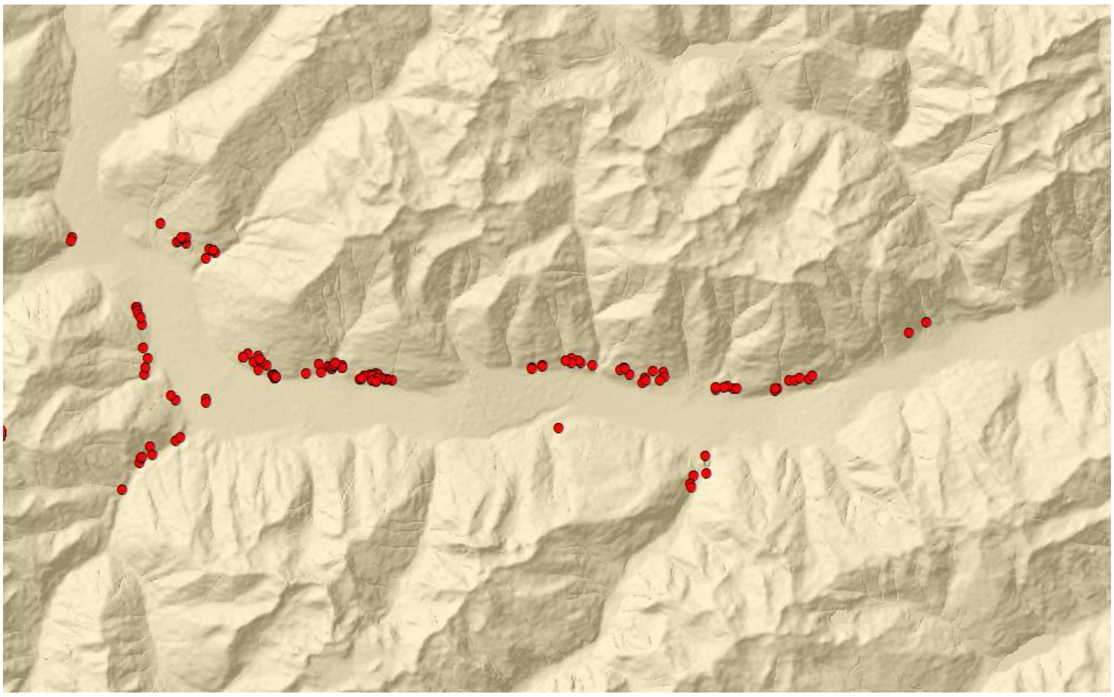


Figure 34: Shapefiles that indicate the presence of the PPM provided by the Forest Service of Autonomous Province of Bolzano. Hillshade generated by DEM is used as base-map to give the impression of a pseudo-3D representation to the user.

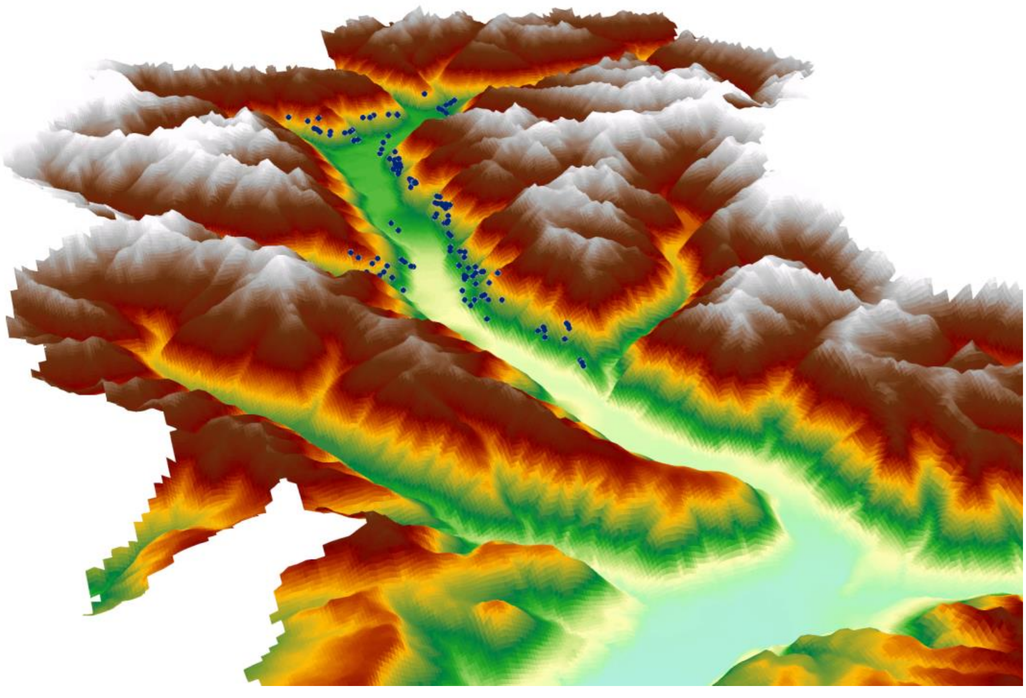


Figure 35: 3D Representation of the PPM presence based on shapefiles provided by the Forest Service of Autonomous Province of Bolzano. Generated in ArcScene by ESRI using a DEM adopted by Copernicus

UAV Imagery

We tested 63 different captures in multiple bands in total with the use of UAV at an altitude of approximately 40 meters above the ground and approximately 15-20 meters above the crown of the trees. Each capture consists of five bands (Red, Green, Blue, Near Infra-Red and Red Edge). To have a better view of each area that we captured, we had to firstly rectify and calibrate the images in order to become perfectly aligned and we continued with combining the three bands (Fig.36) in order to have an RGB image (Fig.37) for each area. In table 4, an example of all the bands of Micasense Red Edge [Table 4 (a-e)], and the result of the Red, Green and Blue band composition is presented [Table 4 (f)].

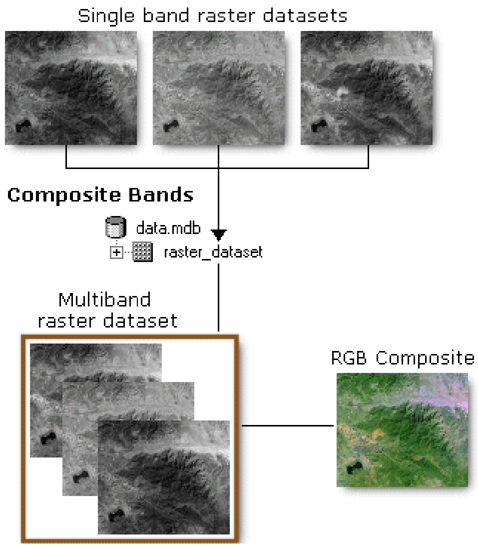


Figure 36: Band composition process. Source: ArcMAP by ESRI

Figure 37: Example of high resolution RGB image occured after RGB bands composition

a) BLUE 	b) GREEN 
c) RED 	d) NIR 
e) RED EDGE 	f) RGB 

Table 4: Area captured by 5 different Micasense bands (a-e) and combined (f) to produce high resolution RGB images

4.1.2 Creating the data to be visualized

Aerial imagery we acquired were used in order to produce high precision maps. As mentioned in previous chapters, for separating trees and nests on images, we used the NDVI index.

For this research we had to create spatial data (shapefiles) that show the boundaries of the canopy and the location of the nests. Spatial data give us the ability for further analysis by setting spatial or attribute queries. For instance, we can select the trees that have nests on them. In Figure 38, an area where the PPM is present shown. In Figure 39, the NDVI calculation result is presented and in Figure 40 the canopy's boundaries are digitized after filtering the NDVI layer.

Figure 38: RGB Aerial Image from which we extracted trees and nest in order to create spatial data for analysis and visualization

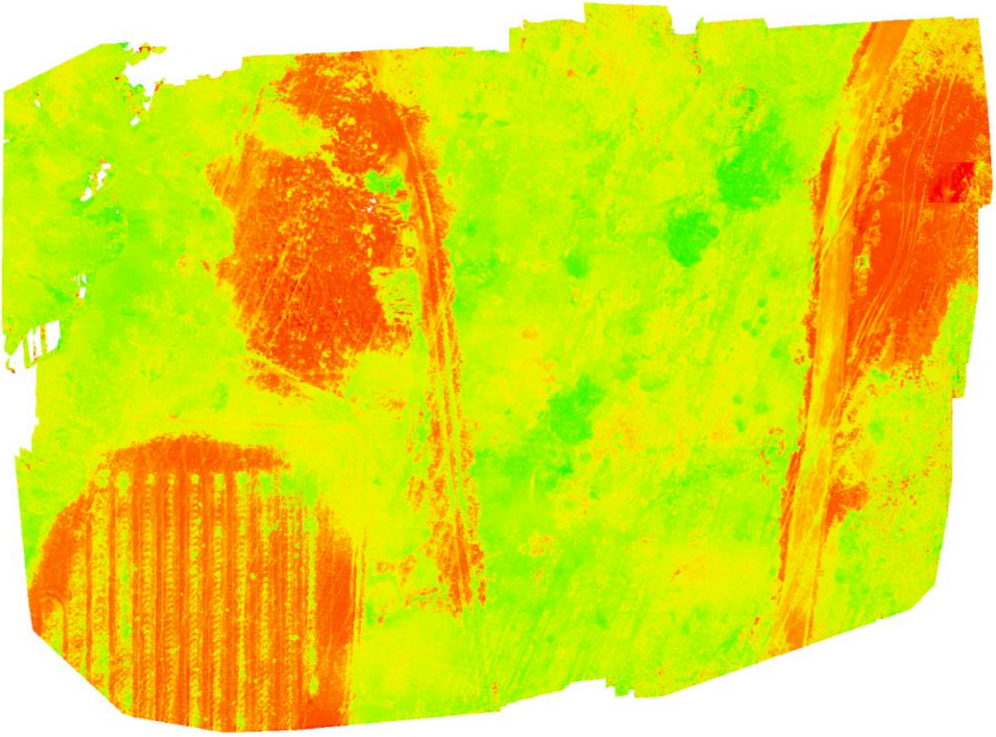


Figure 39: Raster file we produced by applying the NDVI Index to identify vegetation's health

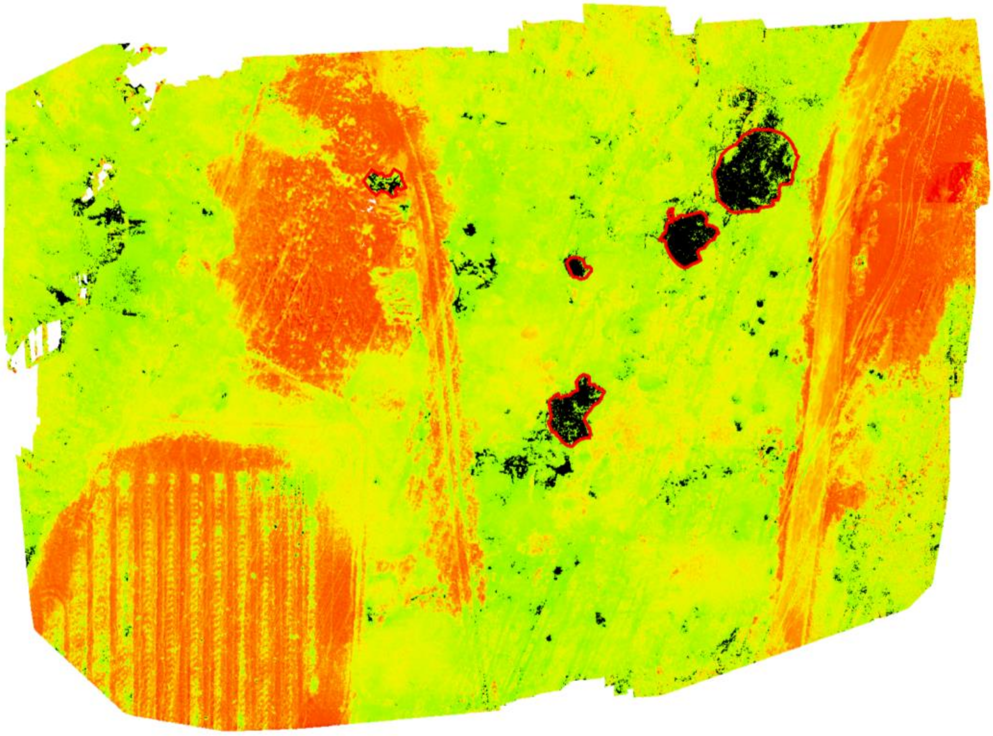


Figure 40: NDVI Raster file. Black areas indicate high values of the NDVI Index that interpreted as healthy vegetation

4.2 Visualization Methods Testing

For this research, after creating the necessary data for PPM monitoring in two areas out of three that we visited, we compared different visualization methods of the same data and asked users to evaluate them and share their experience and their opinion about each method and style.

4.2.1 Choropleth maps

Choropleth maps are ideal to present areas with different characteristics and differentiate them by using different color or color hue intensity. We used this visualization style to illustrate trees' health condition and we tested different color schemas to understand which color represents in a better way healthy and unhealthy vegetation.

Our goal was to understand which color schema has the ability to better fit vegetation's condition regarding its health and which color represents critical areas that need to be prioritized in forest management actions due to high presence of the PPM. Our proposed visualization methods was based on two different scenarios:

- Visualize the degree of the infestation by using multiple colors (Fig.41).
- Visualize trees as binary regarding the infestation by PPM with the use of two basic colors (Infested as green – Not Infested as red) (Fig. 42).

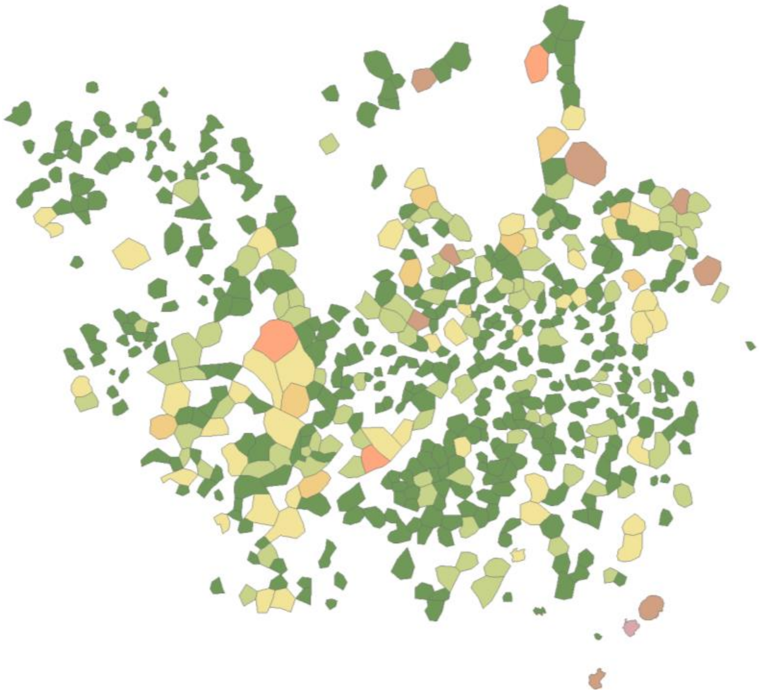


Figure 41: Choropleth map that visualizes trees. Different color indicates different degree of infestation

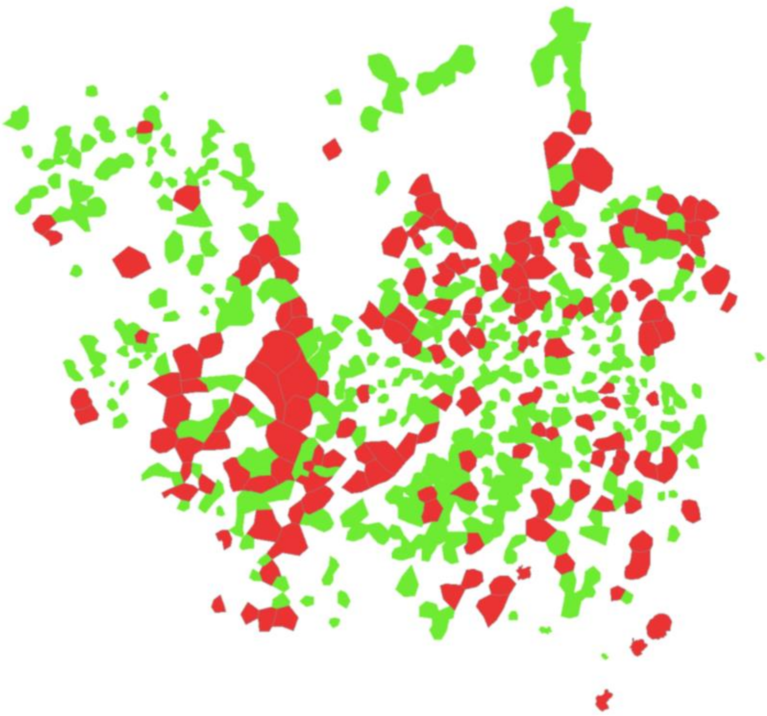


Figure 42: "Binary" visualization of trees. Red represent infested trees whereas green polygons represent non infested trees. The degree of the damage is not presented in that style

4.2.2 Dot Density Maps

PPM nests were visualized as points and more specifically as red dots (Fig. 43). Dot density maps are ideal for representing quantities and are suitable for non-classified data. What is of great significance when visualizing PPM nests is the exact location of every single nest.

By visualizing nests as dots gives the user the potential to separate areas with greater density of the dots. Areas that have a greater density in our case study, represent regions where the presence of the PPM on the trees is increased meaning that the ecosystem’s health condition is critical.

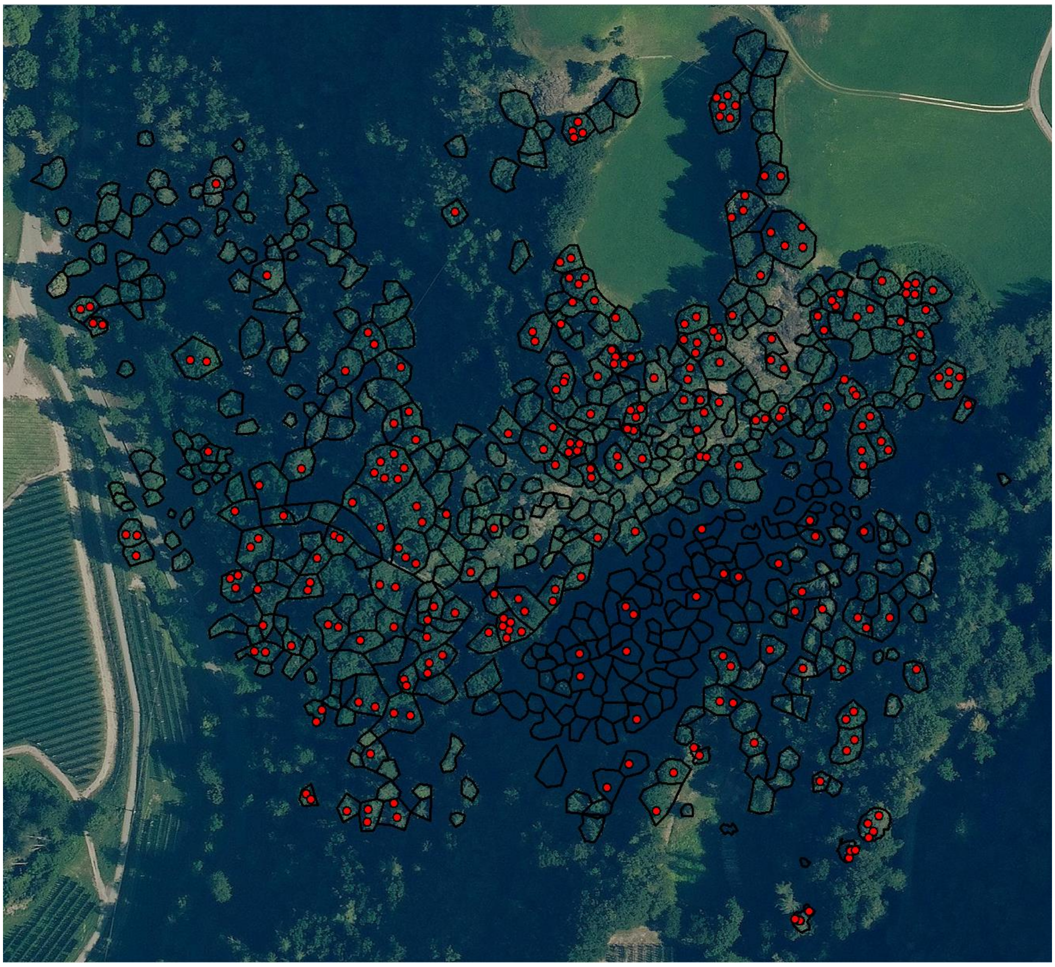


Figure 43: Dot density map. Red dots indicate the presence of a single nest on a tree. Black polygons indicate trees

4.2.3 Graduated symbol maps

The size of symbols is proportionally scaled to the quantity or value at that location on graduated symbol maps (GISGeography, 2018). In our case, each tree that we digitized, had the attribute of the number of the nests on it. That gave us the ability to visualize the nests as a graduated dot according to the number of the nests on the tree. The exact position of the symbol (red dots) on the map was the centroid of each tree polygon meaning that the more the nests on a tree, the greater the shape of the symbol (Fig. 44). The centroid of each polygon is assigned by default by ArcMap.

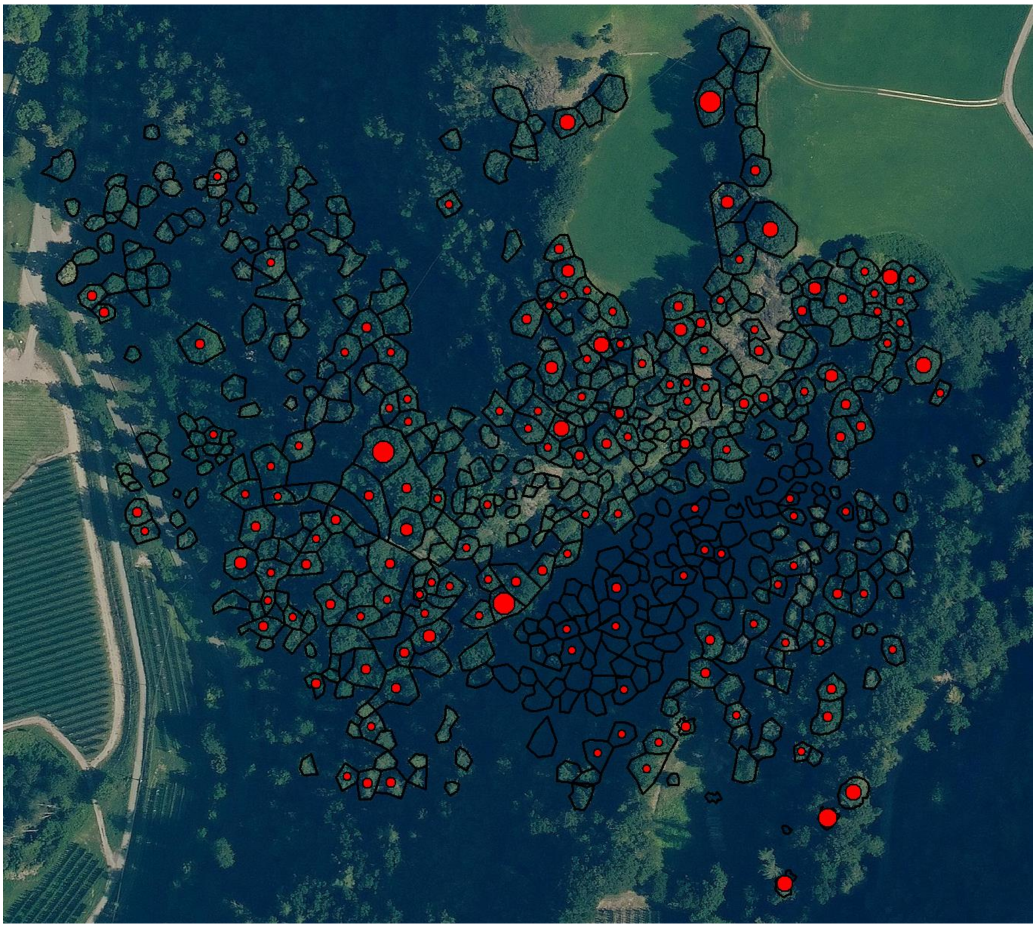


Figure 44: Graduated symbol map. The greater the size of a dot, the greater the number of PPM nests on the tree. Dots' position on the map is the same as the centroid of the tree polygons

4.3 Visualization Methods Evaluation

The user study sought to gain opinions and insights into the proposed design and visualization for a potential web mapping application that will support a decision making system in forestry.

The format we chose to conduct our survey was questionnaire based on static screenshots of the proposed visualization methods. Afterwards a face to face interview was conducted with the participants in order to give them the ability to test the visualization styles on a computer screen on site with the use of ArcMap and ArcScene. Users were asked to freely express their opinion, their thoughts and questions while testing the different styles on the computer. Last but not least, users had the chance to experiment different color schemas that were not presented on the questionnaire.

The questionnaire (see Appendix A) contains qualitative questions. For some of the questions we asked the users in the form of comment box where they were able to freely write their comments. Other types of questions were the multiple-choice questions were the users were allowed to select one response among other choices given on a list. In addition, we asked through single select matrix questions the users to select only one option for each row and we used the same set of column answer choices. Furthermore, rank order scaling question were used in order to better understand the user's preferences among the options that we proposed.

The main purpose of the questionnaire and the interview that we conducted, was to understand how users perceive colors, transparency, crispiness and other visual variable when PPM expansion is illustrated on a web map environment. Setting visualization standards is considered to be helpful for users of different age groups with different experiences in the domain of forest management and protection.

Despite the fact that the target group was expected to be only professional forest scientists and workers we expect that also people without any experience in spatial data visualization will be able to interpret what they see on a map.

4.3.1 Structure of the User Study

Users participating in the study were offered to fill a questionnaire that received via email consisting of introduction, and four main sections: (1). Participants Overview; (2). Tree visualization; (3). PPM nest visualization; (4). Representation of Nests and Trees in 3D Environment. Table 5 outlines the survey's sections and their purpose. In Appendix A, a full outline of the survey's structure can be found.

Introduction
The purpose of the survey is explained.
1. General Questions
Knowing the gender, the age and the experience of the participants related to forest mapping, and spatial data visualization.
2. Tree Visualization
Different styles of tree canopy are presented to understand how users perceive and interpret different colors.
3. PPM Nest Visualization
Different styles of nests are presented to understand how users perceive and interpret different symbol size.
4. Representation of Nests and Trees in 3D Environment
Users were asked to evaluate 3D models that indicate PPM nest locations and judge the value of the models in monitoring PPM

Table 5: Survey sections and their purpose

4.3.2 Pre-Test

We conducted a pre-test of the questionnaire with five participants. All of the participants were experienced forest scientists with many years of experience in forest mapping. We asked them verbally basic questions that referred to the styles that they would use to digitize trees and nests.

After conducting the pre-test, we had a better view of what users need to see when their duty is to manage and protect forest under an imminent threat. We also managed to make decision regarding the styles that we would propose to for visualizing PPM related data and adjustments to the styles and symbols were applied before we distribute the final questionnaire.

5. RESULTS AND DISCUSSION

This chapter discusses the findings of our observations while exploring imagery data for PPM nests identification and the findings of the user survey that we conducted in detail. This chapter consists of two subsections which are Image Processing for PPM Nest Identification (section 5.1), and User Study (subsection 5.2). In the first subsection (5.1) our finding regarding the image analysis and processing for pest identification are presented. The last section 5.2 discusses the findings of our survey.

5.1 Image Processing for PPM Nest Identification

By the term Image processing we refer to methods used in order to perform some operations on an image. The result of those processes are aiming to get an enhanced image or to extract information from it.

For our research we processed and analyzed 321 different images of five different bands that we captured with the Micasense multispectral camera during our flight with the UAV (see Appendix B for camera's technical specifications). Our purpose was to explore different bands of the Micasense camera that we used in order to understand the characteristics of each band regarding the visual representation of a forest that is infested by the PPM and come to the conclusion about which bands are more appropriate for locating trees and more precisely, PPM nests on them. Supervised classification was used to identify PPM nests on pine trees. Training data had to be assigned for five different classes (Fig. 45). The five classes we used were:

- Pine trees
- Deciduous trees
- Bushes
- PPM Nests
- Dead pine trees
- Dead Biomass

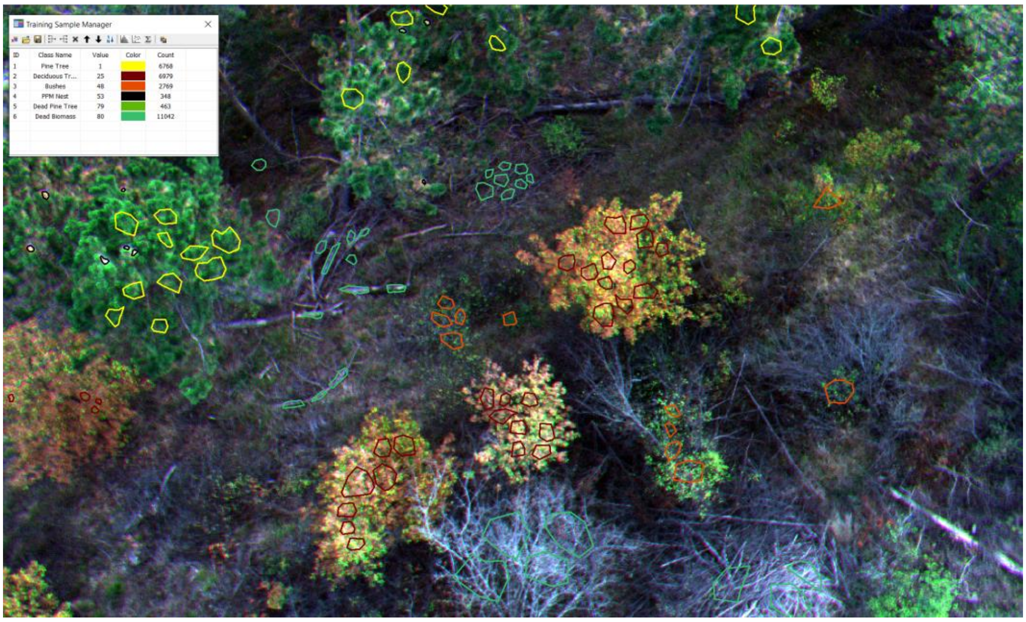


Figure 45: Training samples for supervised classification with the use of "Image classification" toolbar in ArcMap

After training the algorithm in ArcMap, the spectral signature file was exported for each RGB image and then used for classifying the entire image. In Figure 46, an example of the result of supervised classification is presented. Only the PPM nests class is shown in black color. The next step was to convert the results of supervised classification into shapefiles that indicate the PPM nests location and the boundaries of the trees (Fig. 47).

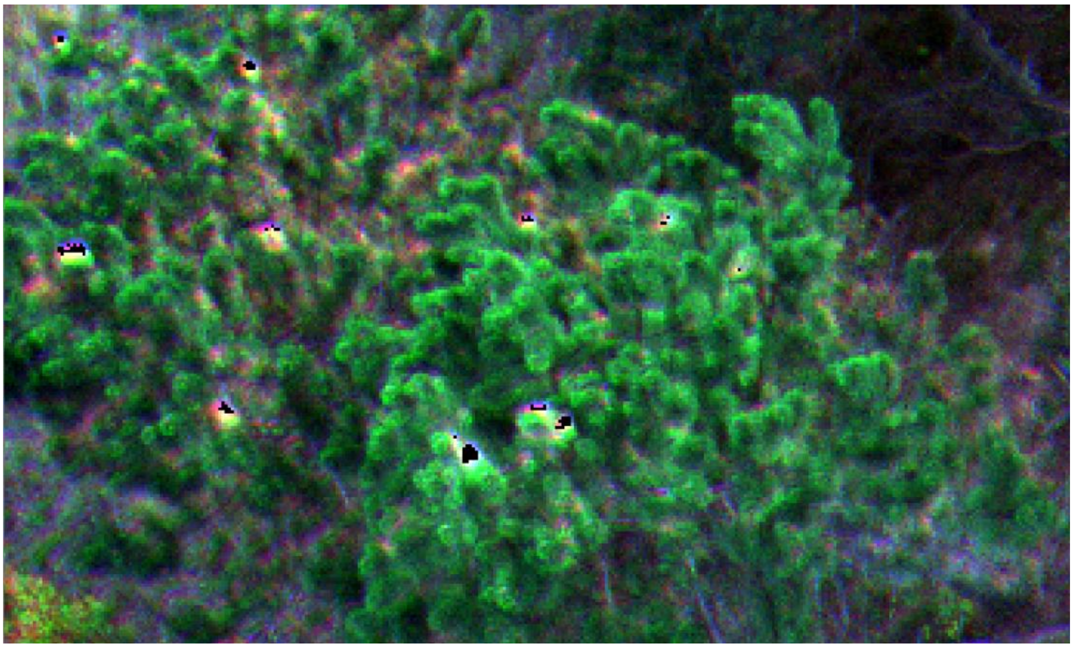


Figure 46: Result of supervised classification showing only the PPM nest class marked in black color

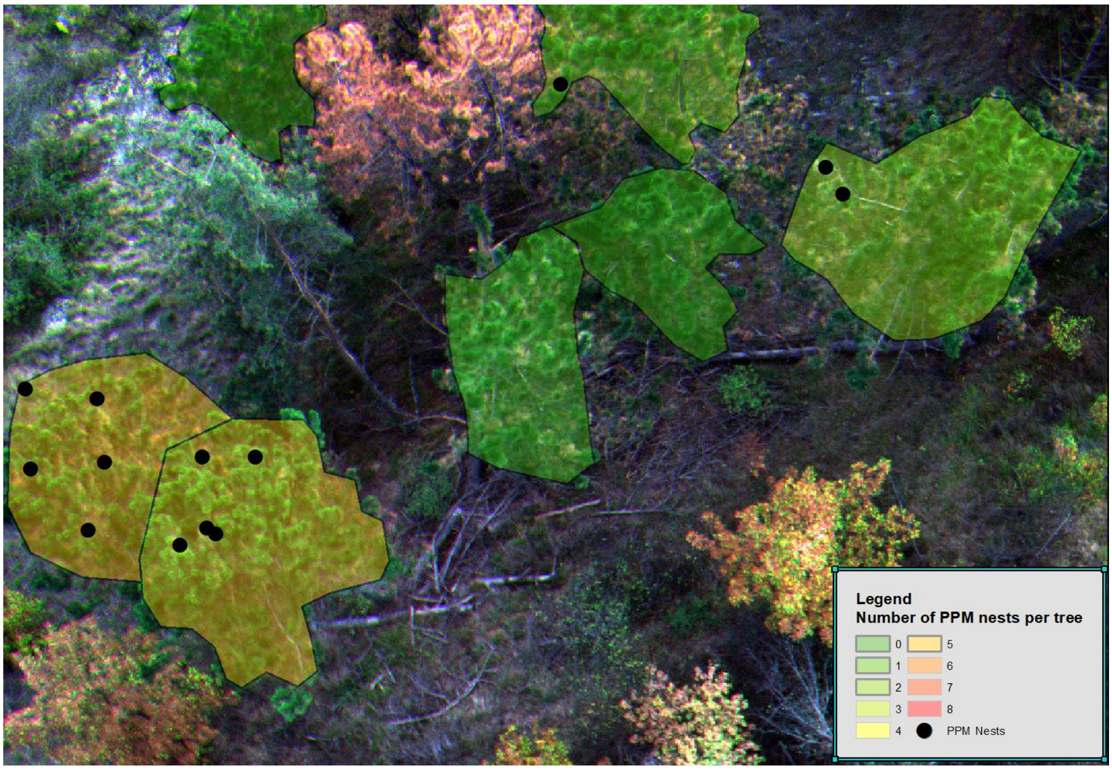


Figure 47: PPM Nests and Canopy's boundaries digitized

Band 1 – Blue – 475 nm

We realized that Band 1 is quite proper band for locating PPM nests as pine trees are shown as darker areas on the image compared to the nests whereas the latter are bright and can be easily spotted due to the slight contrast among tree and nest pixels (Fig. 48). In our case, snow could be found in some spots on the images and when it was on the tree, it made the process of identifying PPM nests quite confusing.

We had to examine and process other bands to understand if the white areas that could potentially be nests were either snow, or a nest. Additionally, blue band, visualized bare soil pretty well and separates it from the forest. Rocks, path trails and road network in the woods are clearly visible.

Figure 48: Blue Band Image obtained with Micasense camera. PPM Nests are visible on the left part of the image

Band 2 – Green – 560 nm

In Band 2 of the Micasense camera, pine trees are easily distinguishable as they are brighter compared to the rest of the forest. This occurs due to the fact that other trees are deciduous and have no leaves during the winter. As a result they reflect green color less than coniferous trees like pines that have green needles during the whole year and that is the reason why deciduous trees are darker in this band (Fig. 49).

As nest are white colored and are located on pine trees that tend to have green needles on their branches, both the tree and the nests are having high values in this band and are shown as bright pixels. As a result, distinguishing PPM nests on the trees is quite difficult with the use of band 2.

Figure 49: Green Band Image obtained with Micasense camera. PPM Nests are hard to be spotted on the left part of the image

Band 3 – Red – 668 nm

Vegetation in red band pops and has a vibrant representation on the image (Fig. 50). Healthy green colored vegetation is darker than unhealthy vegetation due to the presence of chlorophyll (green color) on the leaves. PPM nests can be easily spotted in this band as they are appeared with great contrast when located in green areas that are represented as low valued pixels in this band (Fig. 51).

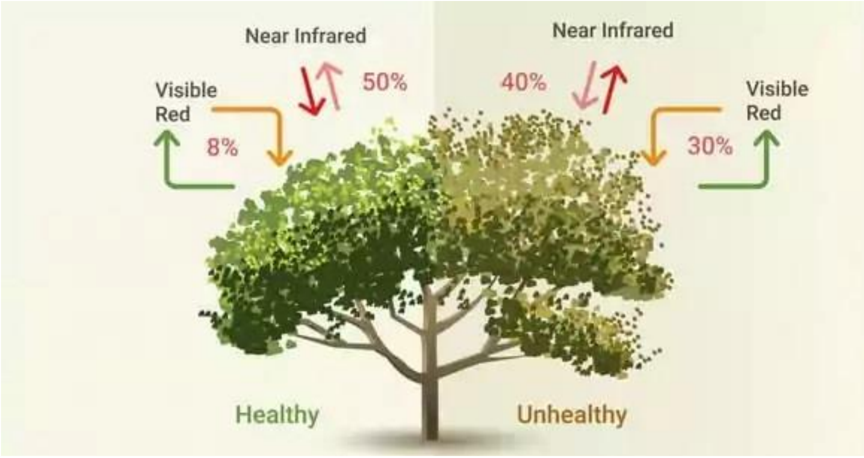


Figure 50: Red and NIR reflectance on healthy and unhealthy vegetation (Bade, 2020)

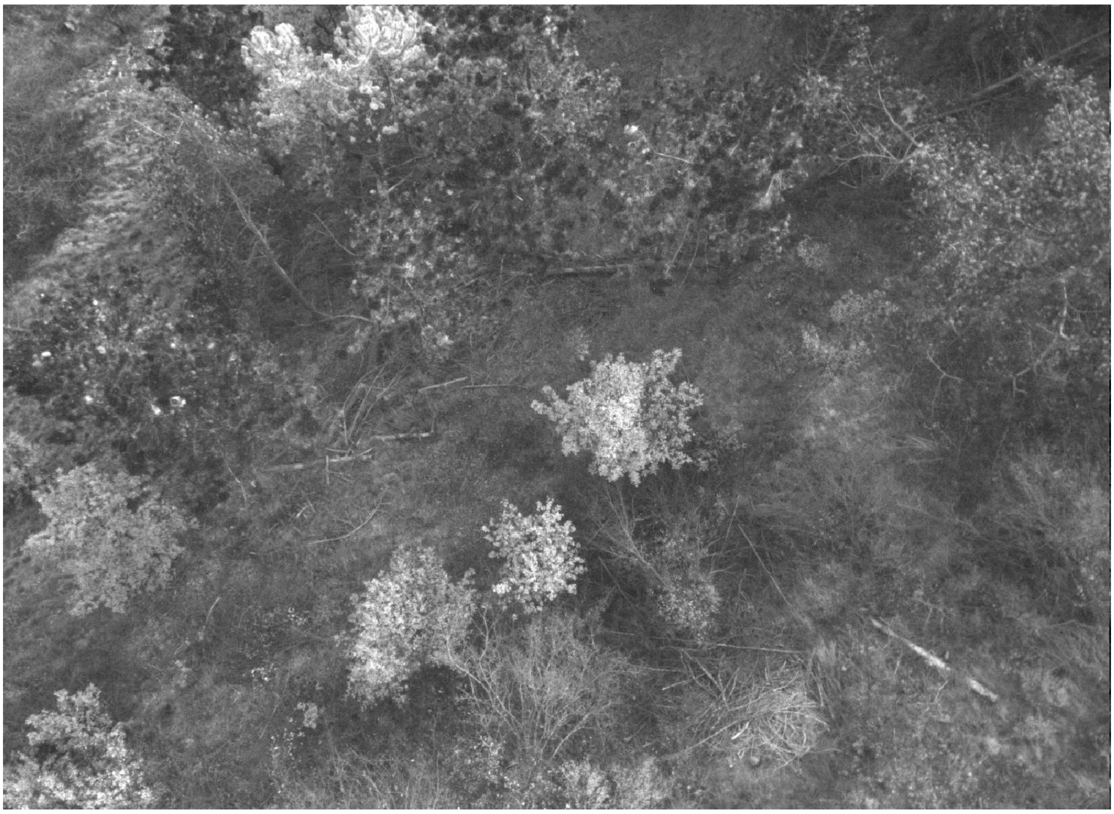


Figure 51: Red Band Image obtained with Micasense camera. PPM Nests can be easily be spotted on the left part of the image

Band 4 – Near Infra-Red – 840 nm

Plants that have more chlorophyll tend to reflect more near-infrared energy than unhealthy plants (NASA, 2012) or plants that have brown leaves during autumn. Pine trees in our case seem to be in a good condition regarding their leaves and as a result they are having very high pixel values making the nest identification impossible. Nests are always represented as bright pixels because their natural color is white. As they are found among healthy vegetation, there is no contrast between the nests and the trees making their identification almost impossible with the use of the NIR band (Fig. 52).

Figure 52: NIR Band Image obtained with Micasence camera. PPM Nests cannot be seen due to lack of contrast between the trees and the nests

Band 5 – Red Edge – 717 nm

Similarly to the Red band, high chlorophyll increases absorption in the red region. In some of the images of our dataset we replaced the red band with the red edge band for calculating the NDVI. **The result was that there was a better separation of the bare soil and the vegetation compared to the calculation with red band**. Although, spotting PPM nests on healthy trees is quite difficult as both the nests and the trees are high valued pixels with reduced contrast.

Band Composition – RGB

Viewing images of the ecosystem in multicolor images is quite helpful when interpreting imagery datasets. Natural colors of the environment that we are examining lead to easier and faster interpretation in most scenarios and cases. In cases where we cannot describe what we see with certainty, RGB images can make it possible (e.g. snow and PPM nests that are both white colored).

In table 6, an evaluation of each band based on our analysis, regarding the visual locating process of PPM nests is provided.

	BAD	AVERAGE	GOOD
BLUE			X
GREEN		X	
RED			X
NIR	X		
RED EDGE	X		
RGB			X

Table 6: Micasense band appropriateness for PPM Nest detection

5.2 User Study

The user study we contacted ran for three days in November 2022. During these three days, 10 forestry experts in forest mapping participated in the user study and provided us valuable feedback, which was considered in the analysis. In the following pages, the results will be explained and discussed based on the four sections of the questionnaire.

5.2.1 Overview of the participants

Out of the 10 responses, 5 identified as male, and 5 as female (Fig. 53). The gender distribution was even and that proportionately to the study. This is beneficial since the participants had to share with us opinions about colors and it is an undisputed fact that men and women may experience color perception differently.

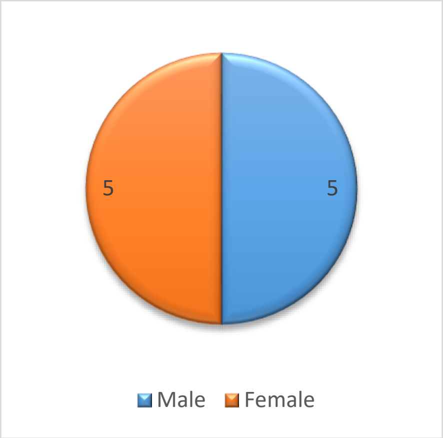


Figure 53: Gender of participants

The dominant age group of participants was 40-49 years old. Fewer users were in the age group of 30-39 and all of the participants were above 18 years old. Figure 54 provides insights into the distribution age among the users who participated in the survey.

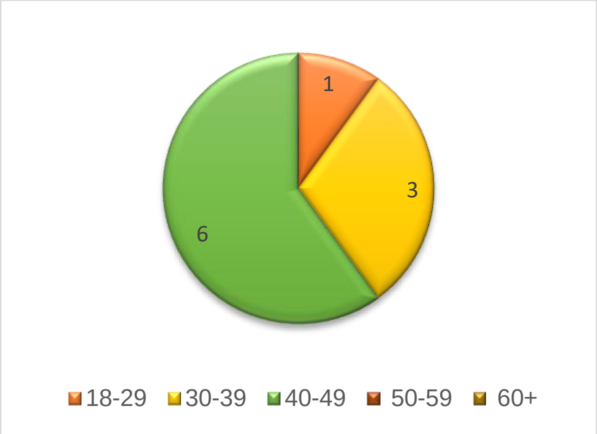


Figure 54: Age of participants

The majority of the people who participated are quite experienced scientists in the domains of forestry (Fig. 55), mapping, spatial data manipulation and visualization. In general, the people who were asked about their experience are quite confident users of GIS software, have a strong background in forest mapping and they support the opinion that their eyes our quite trained to detect patterns when viewing maps (Fig. 56).

Not all the scientists that answered to our questions are specialized in Pest Monitoring. Only one of the users replied that has no experience at all with pest control, management and protection whereas one more user shared with us that although she has some experience in that domain of pest identification and control she would not characterize herself as an expert in that domain.

Half of the participants have an experience in forest mapping that exceed a period of ten years and that gives an advantage to our research as they are sharing with us valuable knowledge regarding crisis monitoring and visualization of forest ecosystems.

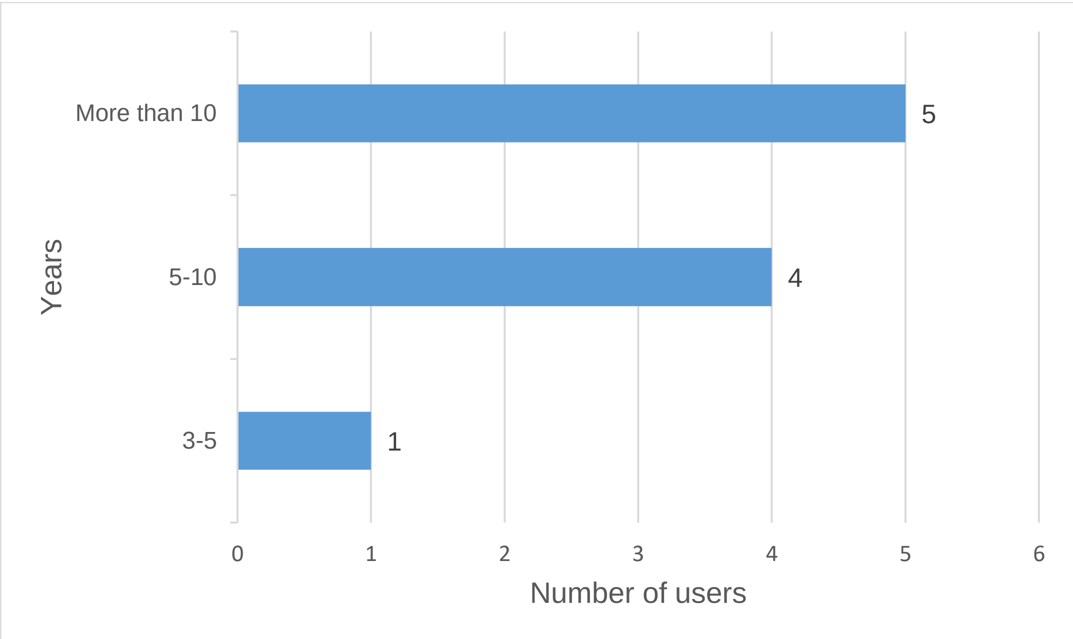


Figure 55: Participants' experience in forestry domain

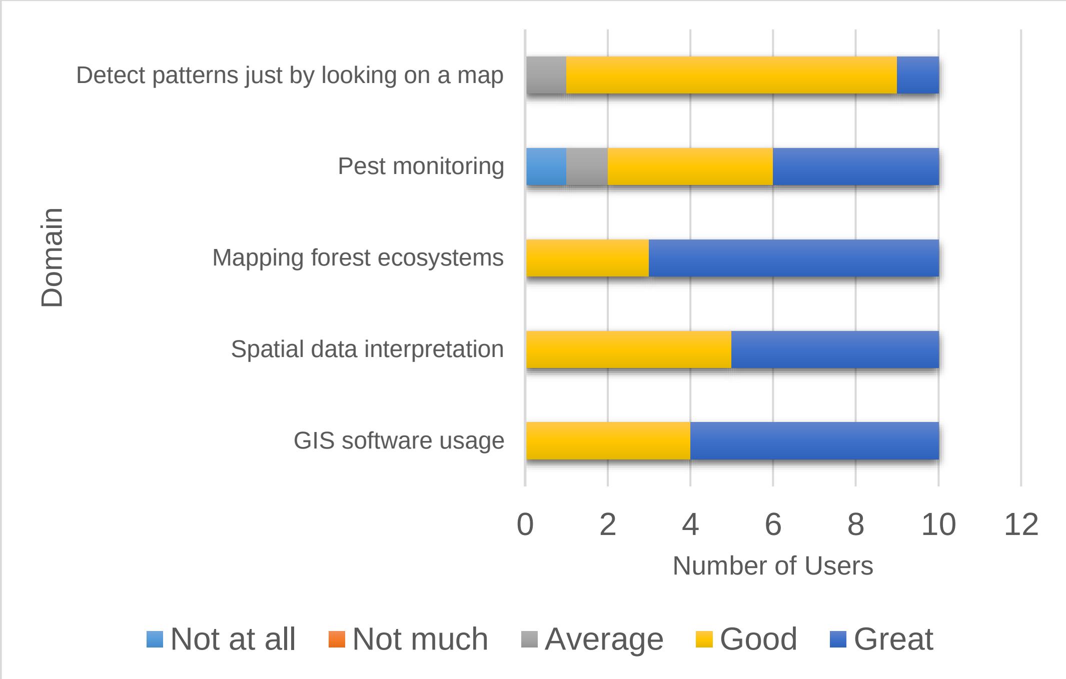


Figure 56: Experience of participants in domains of forestry, mapping and GIS

5.2.2 Tree Visualization and color perception

In the second section of the survey, we asked from the participants ten questions regarding the color for visualizing the trees under the imminent threat of the PPM.

The goal of this section in our questionnaire was to understand how different colors are interpreted by users while looking at them. The users did not know which color or which shade represents healthy and/or uninfected trees and that gave us the advantage to have a better overview of their first impression and thoughts when they are looking at a specific color or color range.

Monochromatic Representation of Vegetation

In the two first questions of the Appendix A (2.1 and 2.2) the trees were visualized in monochromatic grey and green scale respectively (Fig. 57) and gave a hypothesis to the users that darker colors represent healthy vegetation the users to identify the healthy trees and asked them if they agree. In fact, in both 2.1 and 2.2 questions, the darker the color the more critical the condition of the tree was due to increased number of PPM on them. A comparison between green and grey scale results is presented in Figure 58.

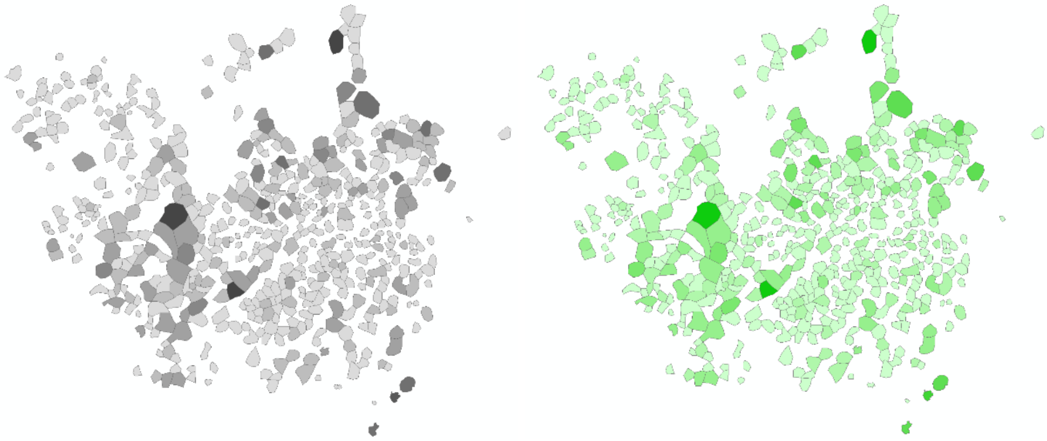


Figure 57: Grey and Green scale visualization of trees for questions 2.1 and 2.2 of Appendix A

The main idea that participants shaped by looking at the grey scale representation of the trees was that the darker polygons illustrate infested trees, which is correct. Only one of the users had a neutral opinion about different tones of grey and what they represent. One of the users mentioned that his opinion is based on his emotion regarding black color. “Black color is mostly connected with unpleasant feelings and that is the reason why I think dark colored polygons represent seriously infested and damaged trees” described.

The user who could not decide whether dark polygons represent healthy of infested vegetation mentioned that he felt confused. She verbally explained during the interview that there might be a connection between dominant dark color and robust health of the trees. She also added that “*light grey polygons could represent sick vegetation due to the lack of vividness in real life and dark grey could express the exact opposite*”. An example of a monochrome grey based choropleth map is presented in Figure 59.

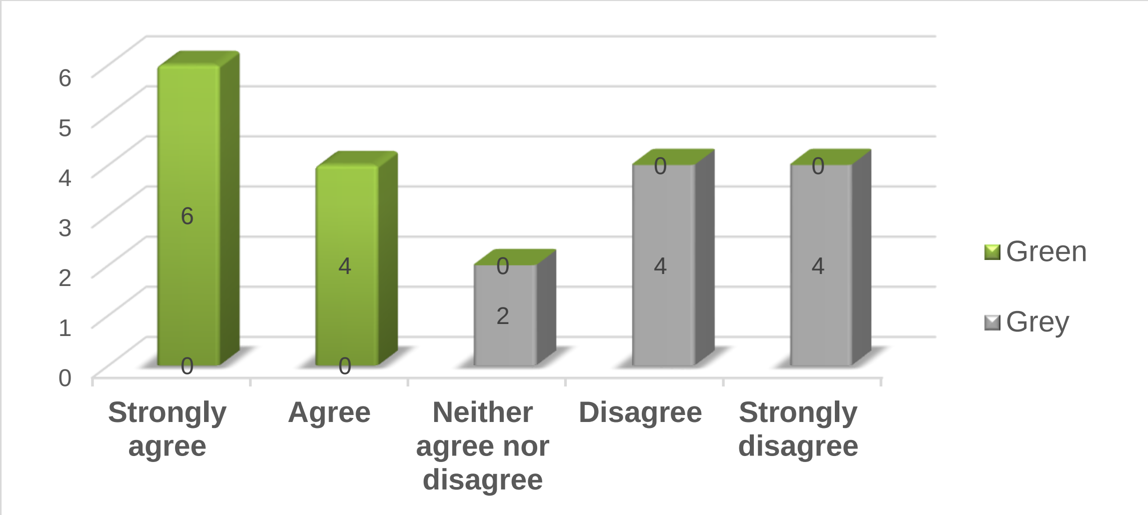


Figure 58: Distribution of answers for 2.1 -2.2 of Appendix A

In case of green scale representation the answers were positive regarding a connection between green colored polygons and healthy trees. In fact, dark green polygons are the ones that are in danger due to the PPM. Users felt confident and the majority of them (six out of ten) strongly agreed that dark green polygons are the trees that are unaffected by the PPM.

We realized that representing vegetation's health with one color was misleading and confused the participants in that case. After the completion of the questionnaire, we revealed that this was a misleading visualization in purpose and how would they visualize it in a better way.

Seven users proposed to use multiple colors for representing the condition of vegetation whereas three of them supported that inverting the scale would represent status of trees' health properly. A participant made the following comment "The greener, the healthier".

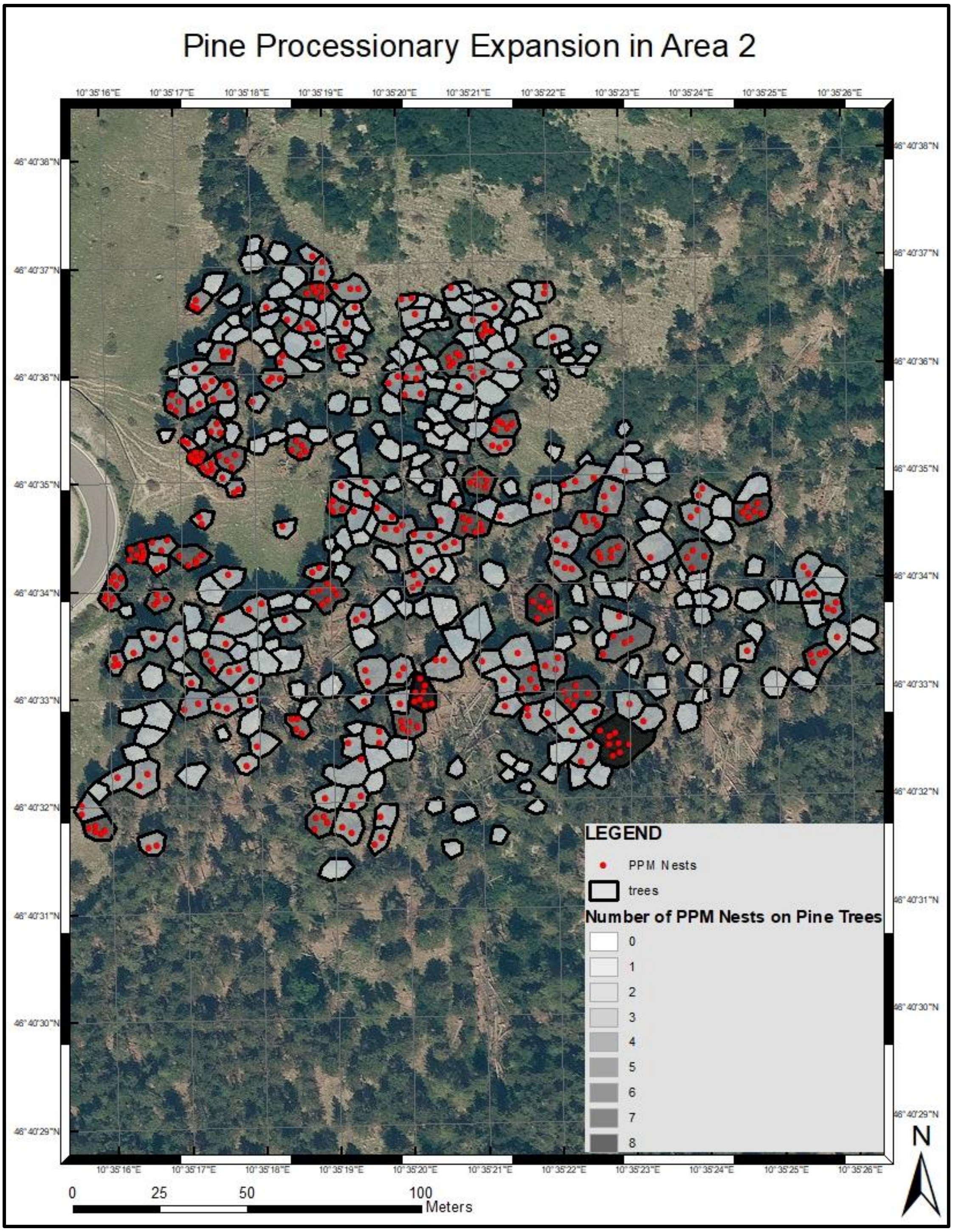


Figure 59: Monochrome choropleth map of Area 2 indicating tree's health condition and exact number of PPM nests

Multicolor Representation of Vegetation

In the following questions of the second section of Appendix A (2.3-2.10) we visualized vegetation with more than one color based on the PPM presence on the trees.

In question 2.3 of Appendix A, vivid red colored polygons represent healthy vegetation in our dataset. We visualized the endangered trees with vivid green and we asked from the users to identify the healthiest trees by looking figure 60.

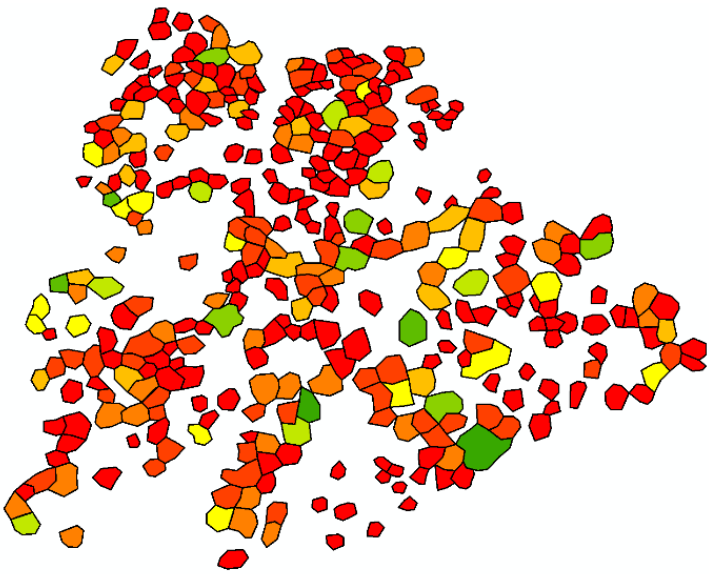


Figure 60: Representation of vegetation for question 2.3

The vast majority of the users, unanimously agreed that vivid green represents healthy trees and mistakenly assumed that area of the image was in critical condition regarding the PPM presence. The results of question 2.3 are shown in Figure 61. We asked verbally the users why they think that green polygons illustrate healthy trees and some of the user comments we received are the following:

"*I thought that green are the healthiest trees as the tend to have more chlorophyll in reality, and high levels of chlorophyll means good health for the tree*"

"*I have green color in my mind as something joyful and healthy that offers positive feelings*"

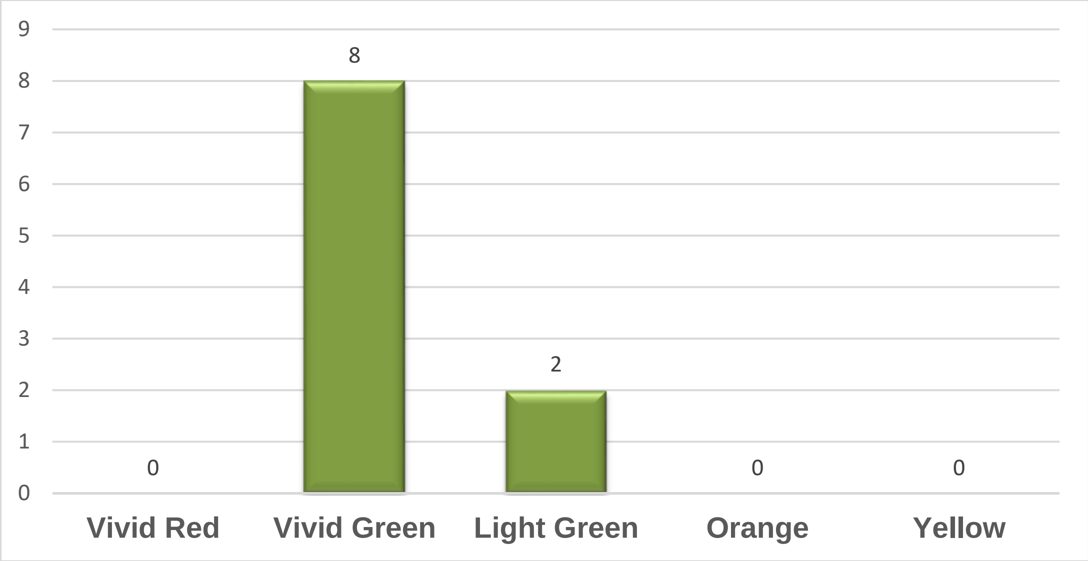


Figure 61: Distribution of answers for 2.3 (Appendix A)

To validate if green color is appropriate for visualizing good health, we visualized another area with different colors. In Figure 62, green color represents healthy vegetation with no presence of PPM nest on the tree whereas light red polygons represent that the tree is in critical condition.

We verbally asked the users if they could rank other colors according to how seriously infected the trees are. Six of the users answered that the trees that are threatened are visualized in light red, which is correct in our scenario (Fig. 63).

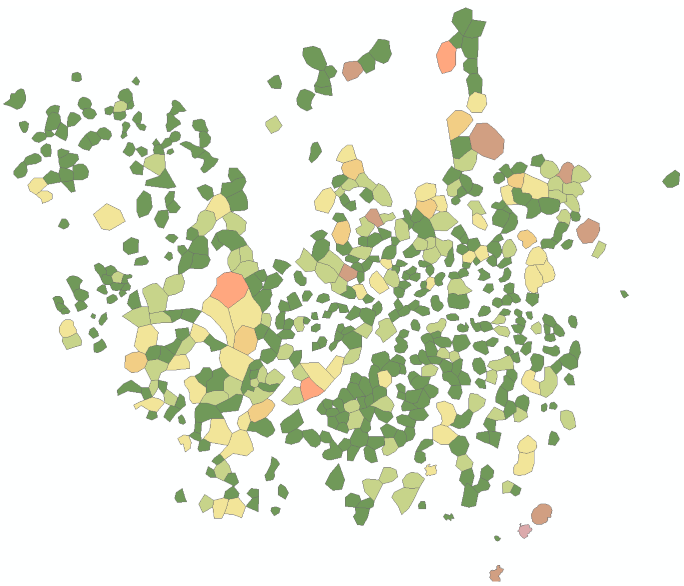


Figure 62: Representation of vegetation for question 2.4 (Appendix A)

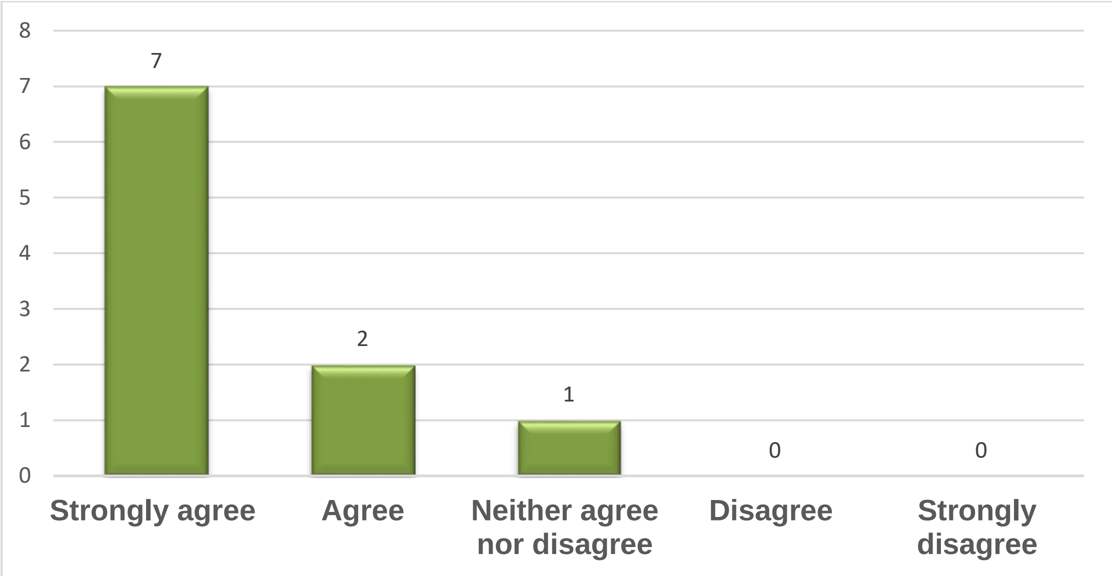


Figure 63: Distribution of answers for 2.4 (Appendix A)

Only one user expressed that couldn't state with confidence if green colored polygons represent healthy vegetation. None of the users denied that green color is a bad choice for visualizing healthy vegetation and the comments that we received verbally during the interview with each user were neutral regarding this style of visualization. One of the users claimed: "*Green color seem to be healthy vegetation, light green infested but still healthy, red seem to be critical but the rest of the colors are hard to be interpreted without knowing what they exactly represent*".

For the remaining questions of this section (2.5-2.10 of Appendix A) we present two different areas with different visualization styles. For area 1, we digitized 530 trees and 271 nests in total for illustration purposes. The number of the infested trees in area 1 is 163 (Fig. 64). In area 2 we digitized 351 trees and 369 nests in total that affected 152 trees. **Area 2 seems to be slightly in a more critical condition** (Fig. 65). The purpose of the nest questions is to clarify which colors better represent a critical situation regarding a PPM population breakout.

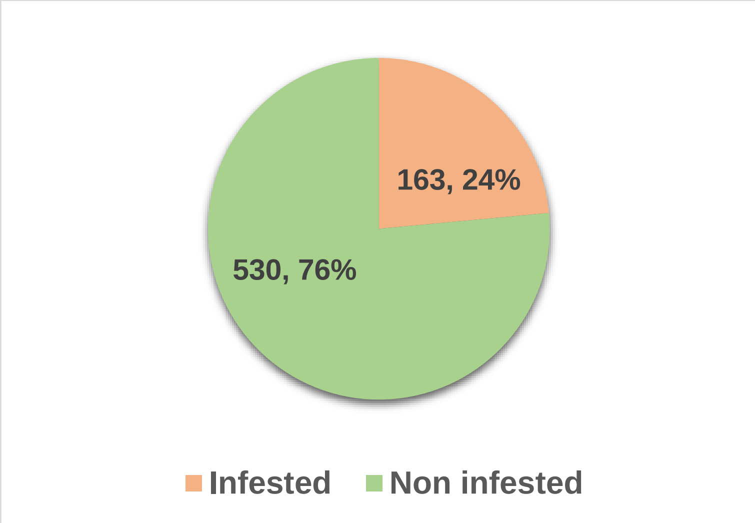


Figure 64: Infested and non-infested trees of Area 1

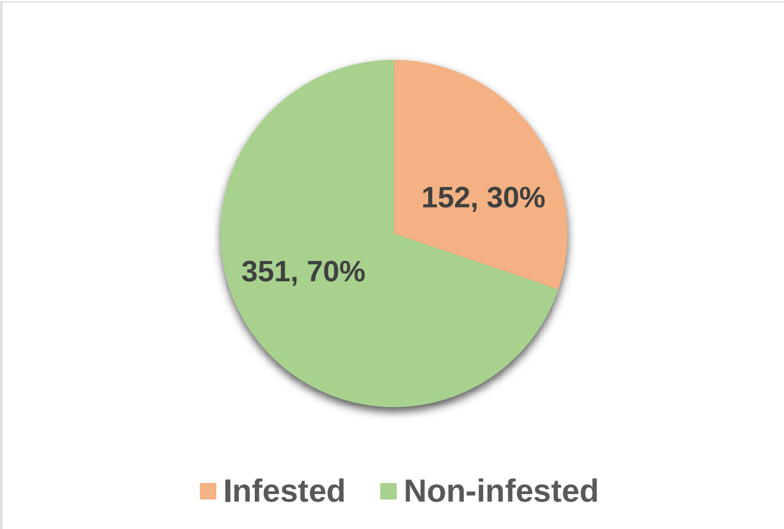


Figure 65: Infested and non-infested trees of area 2

In question 2.5 of Appendix A, we present the two areas using with the same visualization style and colors and ask the users to share with us which of the two areas is in a more vulnerable to a PPM population breakout and how they came to this decision (Fig. 66).

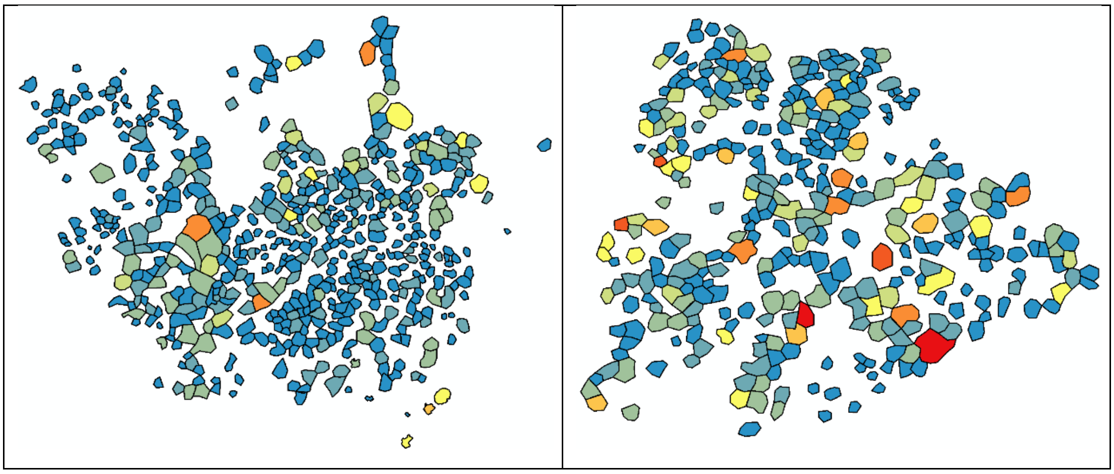


Figure 66: Representation of vegetation for question 2.5 (Appendix A)
Area 1 on the left, Area 2 on the right

The majority of the participants gave a correct answer for choosing the second area as more vulnerable (Fig. 67). In the comments box below they claimed that the presence of red color made them to come to this conclusion. They also supported that light yellow color gave them the impression that "something is going wrong" in the second area whereas blue and light green colors seemed to illustrate a safe condition of the trees. Users who had difficulties to decide which area is jeopardized, mentioned that they would prefer a color palette that contains green for healthy and red for infested trees. Blue color was characterized as indifferent and neutral.

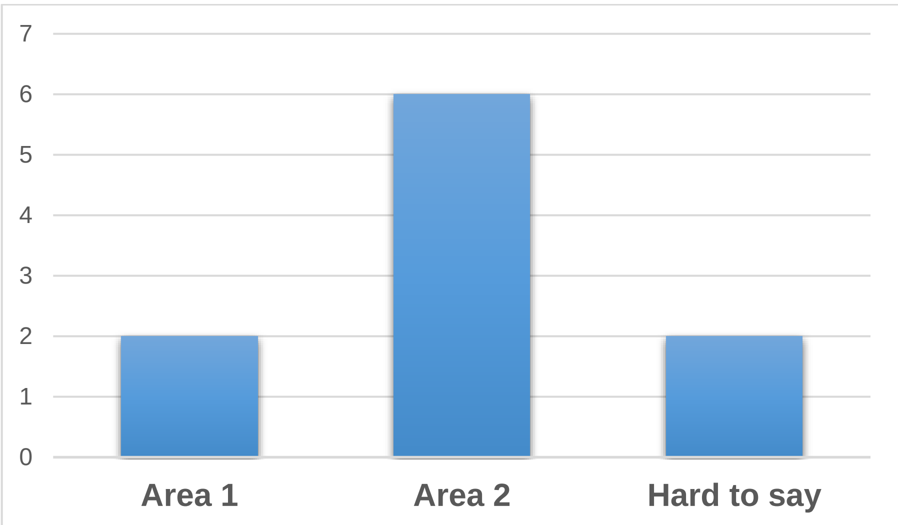


Figure 67: Distribution of answers for 2.5 of Appendix A

In questions 2.6 and 2.7 of Appendix A, we intend to test the certainty of a user to judge if an area is critical against the PPM presence or not based on two different color palettes (Fig. 68). The questions were the following: "*Based on the color of the polygons that indicate the density of PPM presence, how would you describe the general condition of this area?"* The options they had were: "*Critical, Alarming, Safe, and Hard to say*".

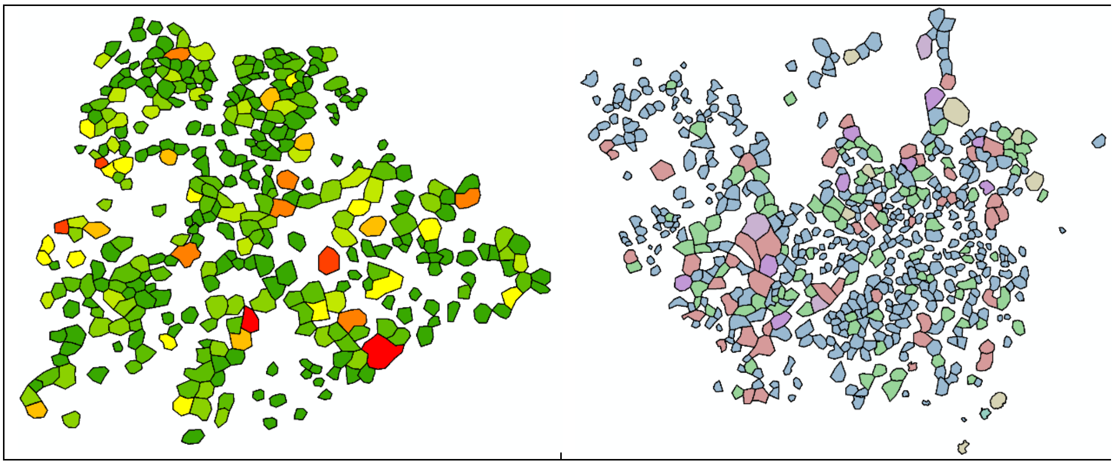


Figure 68: Representation of vegetation for question 2.6 (left) and 2.7 (right) (Appendix A)

For question 2.6 of Appendix A, users felt confident to characterize the area and the majority of the users guessed correctly that the condition is non critical. On the other hand, for question 2.7 where the colors are of low saturation, made the majority of the participants unable to distinguish the status of the area regarding the health of the ecosystem. Only two users felt confident to name the area as safe. The distribution of the users' answers for the two different color pallets of questions 2.6 and 2.7 are given in Figure 69.

Colors with reduced saturation seem to leave the user indifferent and unable to judge by just looking on the screen if the ecosystem is either in danger or not. "*When the dominant color on the screen is green, the ecosystems looks fine. Presence of red on the screen makes me pay attention to that*" stated one of the users.

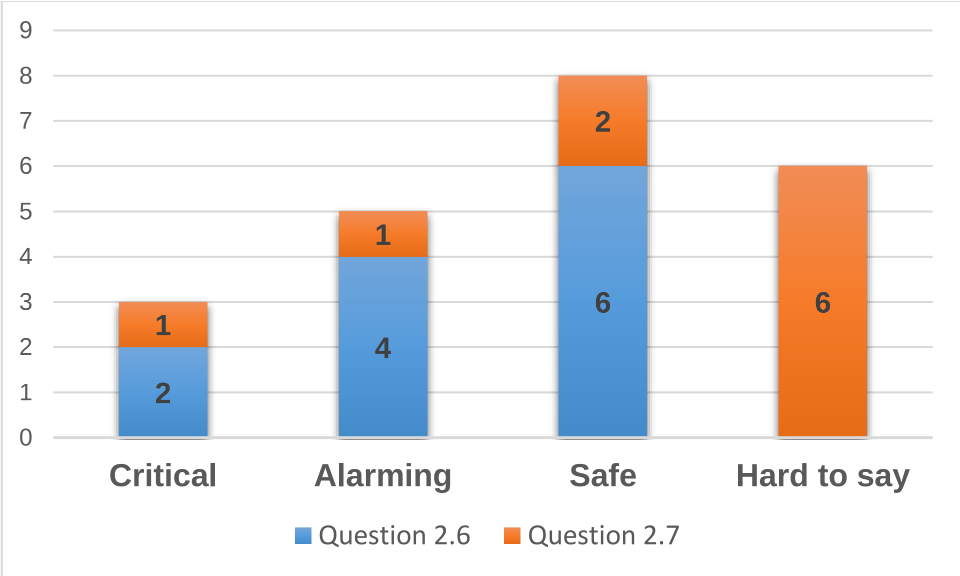


Figure 69: Distribution of answers for questions 2.6 and 2.7 of Appendix A

For question 2.8 of Appendix A, we inverted the colors that we used for question 2.6 and ask the users to characterize this area again while red and orange are the two dominant colors on their screen (Fig. 70).

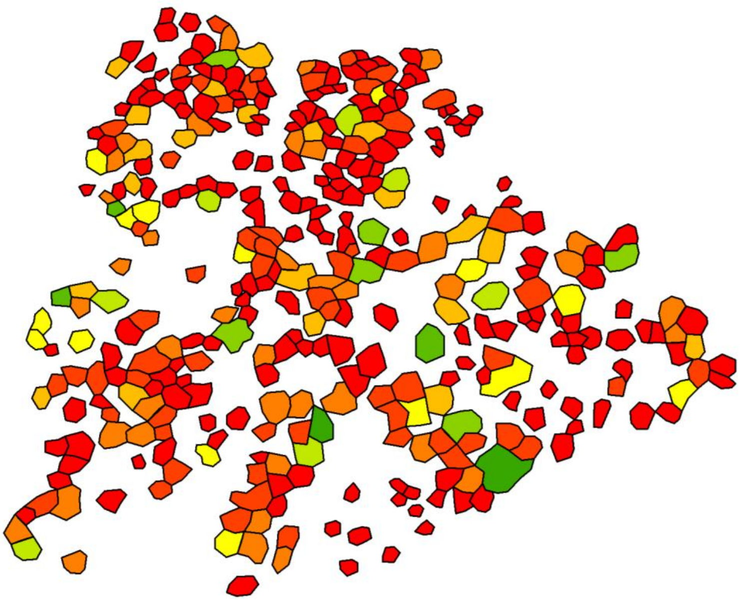


Figure 70: Representation of vegetation for question 2.8 (Appendix A)

No users characterized the area as safe and none of the users had uncertainties that the area is not in danger due to PPM presence. Dominance of red and orange color gave to all the users the impression that the condition is rather critical or alarming as shown on Figure 71. One user expressed: "*Red* *color gives me the impression that something serious and alarming is happening in the area.*" Another user claimed that: "Red color means problem".

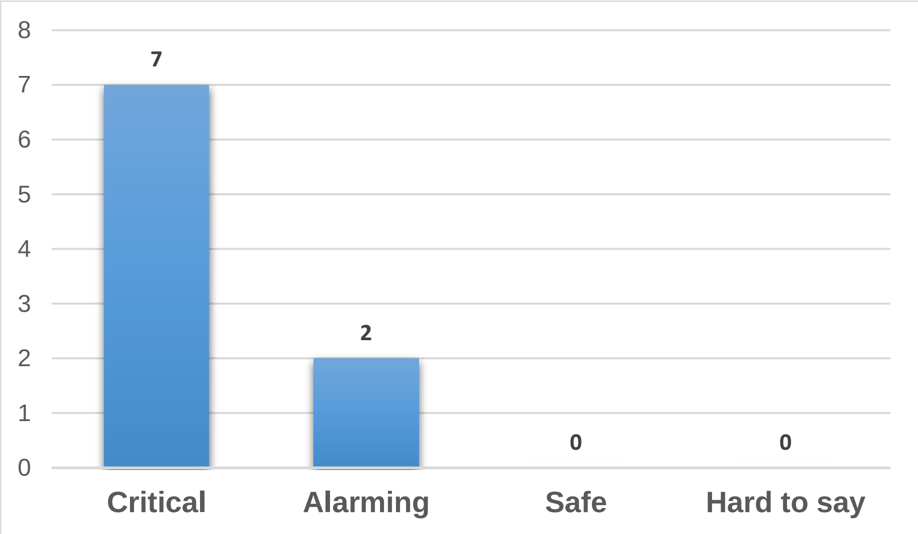


Figure 71: Distribution of answers for question 2.8 of Appendix A

In question 2.9 found on Appendix A, we tested the ability of users' eyes to evaluate an area's condition by visualizing the trees with only two colors. Red color indicate that there is at least one nest on that whereas green color indicates that there is no nest spotted on the tree and that there is no danger at all for its health condition. We presented two different areas visualized as described above and asked them to evaluate which of the two areas is in a greater risk because of the PPM and explain in short why (Fig. 72).

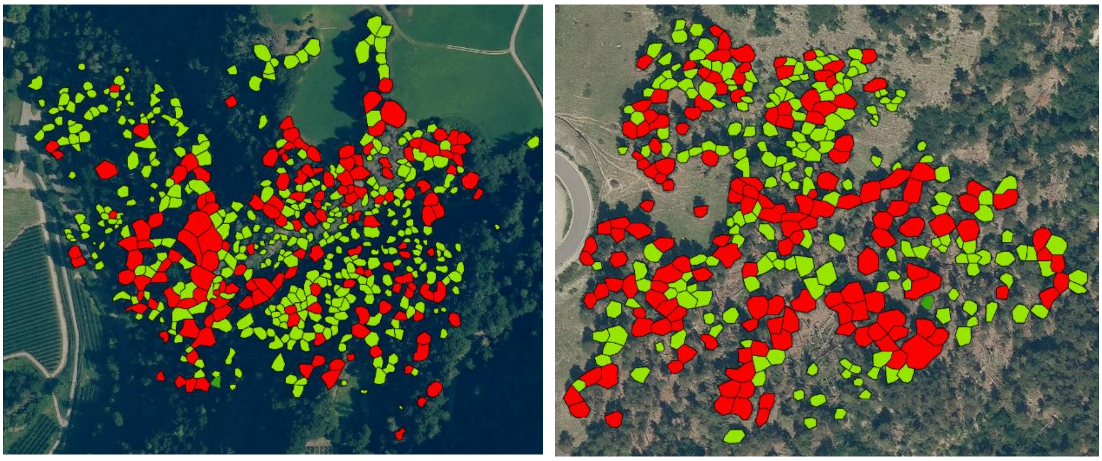


Figure 72: Two-color vegetation's representation of Area 1 (left) and Area 2 (right) for question 2.9 (Appendix A)

User’s opinion was not quite clear in this type of visualization and expressed their worries as they don’t know the how advance the level of the PPM infestation is (Fig. 73). One user mentioned: “*In some cases multiple trees can be infested by the PPM but not in an alarming scale. Having only one or two nests on a robust tree is not a serious issue. A multiple color visualization can give us better visual result because we need to know if the presence is intense*”.

“*To have a better overview of an area’s condition and evaluate the seriousness of the PPM nest, quantitative information indicated by different colors is a better option*” noted another user. “Binary” representation can be misleading in that case as seriously damaged trees and trees that are not in risk but are infested are illustrated with the same style. As a result, in some cases, a serious threat might not be seen with caution by users or a non-serious situation might be receive unnecessary interest and time for further analysis by the users.

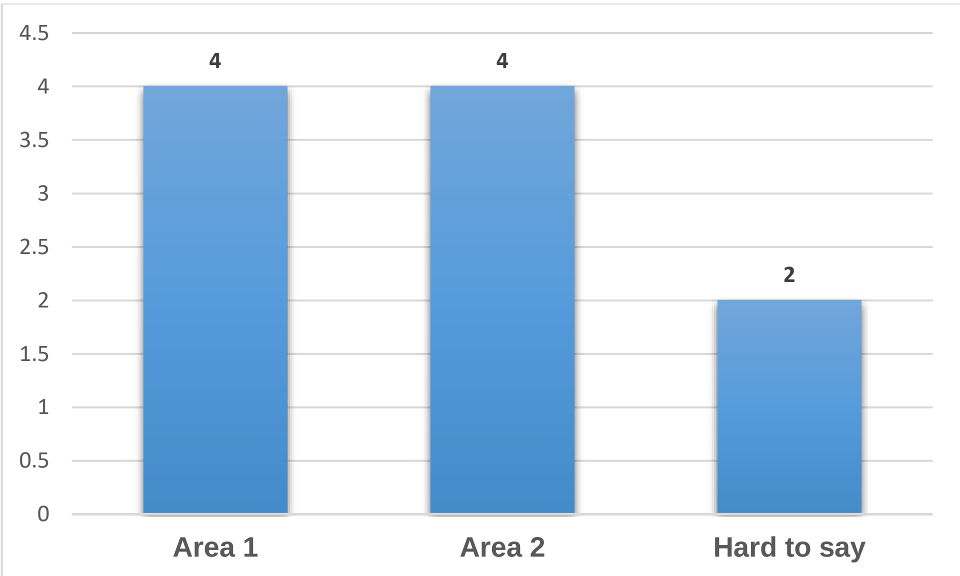


Figure 73: Distribution of answers for question 2.9 of Appendix A

For the last question (2.10) of the second section of our survey in Appendix A, we tested users’ perception about the same areas but visualizing them with multiple colors to see if it helps them to better evaluate an area as presented in Figure 74.

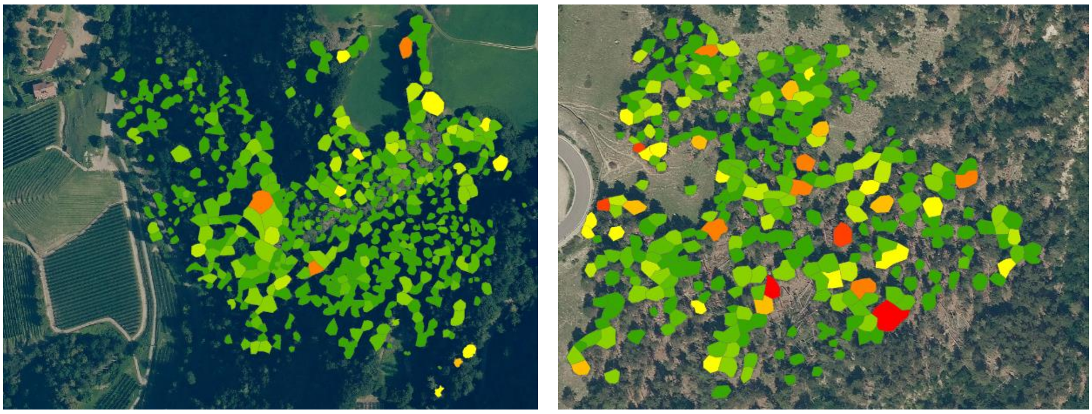


Figure 74: Multi-color vegetation's representation of Area 1 (left) and Area 2 (right) for question 2.10 (Appendix A)

In that case users seemed to feel more confident about their answers and the majority guessed correctly that the second area is more vulnerable against a PPM population breakout (Fig. 75). Red color on the second area lead more users to understand that some of the trees are in critical condition. In first area, green color is quite dominant whereas light yellow and orange polygons spread in wide area and with great distance between them, don’t seem to attract user’s attention in order to evaluate the area as endangered.

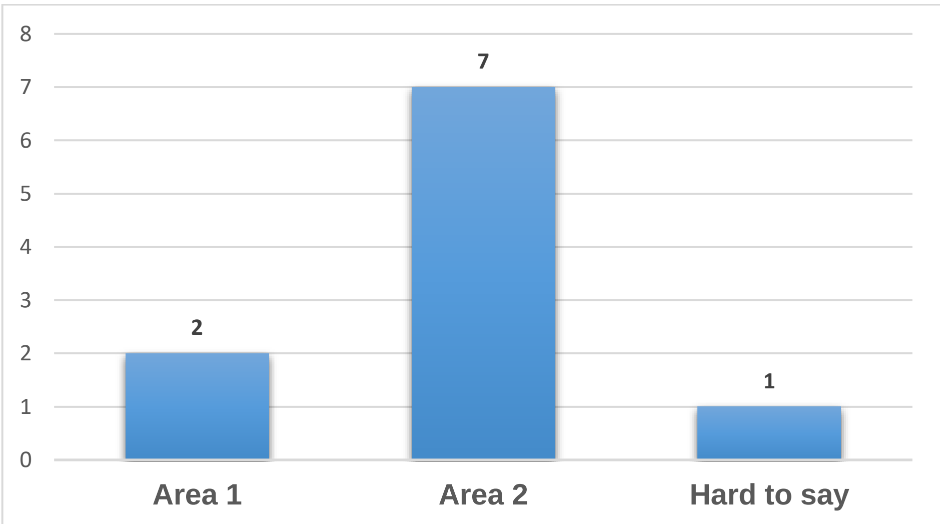


Figure 75: Distribution of answers for question 2.10 (Appendix A)

By comparing the results we extracted from question 2.9 and 2.10 of Appendix A, we assume that color usage improves the perception of users’ eyes and a better communication between the user and the cartographer can be succeeded. Legends on maps are essential but in that case we investigate how the participants connect colors with mapped vegetation's health condition.

Using multiple colors instead of using just two for infested and non-infested trees, dramatically improves the message that cartographer is trying to share through mapping. Users feel more confident about evaluating an area and the results of their answers are satisfactory. In Figure 76, we compare the answers of questions 2.9 and 2.10 of Appendix A.

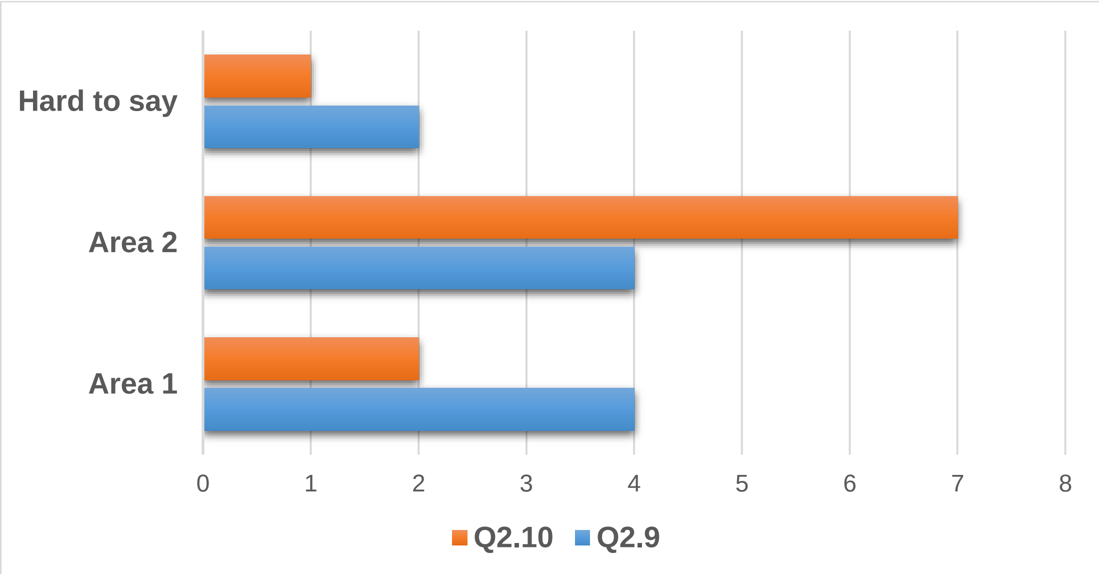


Figure 76: Comparing answers given by users about binary and multi-coloring

5.2.3 PPM Nest Visualization

In the third section of the survey, we asked from the participants six questions regarding different styles for visualizing the PPM nests we managed to locate on the trees.

This section's main purpose is to understand how different styles of illustration are interpreted by users while looking at them. The users had to evaluate the given visualization methods not only for the nests but also combination that includes trees and nests as well.

For question 3.1 of Appendix A, we visualized the PPM nests as red dots on the map, using airborne imagery as base-map (Fig. 77). The purpose of this question was to understand if simple dots are adequate to help users decide which of the two presented areas is in greater risk.

Figure 77: PPM Nest representation as red dots in Area 1 (left) and Area 2 for question 3.1 (Appendix A)

Most of the participants were able to correctly understand that area 2 is in a more critical condition (Fig. 78). Their choice was based in dot density. “From that scale, in many spots of Area 2 seem to be illustrated as one object and that gives me the impression that increased density of the dots means that there is an issue with PPM” supported one of the participants.

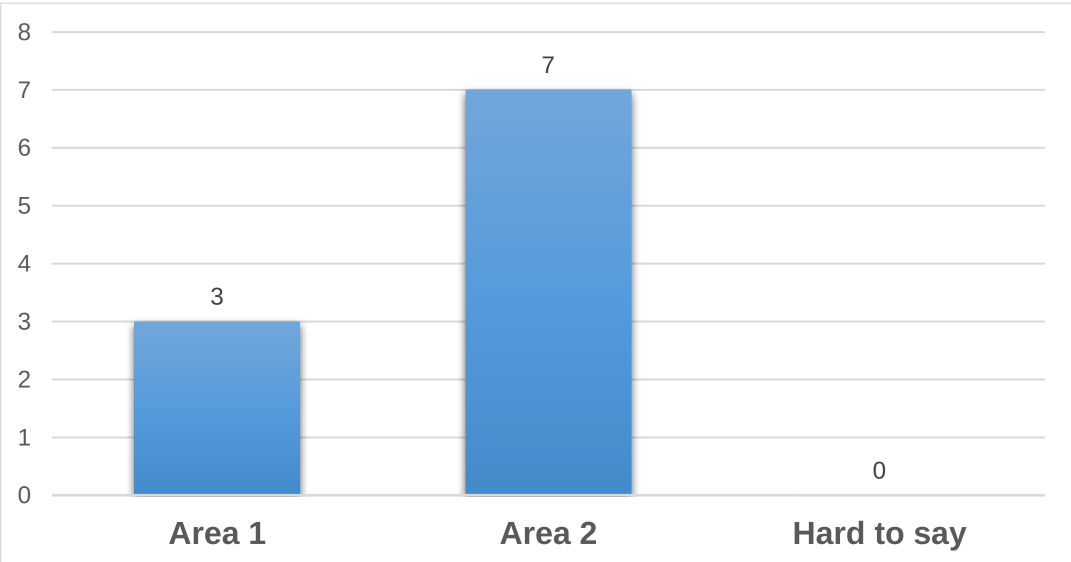


Figure 78: Distribution of answers for question 3.1 (Appendix A)

In questions 3.2 and 3.3 we presented to the users a combination of visualization styles for both trees and nests where the black dots represent nests located on the trees and the polygons represent trees (Fig. 79). The different color of each tree is related to the number of the nests on it and we asked them to evaluate which of the two areas would is in a greater risk because of the PPM and if the presence of dots helps them to better understand which trees are the mostly infested by the PPM.

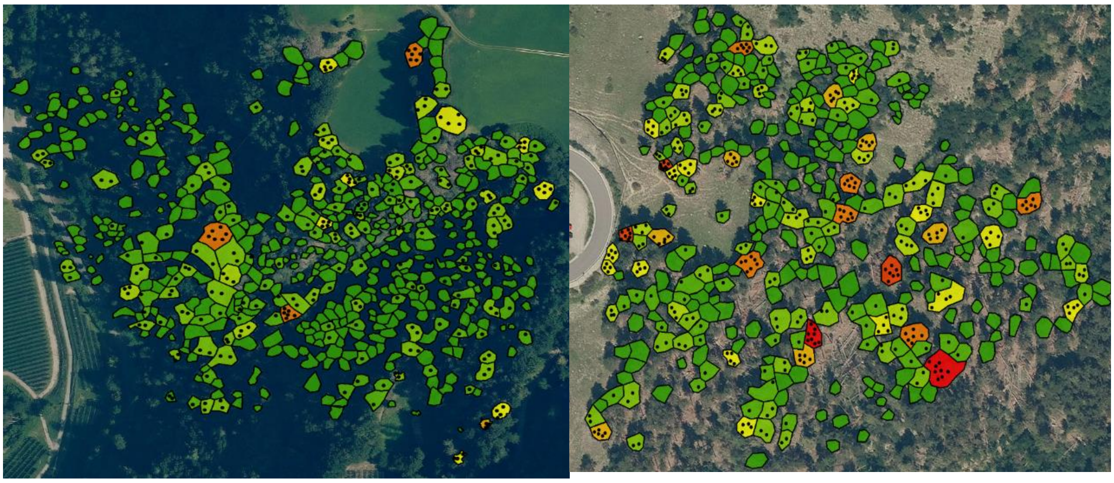


Figure 79: Combination of visualization styles for nests and trees in Area 1 (left) and Area 2 (right)

There was great increase at the number of the participants that chose Area 2 as the critical one (Fig. 80). **Red color polygons significantly helped users to make a correct choice**. A prototype map that shows the combination of the methods can be found in figure 81.

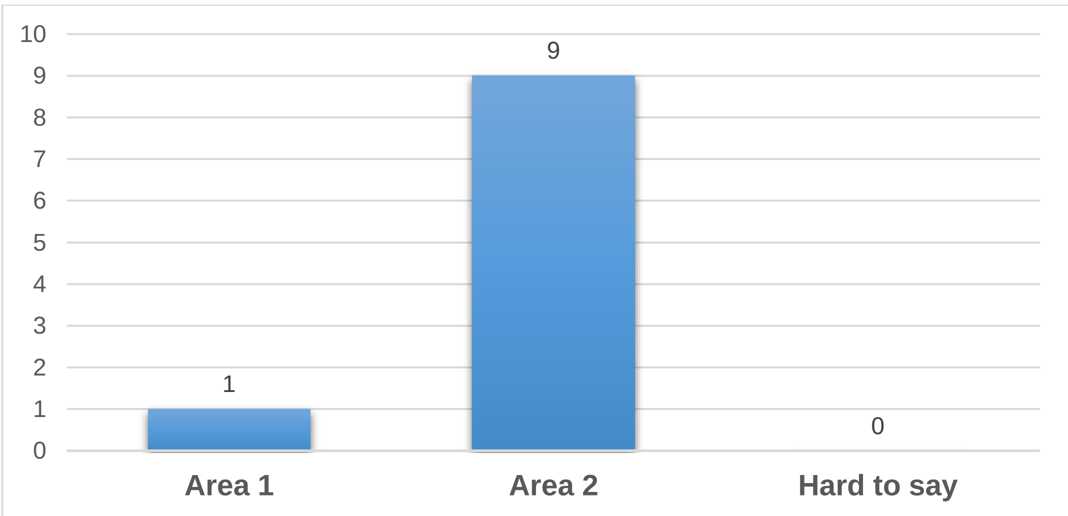


Figure 80: Distribution of answers for question 3.2 (Appendix A)

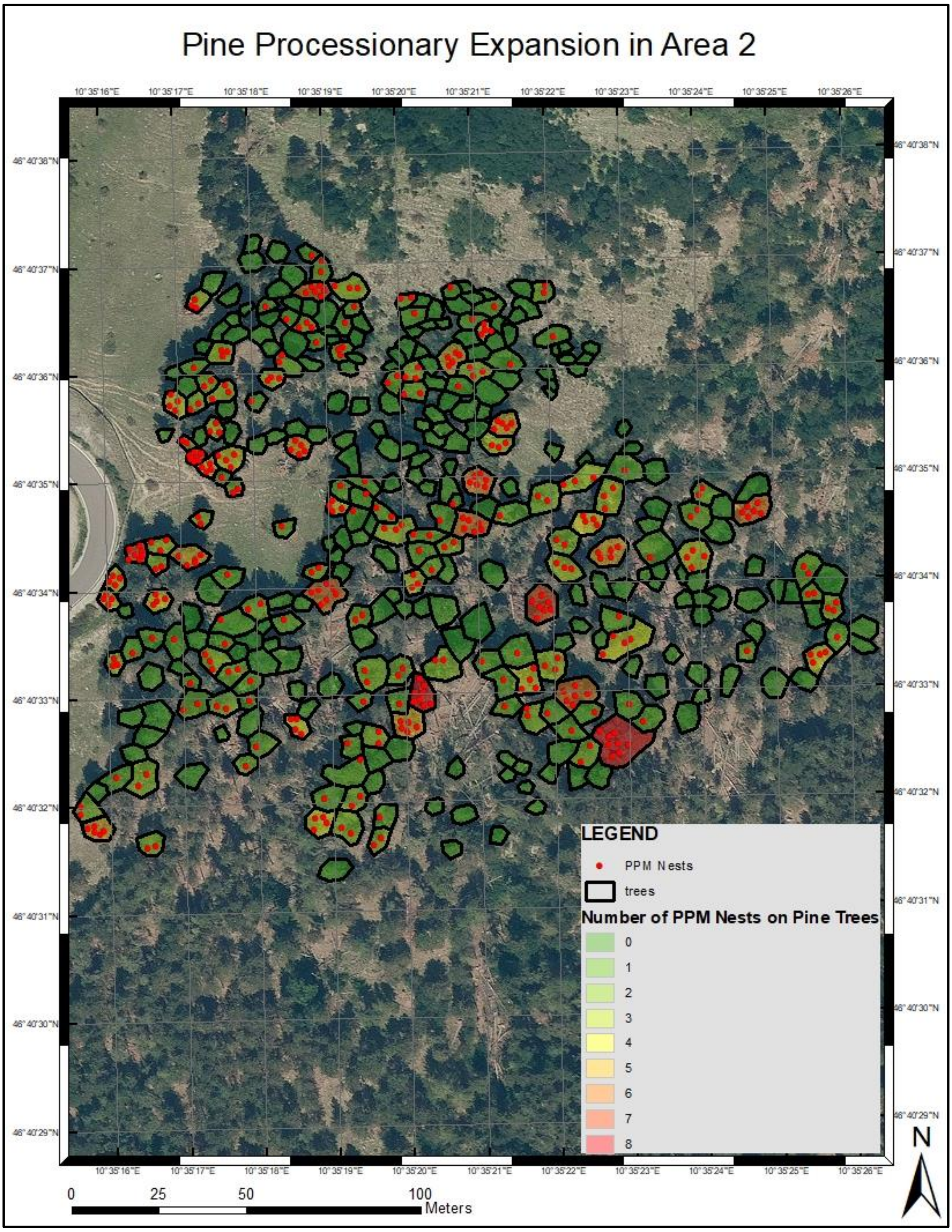


Figure 81: Multiple-color choropleth map of Area 2 indicating tree's health condition and exact number of PPM nests

Regarding the presence of dots, the distribution of the users' answers was equal (Fig. 82). Half of the users supported that it is a visual advantage that can help them have access to the exact number of the nests on a tree, whereas other users noted that dots are considered as “noise” when colored polygons indicate trees’ health condition.

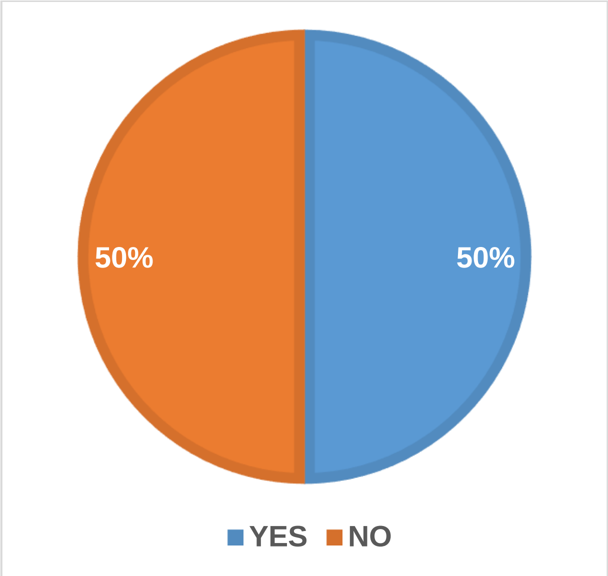


Figure 82: Distribution of answers for question 3.3 (Appendix A)

In question 3.4 of Appendix A, we visualized not the exact location of the nests as we did in previous visualization methods but we illustrated trees both as polygons and as graduated size dots according to the number of the nests on them (Fig. 83).

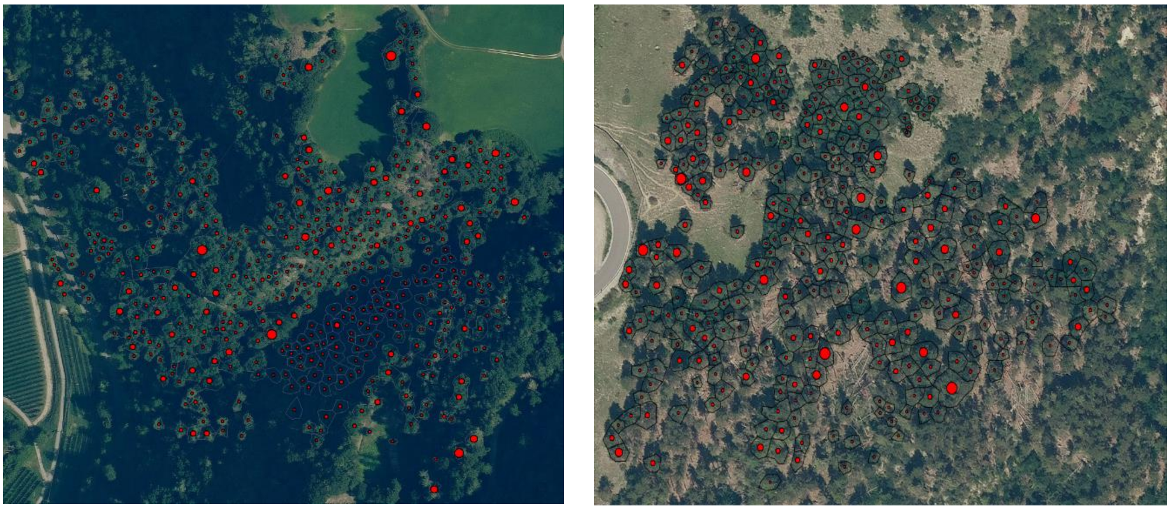


Figure 83: Tree representation as graduated symbol based on the number of PPM nests in Area 1 (left) and Area 2 for question 3.3

The majority of users picked a wrong answer, claiming that area 1 is in a greater danger due to the PPM presence. Two of the users could not decide whether the first or the second area faces an imminent threat. One user noted that he picked the first area as more vulnerable because red dots seemed to be much more than in the second area (Fig. 84). This visualization method was evaluated as misleading by the users.

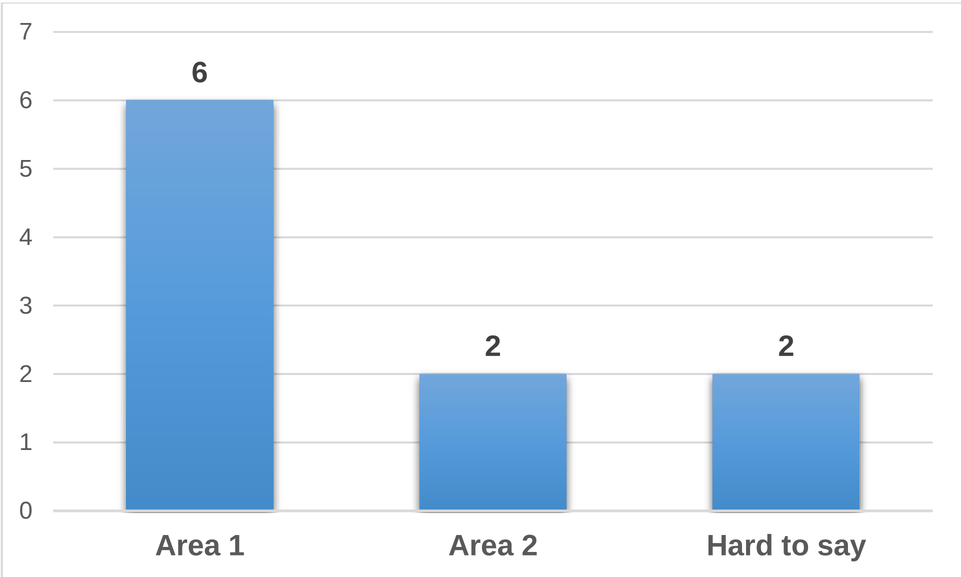


Figure 84: Distribution of answers for question 3.4 (Appendix A)

In order to visualize healthy vegetation in a better way that stands out from the infested trees we proposed two adjusted methods for visualizing healthy trees in the two last questions of this section of Appendix A (Questions 3.5 and 3.6).

In question 3.5 we propose to illustrate infested trees as in the previous method but mark the healthy vegetation with a green dot in the centroid of each tree polygon and asked them to evaluate if marking the healthy trees with green dots helps them to have a better overview of the region's health condition (Fig. 85). The centroid of each polygon that describes a tree as an entity is used by default by ArcMap.

In question 3.6 of the Appendix A we asked from the users to evaluate if the lack of any symbol within the polygons that represent healthy trees helps them to better perceive the situation in the area regarding the PPM presence. Trees in that case were represented as simple polygons with black outline and no fill.

Infested trees had a graduated symbol of red color in the centroid of the polygon which represents a tree (Fig. 85)

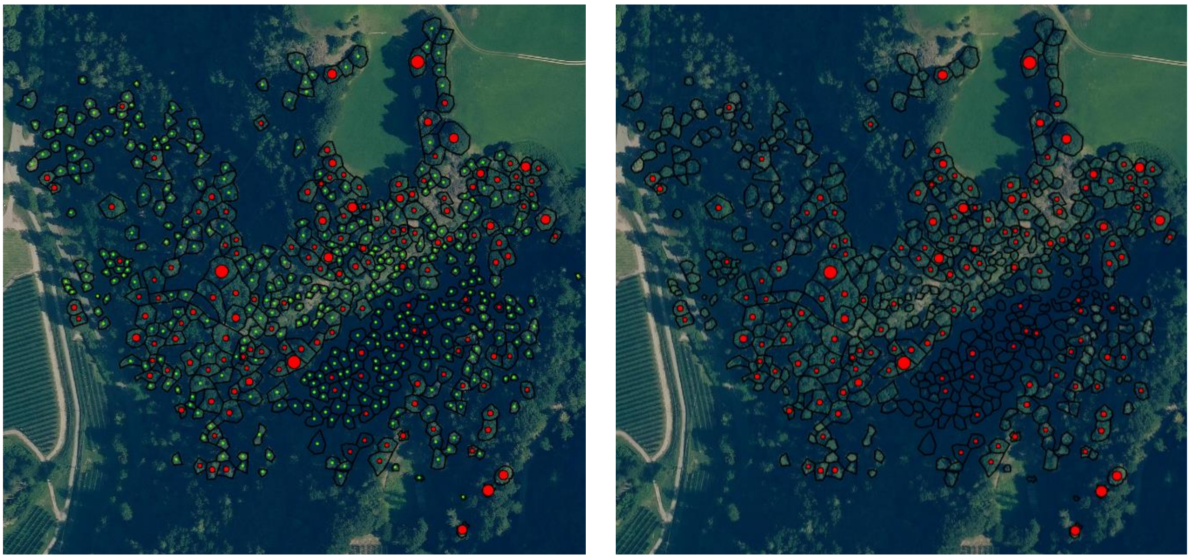


Figure 85: Healthy trees represented as green dots for question 3.5 (left) and as simple polygons for question 3.6 (right)

A prototype map where trees are described as polygons and graduated dots describe the number of the PPM nests on them can be found in Figure 86. Trees that are not infested are illustrated only with the use of polygon and no dot is used for them.

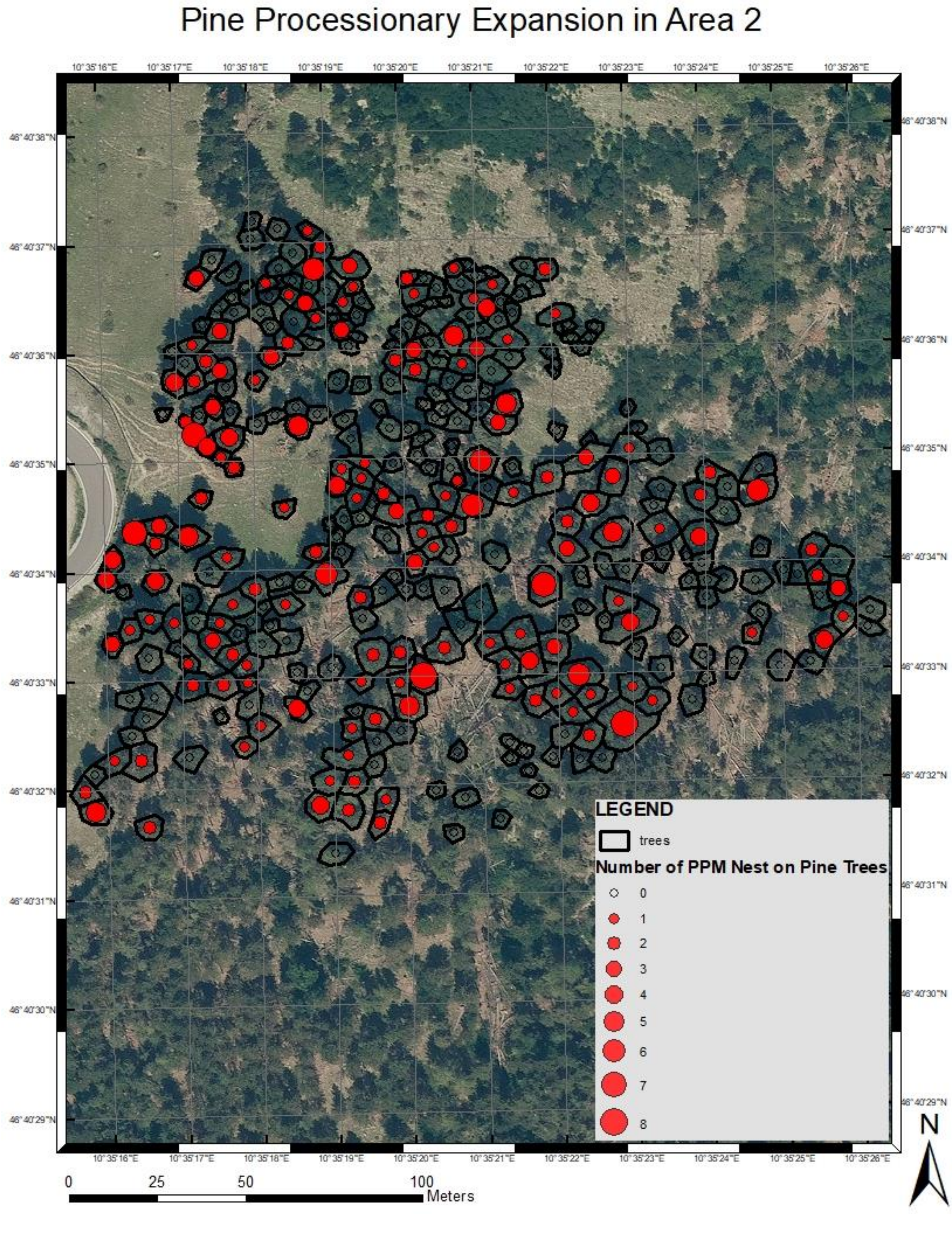


Figure 86: Map prototype where PPM nest number per tree represented as graduated symbol

Users supported the green dot representation of healthy vegetation combined with graduated red dots for infested trees whereas seemed to hesitate to choose a non-filled polygon as proper visualization for healthy and unhealthy vegetation (Fig. 87).

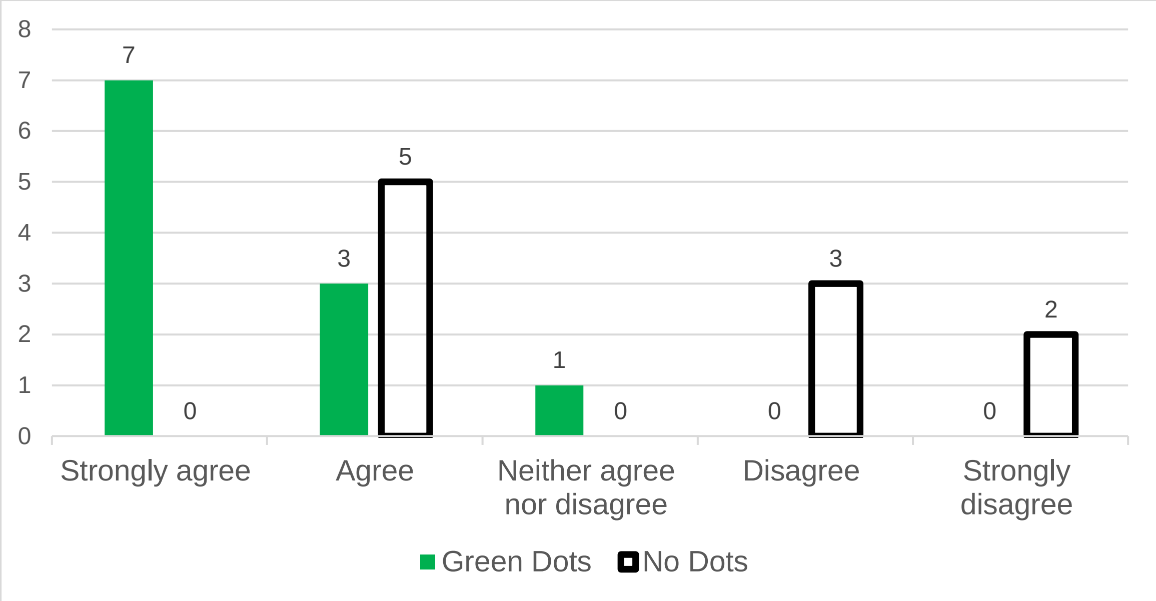


Figure 87: Distribution of answers for question 3.5 (Green Dots) and 3.6 (No Dots) of Appendix A

"*When healthy trees are illustrated with green dots, I can clearly see that green is dominant and that means that the ecosystem is not jeopardized by the PPM. When symbol is absent, automatically red color becomes dominant giving me the impression that the area is danger. When all the trees infested and non-infested have a red dot, I believe that the ecosystem is in a critical condition*" was mentioned by a user during the interview.

5.2.4 Representation of Nests and Trees in 3D Environment

In the last section of the survey, we presented to the users a 3D representation of an area that we conducted a flight with the UAV and visualized the nests of the PPM on the trees. We asked from the users to rank which visualization methods.

The purpose of this section is to understand if 3D representation of areas that are infested by the PPM can help in decision making. To achieve that we have integrated open text questions where users can freely share their opinion beyond the choices we offered in previous sections.

In question 4.1 of Appendix A we asked the users if nests are visible enough on the 3D prototype we presented to them (Fig.88). The vast majority of users (70%) gave a positive answer, confirming that the resolution of the prototype is quite satisfactory (Fig. 89).

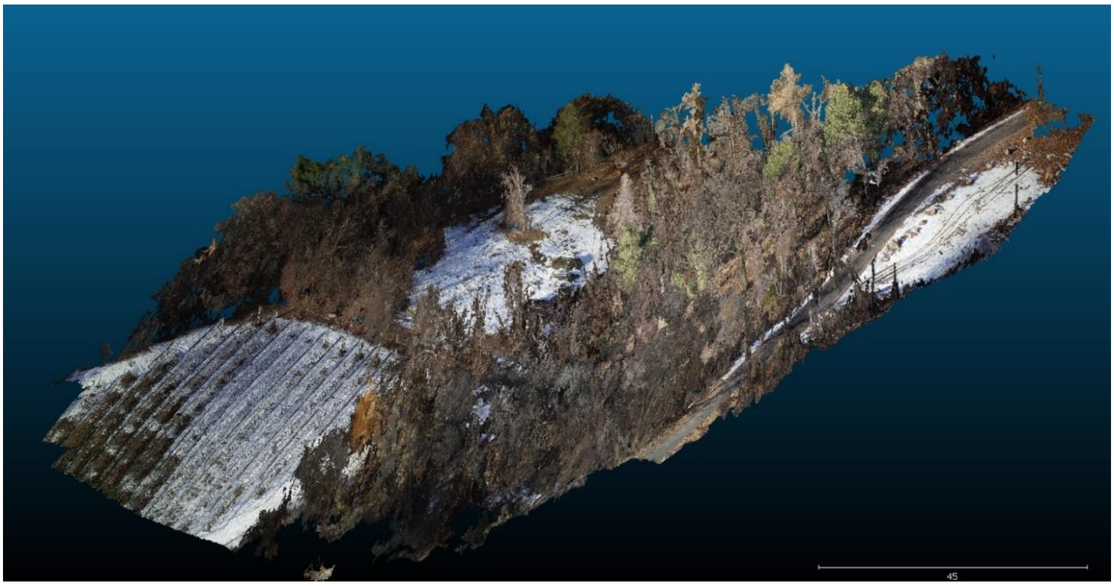


Figure 88: 3D Representation of Area 1 (Appendix A)

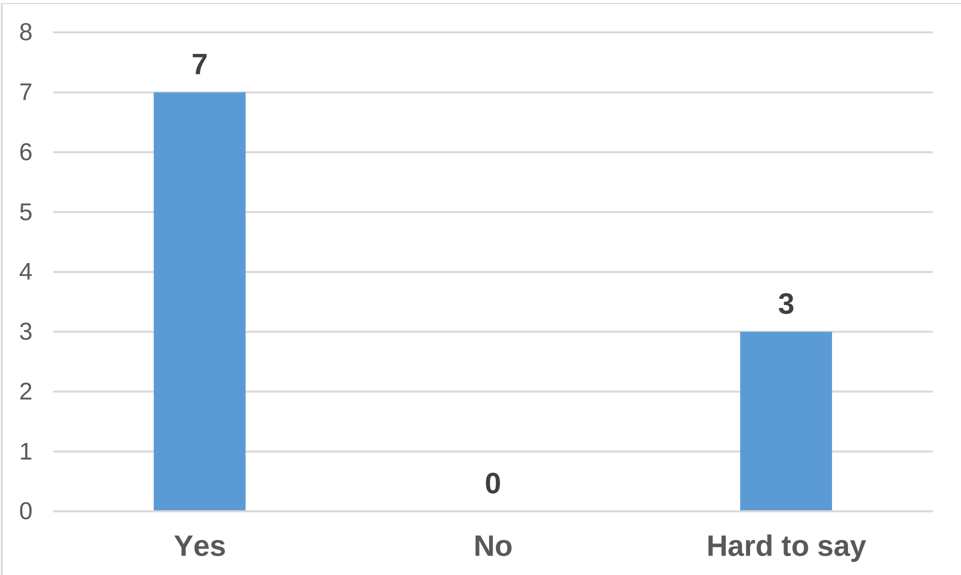


Figure 89: Distribution of answers for question 4.1 (Appendix A)

For questions 4.2 - 4.3 in the Appendix A, we presented four different visualization methods of the PPM nests and requested from the users to evaluate them based on the harmony between the visualization method and the background of the 3D representation (Question 4.2), on their convenience to detect nests (Question 4.3), and give an overall evaluation of their favorite style (Question 4.4). The visualization styles we used are the following:

- Nests emphasized and enhanced with white color
- Nests illustrated as red dots strong silhouette
- Nests illustrated as red dots with 70% transparency
- Nests illustrated as red dots with reduced crispness

The proposed visualization methods of the nests in 3D environment can be found on Figure 90.

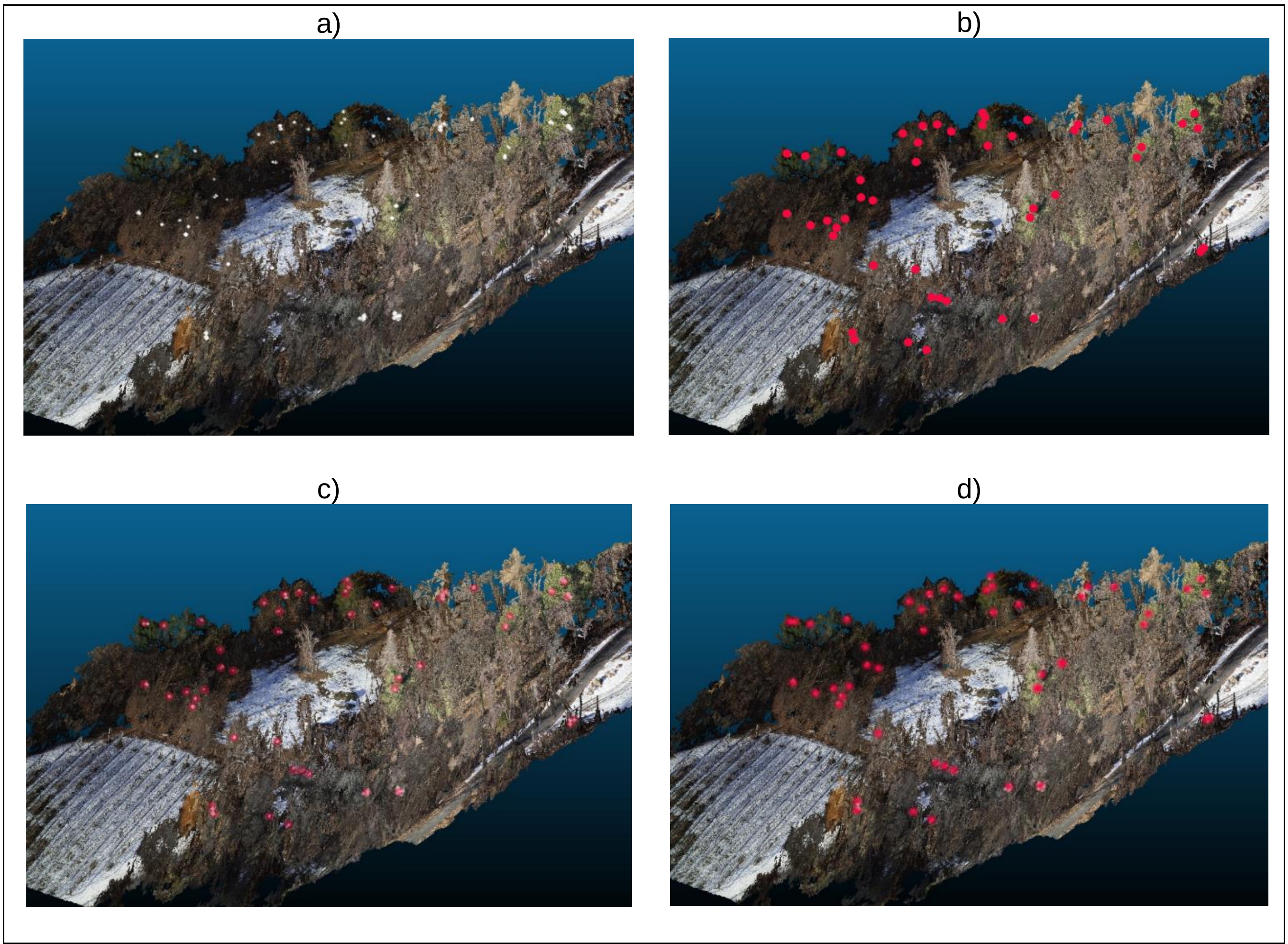


Figure 90: Visualization options of PPM nests in 3D Environment a) Nests Enchanced with white color, b) Red dots with strong sihlouette, c) Red dots with 70% transparency, d) Red dots with reduced crispness

The most harmonized visualization style according to the users is the enhanced white color of the nests. Nests have white color in real life and as a result when they are visualized as white, they have a good contrast with the green background of the trees and feels natural to the eyes of the participants. The less preferred option is the strong red dots as they stand out from the background and feel less natural (Fig. 91).

Regarding the convenience of the users to easily spot the PPM nests, the two most preferable options are the red dots with strong outline and the enhanced white color that has a shape similar to the nest. Red dots with transparency are the less visible option according to the users' opinion as shown in Figure 92.

Surprisingly, users voted us the best visualization method for the PPM, the enhanced white color and not the red dots that are much easier to be seen. Users voted based on how harmonized with the background a nest looks like on the map. Another important issue that we addressed is that crispiness in symbology can add value to the visual result as in all cases the ranking of the dots with increased crispness was high (Fig. 93).

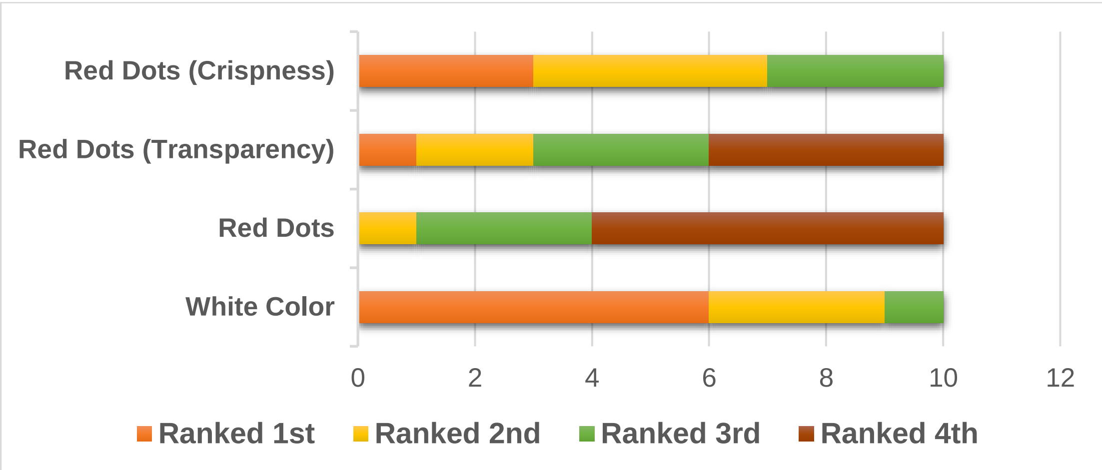


Figure 91: Distribution of answers for question 4.2 (Appendix A)

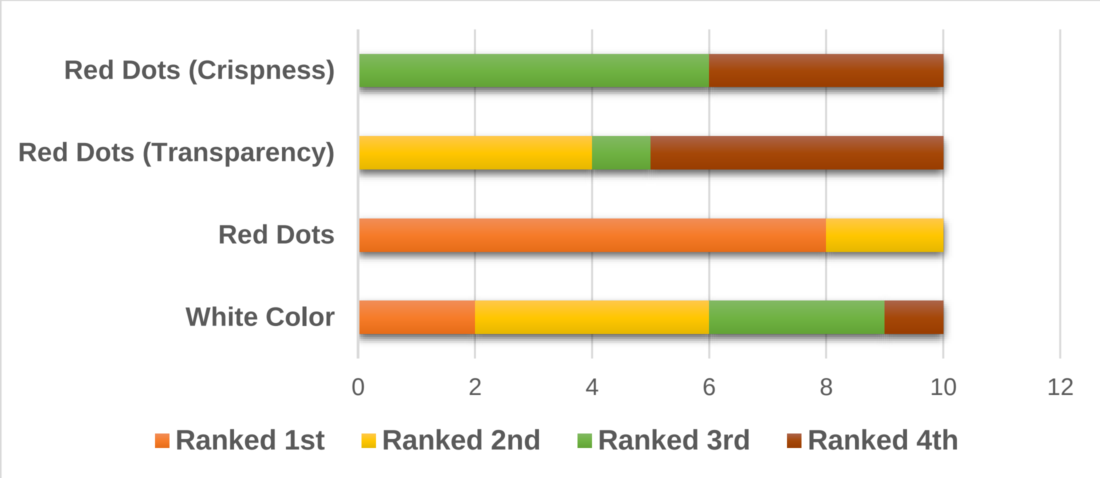


Figure 92: Distribution of answers for question 4.3 (Appendix A)

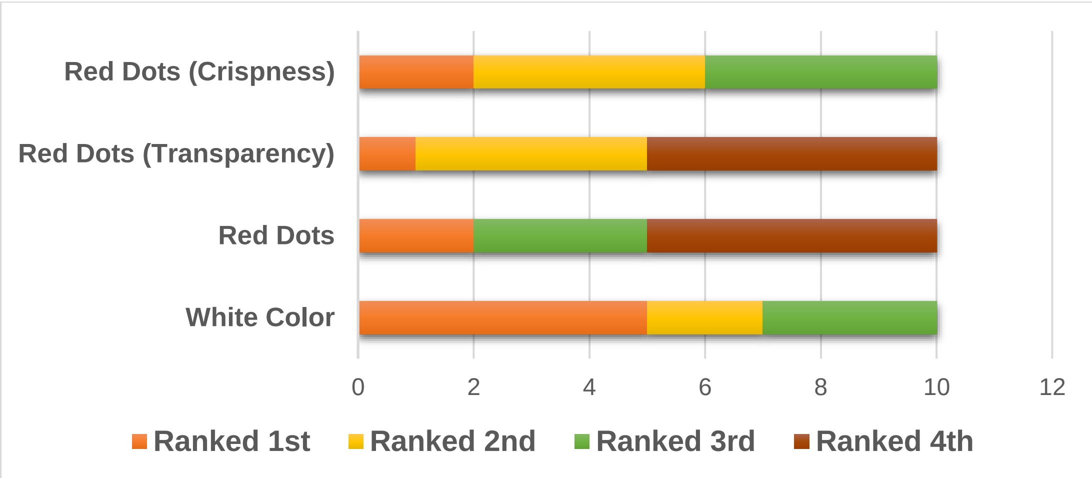


Figure 93: Distribution of answers for question 4.4 (Appendix A)

Regarding question 4.5 and 4.6 we let the users to express themselves verbally during the interview.

In question 4.5, the participants who looked the 3D representation of the Digital Elevation Model, unanimously agreed that combining their knowledge related with forest and pest ecology and cartography, they can derive conclusions that can somehow validate their academic background in the field of forestry. One user noted the following:

"*I know from experience that PPM prefers to live in places that receive a lot of sunlight during the day. While looking on the 3D representation, I figure out that* *the presence is mostly in slopes that face towards south. That helps me as scientist to predict potentially vulnerable areas by just exploring a 3D map*"

Another user expressed:

"*By looking at this 3D Digital Elevation model I can understand the spatial limitation that PPM has. It cannot reach above one certain altitude due to low temperatures. Having an overview of an area, you can predict the behavior of the best with good accuracy. Of course other factors need to be considered, but a first estimation, can be succeeded by just looking a prototype or a map*".

In general, the participants support that 3D representation can be helpful for them so that they can better understand an area. This can contribute by having a first idea of what should they expect when visiting an area regarding the terrain and the slopes. Another potential they can see by having 3D representations of areas is that they can better educate or train other people in matters of the climate conditions as terrain and natural phenomena are correlated.

Users mentioned that 3D maps can be impressive and very attractive for visualization purposes but when it comes to the spatial analysis part of a research, there are limitations.

In general, cartography is a powerful tool that humanity has developed in order to answer questions that are spatially related. Visualizing phenomena help us to better understand the world we live in. Patterns can be detected and trends can be predicted.

In forestry, proper visualization methods can lead to a dramatic reduce of management's and protection's costs. Viewing the bigger picture on maps, analysis and interpretation can be more accurate and more effective. The ability to predict a threat is one of the benefits that cartography offers in terms of ecosystem management and protection.

6. Conclusion and Outlook

One of the functions in forestry mapping is the representation of areas that are vulnerable to pest threats. This thesis aimed at spotting, visualizing, and evaluating spatial data that are essential for decision-relevant map for web-based applications for supporting decision making focused on monitoring the Pine Processionary Moth. This chapter reports on the main findings and gives a view towards future research that needs to be conducted in this field.

6.1 Answers to the research questions

In order to achieve the research objectives, all research questions were investigated. Based on the current state of the art, a methodology was developed and applied to a prototype, which in turn was evaluated in a user study.

To answer Research Question 1 "*In what degree and in what manner can cartography improve the management and protection of forests that are threatened by the existence of malicious pests when outnumbered*" a survey asking experienced forest scientists was conducted. Cartography is a set of tools that can contribute in ecosystem management and protection by visualizing effectively natural phenomena. This gives scientists the ability to have a spatial overview of where those phenomena are happening and in what degree. **By looking at 3D maps that we generated with the use of DEM we can clearly see that the pest populations appear to adapt higher elevation than they used to before and also tend to move to the north due to climate change**. Maps that precisely indicate the position of PPM nests, when carried by rangers and forest scientists (in digital or printed form) when being in the field can dramatically reduce the cost of ecosystem stability operations (e.g. data collection) as their actions become more purposeful.

Explorations for situation report and ground control purposes into the forest take less time by using precision maps and a smaller number of forest rangers is required. As high precision maps allow scientists to have an overview of prone areas remotely, they have the fluency to take faster action before a situation turns into critical, damaging and non-reversible for the ecosystem.

Another advantage that cartography provides is that natural phenomena can also be visually measured, mapped and evaluated. Further questions like "*where is the ecosystem more vulnerable because of the temperature*" can be answered when data are properly visualized and filtered. Cost and time of response against a threat is significantly reduced when appropriate and validated data are being mapped.

To answer Research Question 2**, "***How UAV imagery data can contribute in monitoring pests*", a dataset of 321 images acquired with a UAV were analyzed and evaluated**.** UAVs have the ability to fly over distant areas where personnel cannot easily reach. In forests, steep slopes, dense vegetation and long uphill routes are often, especially on alpine ecosystems. With the use of UAVs that carry high resolution multiband cameras, a great overview of an area can be achieved. With the use of satellite imagery we are incapable of spotting PPM nests but **with the use of UAVS nests can be spotted with high accuracy** and further analysis can provide the user with essential information regarding the vegetation's condition. When this information is visualized with high spatial precision, people who are related with forest management are equipped with one more useful tool that can save them time and unnecessary effort as UAVs can offer a real time fly over coverage of an area.

To answer Research Question 3, "*Are 3D maps more suitable for the specific case study compared to 2D maps*" ten experienced forest scientists were asked to evaluated a 3D prototype that we created by rendering UAV imagery and 3D Elevation Model. 2D maps seem to have a better application in visualizing a in a much simpler way vital data that are necessary for pest monitoring.

Further analysis such as buffer zones in 2D maps were characterized by the users more functional and can give the user a better view that will help in decision-making according to his/her knowledge in forest ecology. 3D maps though can provide the user an impressive overview of an area and help scientists having an idea of the slope, the terrain and the vegetation type that covers an area. To conclude, 2D maps tend to be more effective for monitoring and operational purposes when referring to pest control as further spatial analysis operations can be done (e.g. buffer zones and proximity analysis).

To answer Research Question 4**, “**What colors should be used to emphasize to the user an imminent threat”, a plethora of different color palettes was presented to ten experienced forest scientists and were asked to evaluate them. In general, users tended to consider green color as something positive and healthy whereas red, pink and orange give the user the impression that something threatening is visualized. Yellow color seems to be interpreted as a color that indicates a neutral status when vegetation is visualized. Polygons with multiple colors that indicate tree’s condition was the most popular visualization method for visualizing vegetation’s condition effectively as there was a high percentage of correct answers when green color was used for good health condition, red for critical and yellow for an intermediate status. Choropleth maps that indicate the health condition of each tree looks that is the most ideal style among the proposed.

6.2 Limitations and future work

This thesis investigated the role, the importance and the contribution of cartography by testing visual variables while parameters that need to be visualized on a screen for combating the PPM. Trees and nests are the most important elements of a map but other layers can contribute for a better and holistic understanding of the conditions in an area where the vegetation is threatened. For instance, layers that provide information about air or ground temperature, sun radiation, slope or aspect should be integrated and be at users’ disposal when required for analyzing the probability of PPM expansion.

Regarding the image processing and analysis, other vegetation indices can be used for further research. In this thesis we based the tree identification on the NDVI index whereas other vegetation indices such as EVI (Enhanced Vegetation Index), and/or MSAVI (Modified Soil Adjusted Vegetation Index) and/or NDRE (Normalized Difference Red Edge) for instance could possibly be tested for locating trees and their health condition in future research.

Potentially, other zoom extends should be investigated as in different level of detail users might expect to see something different than polygons or dots. For instance, when a user zooms in to view an area in detail, no visualization at all of polygons or dots might be a better option to view only the base map. The scale range that vegetation information is visible could be a topic of further investigation. Scale depended map-making relies on cartographic generalization, which aims at reducing the complexity in a map by reduction of the detail but maintaining the essential spatial information (Weibel, 1997; Raposo, 2017).

Trees are threatened by multiple factors in forest ecosystems. Thus, developing camera sensors that detect changes in specific spectral wavebands, particularly in the NIR and SWIR is needed. Application of thermal cameras might overcome the problem of confusing snow with PPM nests and further investigation should be conducted.

In conclusion, UAVs equipped with high resolution multispectral cameras provide us with imagery that deliver useful information to be mapped for PPM monitoring with many benefits and great potential for further application development. The majority of the proposed visualizations of the trees and nests have potential since the people who participated in our survey stated that they can be helpful and support the decisions for pest monitoring and behavior prediction as compared to satellite data, they are much more frequent, can be acquired on demand and offer the user the ability to view the PPM nests.

The use of multispectral camera sensors gives us the opportunity to individuate the PPM nests and the trees one by one due to the high resolution of the images and the increase albedo in that scale. Multispectral imaging is taking pictures of a scene or an item using a variety of distinct wavelength bands and then extracting the spectral information from the resulting data. Vegetation properties can be measured, vegetation can be mapped with great precision, vegetation degradation can be detected, and changes can be monitored.

As multispectral imagery data is the key and the foundation in combating threats that jeopardize forest ecosystems, further research regarding image classification and spectral signature analysis related with PPM nest identification should be conducted.

APPENDIX A: QUESTIONNAIRE

Dear Participant!

I would like to welcome you and thank you for your time that you spend on this questionnaire about helping us understand what kind of visualization you prefer to illustrate a Pine Processionary Moth population (PPM) breakout.

This study is a part of my M.Sc. Cartography thesis at the Technical University of Munich in Germany. The survey will ask you about your thoughts and perception of the proposed design and visualization and how you understand them. 20-25 minutes are approximately required to be completed.

It is best if you do it on the PC screen. All the information you share with us is anonymous and will only be used for the master thesis outlined above.

In case you have any questions or difficulties, please do not hesitate to contact me via email at alexandros.theofanidis@tum.de

Section 1. General Questions

1.1 What is your gender?

1. Male
2. Female
3. Rather not to say

1.2 How old are you?

1. 18-29
2. 30-39
3. 40-49
4. 50-59
5. 60+

1.3 Do you have any forest sciences academic background?

1. Yes
2. No

1.4 How many years of experience do you have with spatial data?

1. 1-2
2. 3-5
3. 5-10

1.5 Please rate the following statement

	Strongly Disagree	Disagree	Neither Agree or Disagree	Agree	Strongly Agree	N/A
I think I am a confident user of at least on GIS software	☐	☐	☐	☐	☐	☐
I think I am a quite experienced with spatial data interpretation	☐	☐	☐	☐	☐	☐
I think I am quite experienced with mapping forest ecosystems	☐	☐	☐	☐	☐	☐
I think I am quite experienced with pest monitoring	☐	☐	☐	☐	☐	☐
I think my eyes are trained enough to detect patterns just by looking on a map	☐	☐	☐	☐	☐	☐

Section 2. Tree visualization.

Fill and Color perception

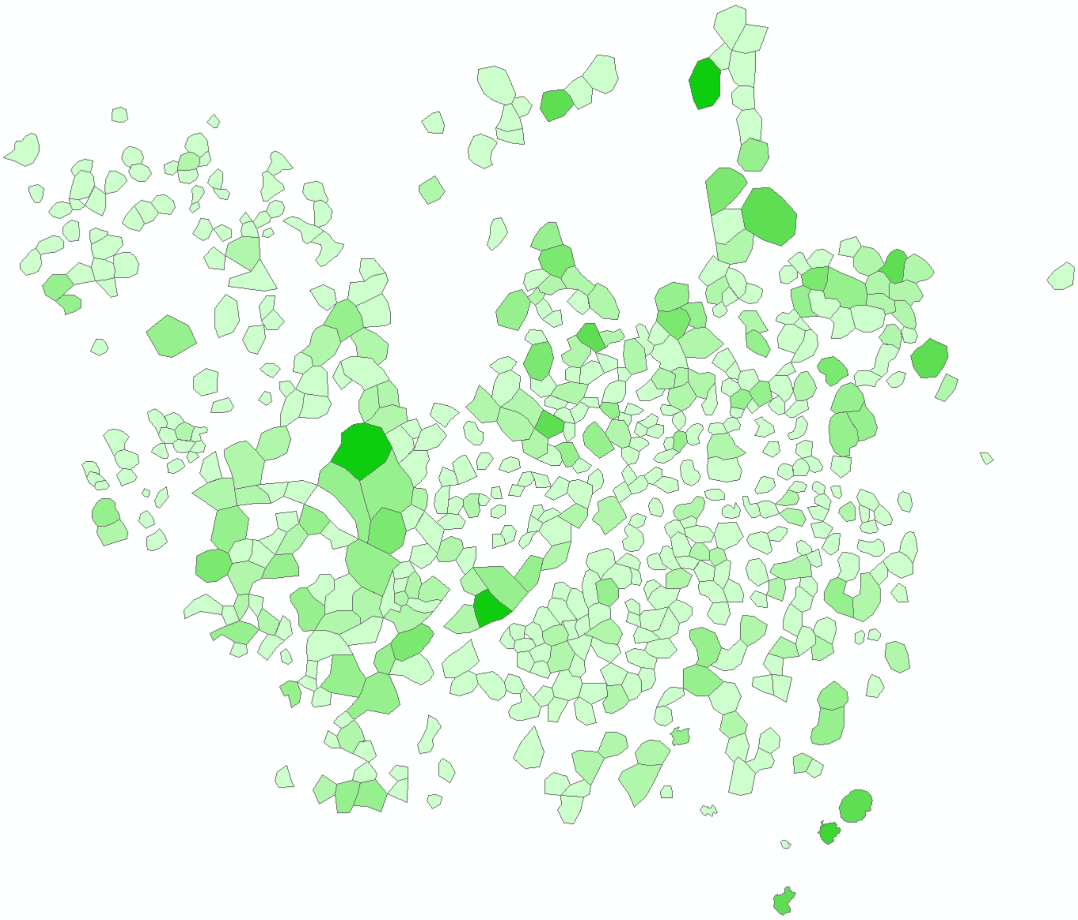
Visualizing the health condition of the trees based on the presence of PPM nests on them is the main subjects of this research. The polygons of the following screenshot represent tree canopies. The difference in the darkness, color hue, or color saturation of each polygon represents the density of the presence of PPM (Pine Processionary Moth) nests on a tree.

2.1 Please rate the following statement: Darker polygons represent trees that are healthy and have a small number of PPM nests or no nests at all on them.

1. Strongly agree
2. Agree
3. Neither agree nor disagree
4. Disagree
5. Strongly disagree

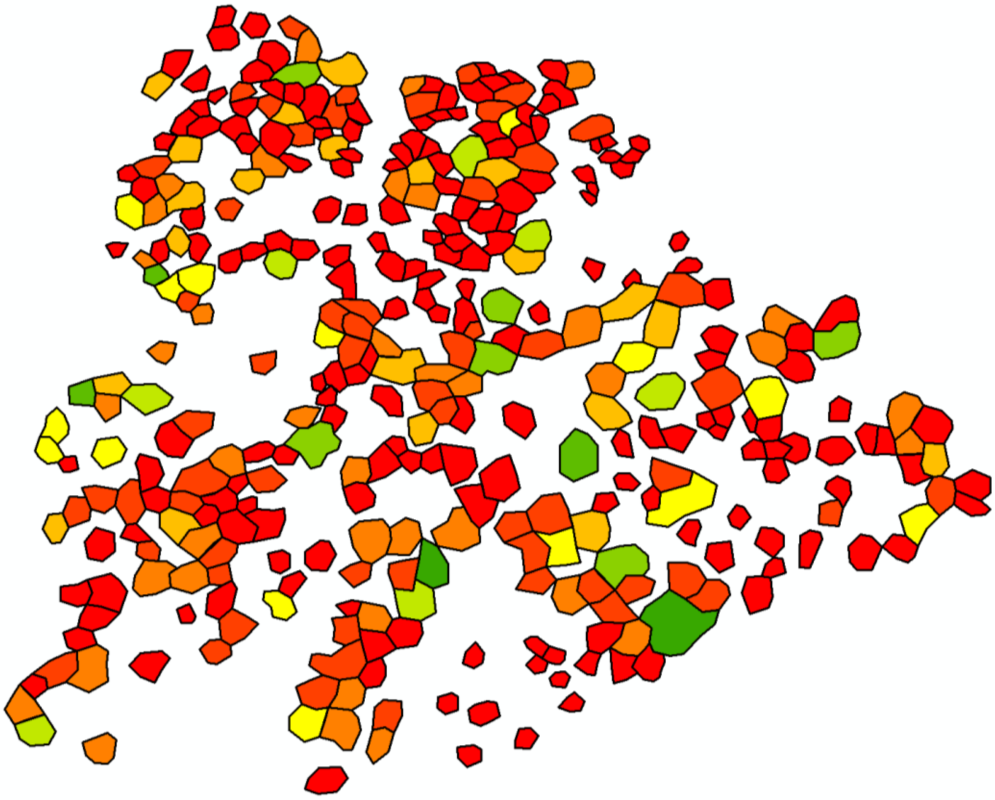
2.2 Please rate the following statement: Darker polygons represent trees that are healthy and have a small number of PPM nests or no nests at all on them.

1. Strongly agree
2. Agree
3. Neither agree nor disagree
4. Disagree
5. Strongly disagree



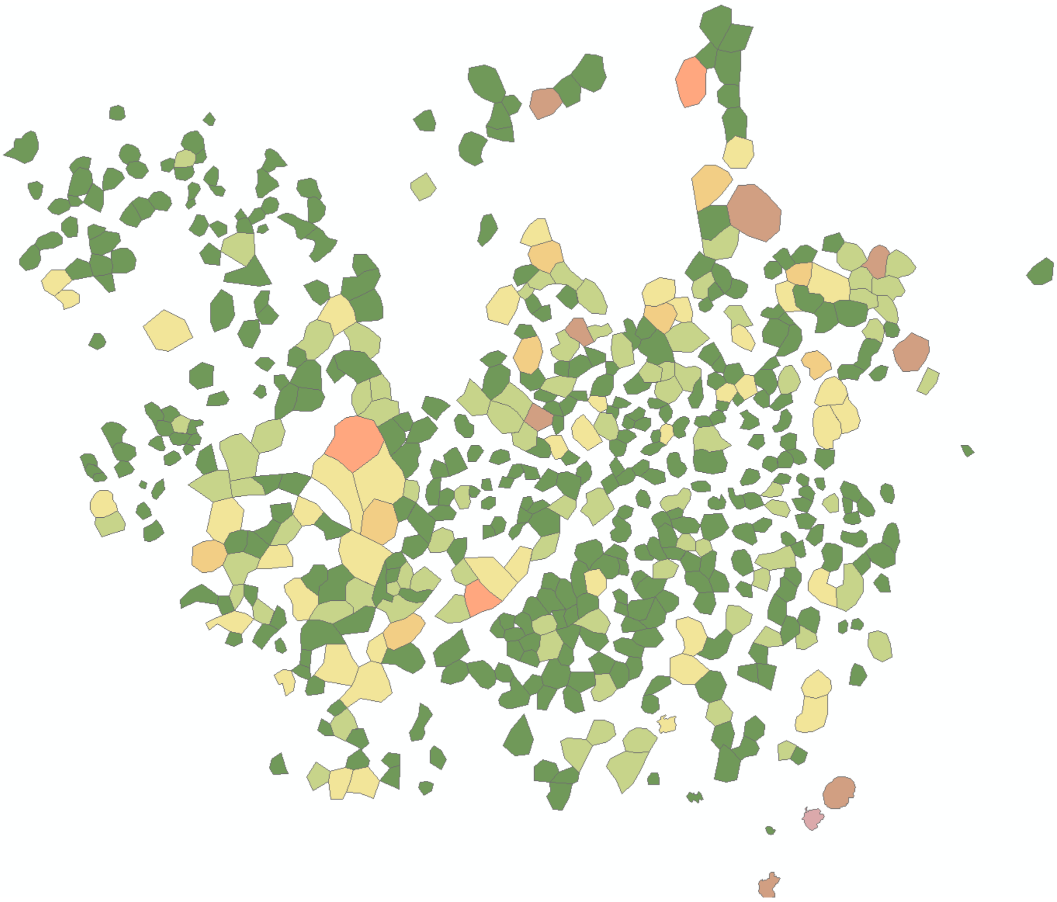
2.3 The polygons below the indicate trees of another area. Based on the color, you would assume that the healthiest trees with the less PPM nests on them are:

1. Vivid Red
2. Vivid Green
3. Light green
4. Orange
5. Yellow



2.4 Please rate the following statement: Green polygons represent trees that are healthy and have a small number of PPM nests or no nests at all on them.

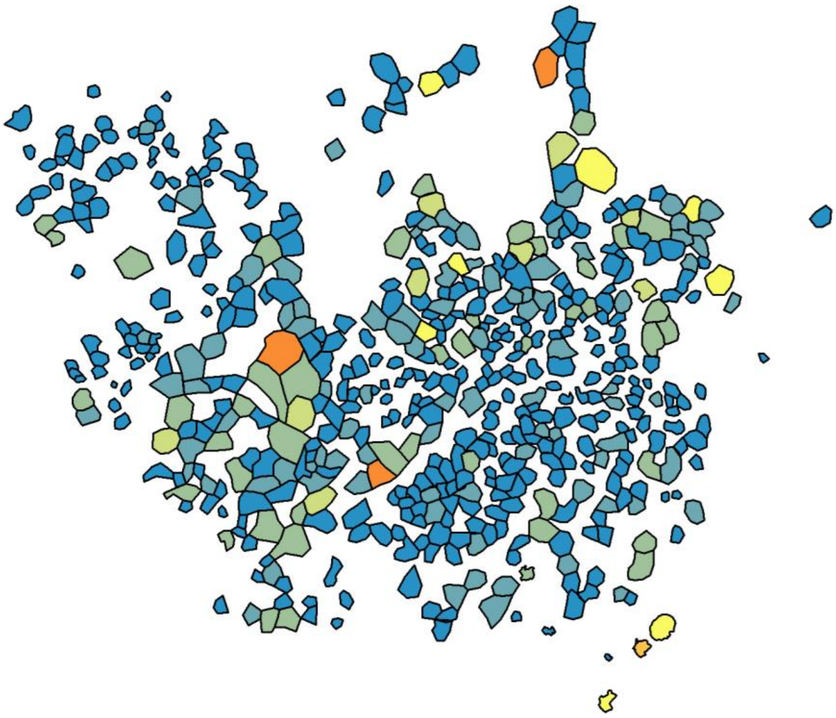
1. Strongly agree
2. Agree
3. Neither agree nor disagree
4. Disagree
5. Strongly disagree



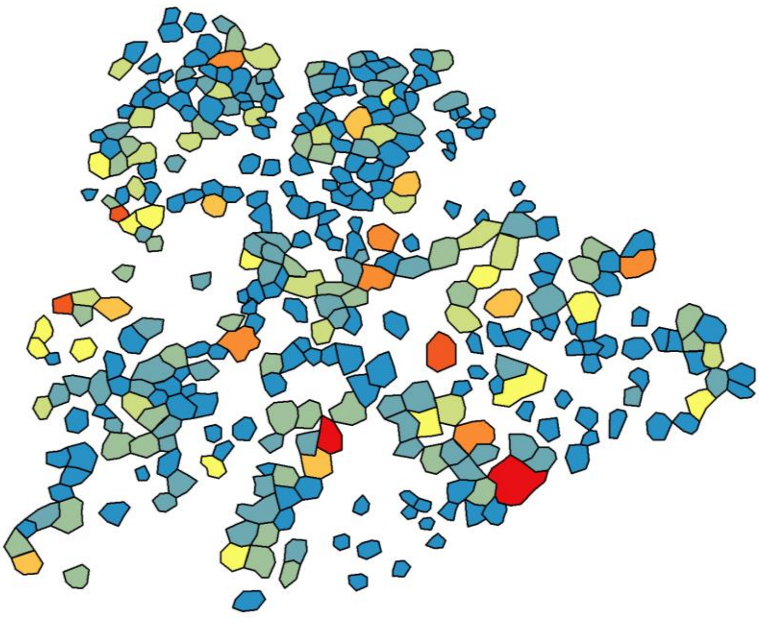
2.5 The two following pictures illustrate the trees of two different areas. Which area you think is more vulnerable to PPM and why?

1. Area 1
2. Area 2
3. Hard to say

AREA 1

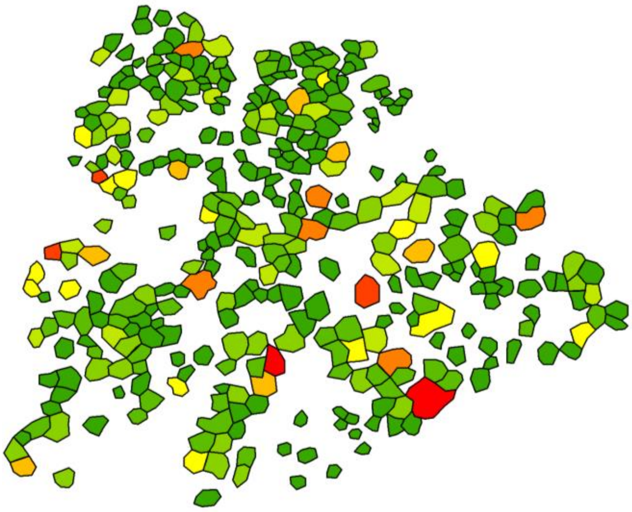


AREA 2



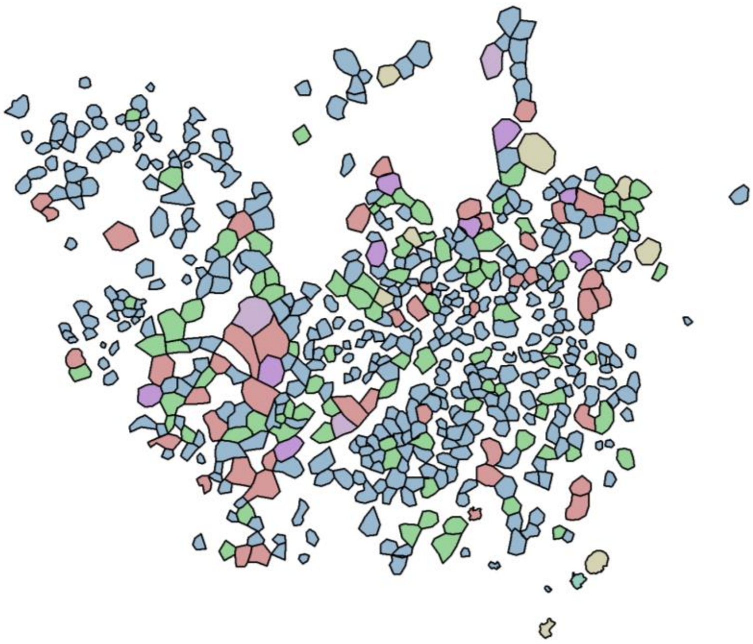
2.6 Based on the color of the polygons that indicate the density of PPM presence, how would you describe the general condition of this area?

1. Critical
2. Alarming
3. Safe
4. Hard to say



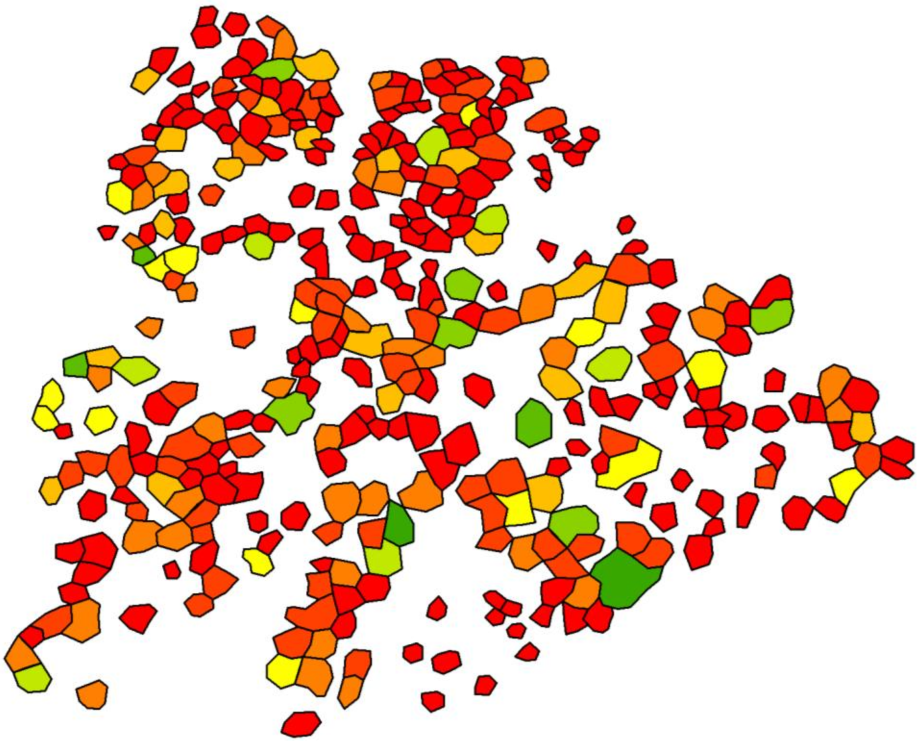
2.7 Based on the color of the polygons that indicate the density of PPM presence, how would you describe the general condition of this area?

1. Critical
2. Alarming
3. Safe
4. Hard to say



2.8 Based on the color of the polygons that indicate the density of PPM presence, how would you describe the general condition of this area?

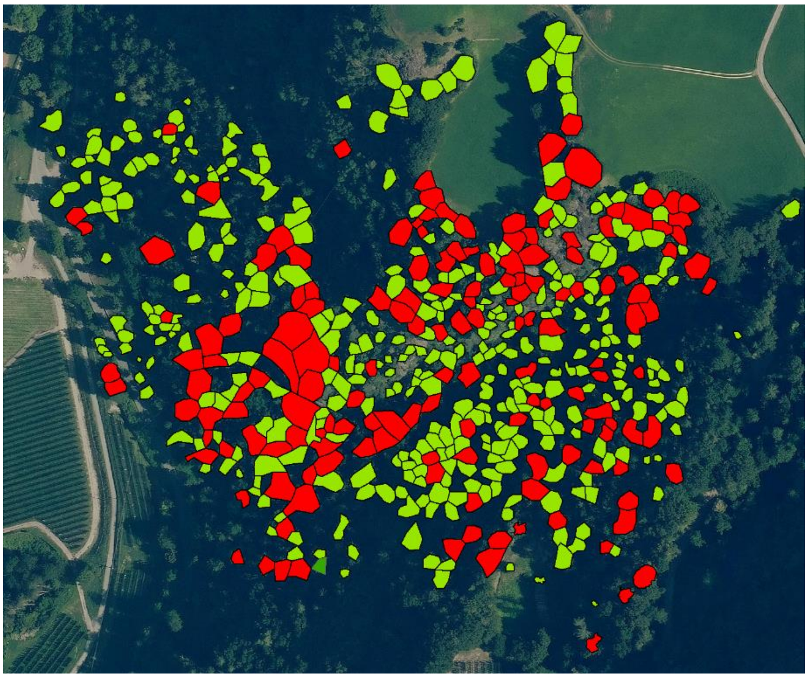
1. Critical
2. Alarming
3. Safe
4. Hard to say



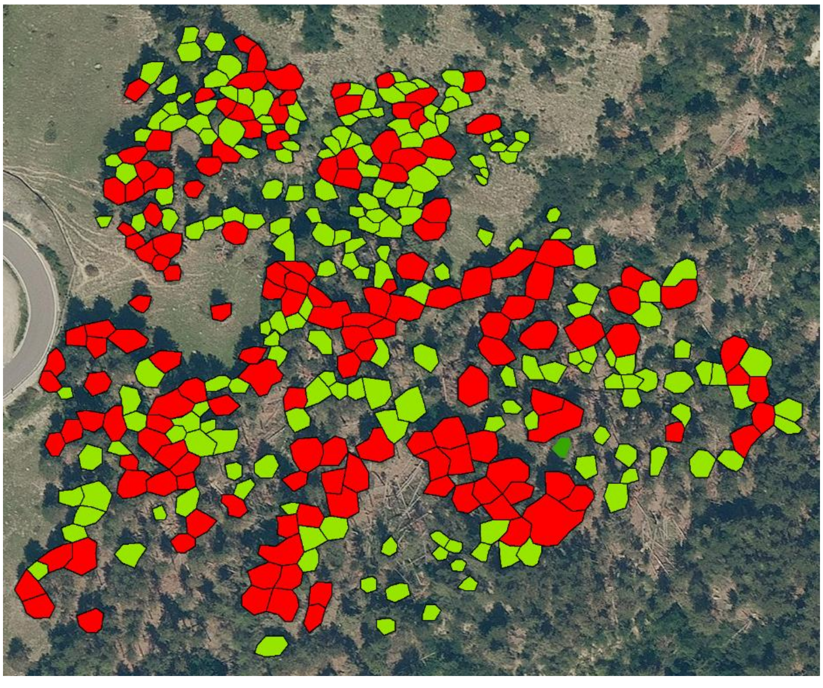
2.9 In the two following images trees are represented by two only colors. Which of the two areas would you say that is in a greater risk because of the PPM? Explain in short why.

1. Area 1
2. Area 2
3. Hard to say

AREA 1



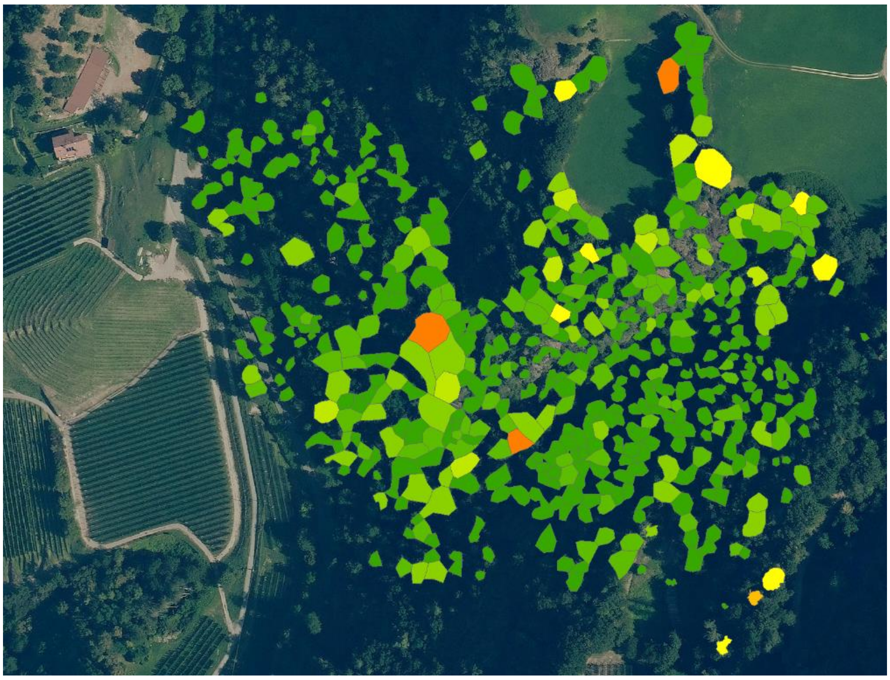
AREA 2



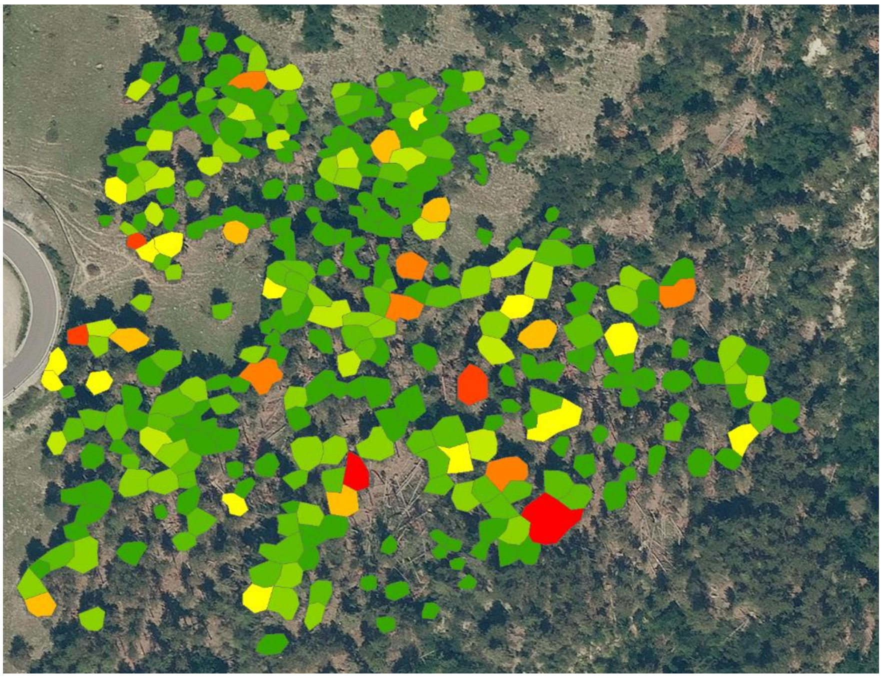
2.10 Which of the two areas would you say that is in a greater risk because of the PPM? Explain in short why.

1. Area 1
2. Area 2
3. Hard to say

AREA 1



AREA 2



Section 3. PPM Nest Visualization

In this section, you will explore the proposed ways of visualizing the nests that we located on the trees.

3.1 The red dots represent nests located on the trees. Which of the two areas would you say that is in a greater risk because of the PPM?

1. Area 1
2. Area 2
3. Hard to say

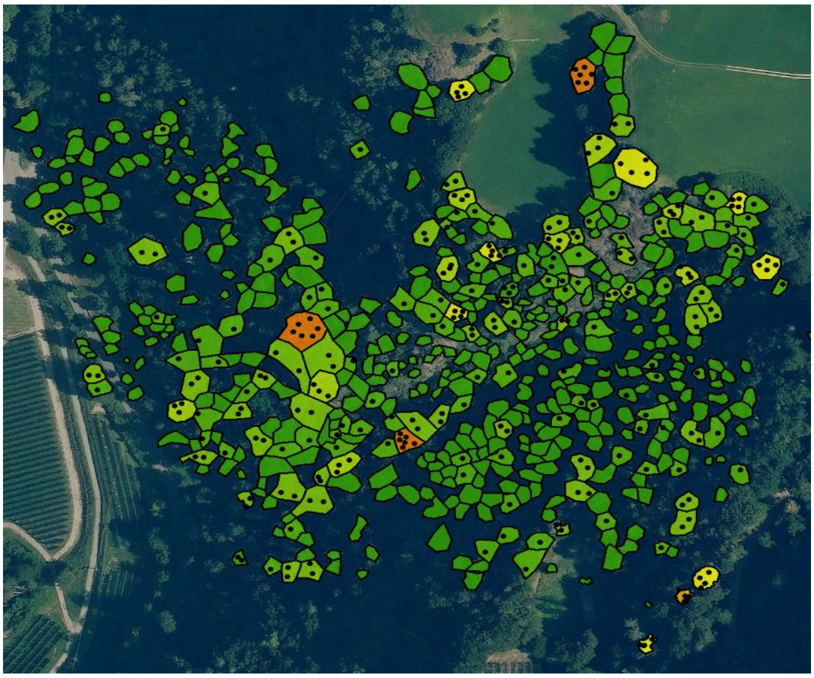
AREA 1

AREA 2

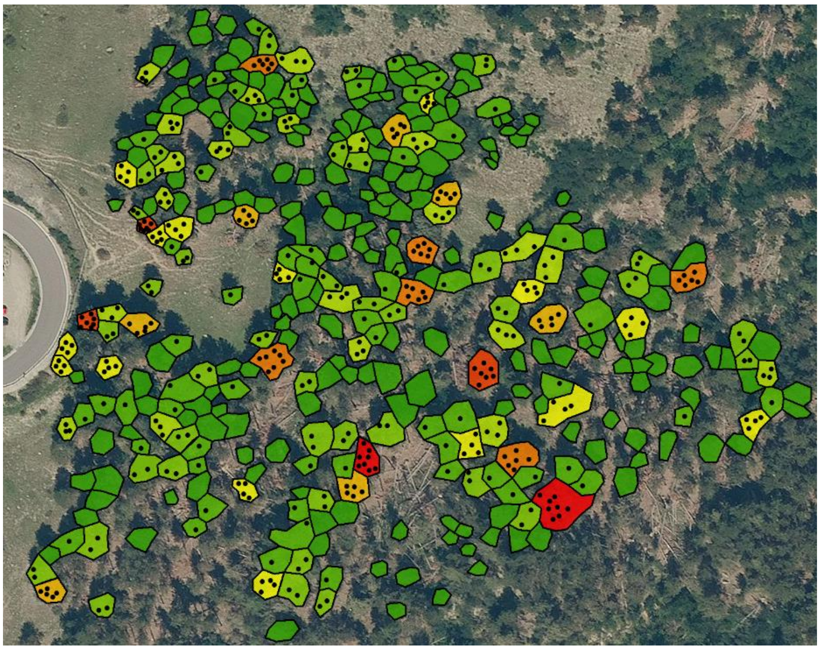
3.2 The black dots represent nests located on the trees and the polygons represent trees. The different color of each tree is related to the number of the nests on it. Which of the two areas would you say that is in a greater risk because of the PPM?

1. Area 1
2. Area 2
3. Hard to say

AREA 1



AREA 2

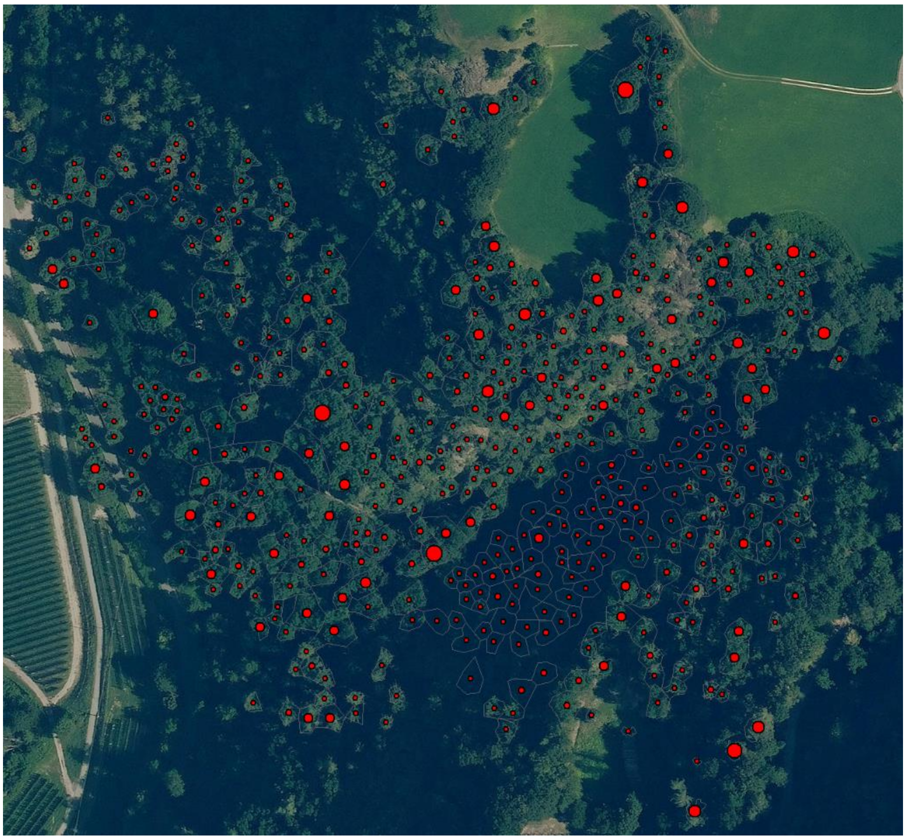


3.3 Can dots help you to better understand which trees are the mostly infested by the PPM?

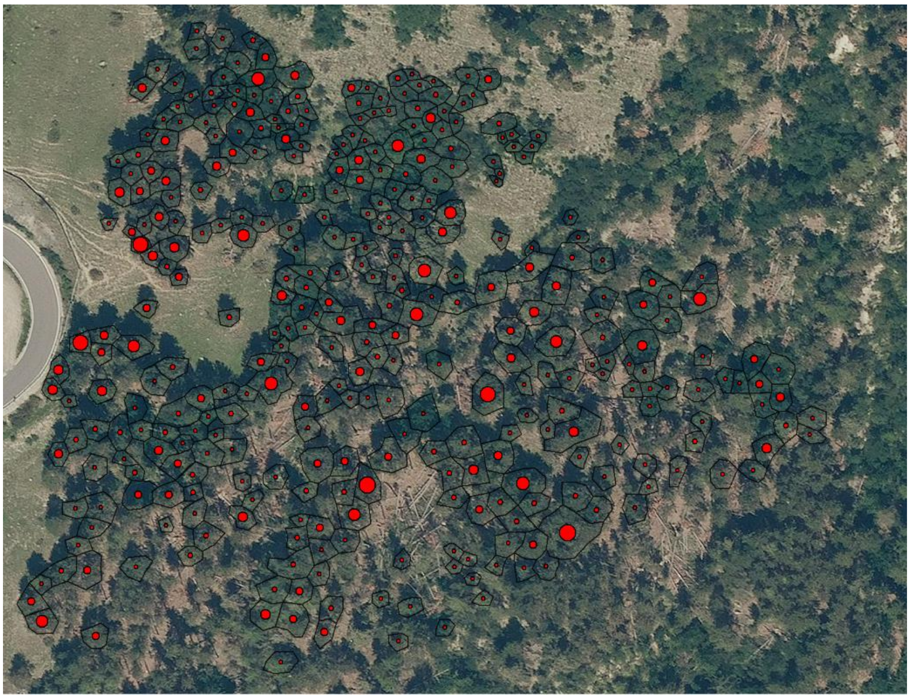
1. Yes
2. No

3.4 The red dots represent nest presence on the trees and the polygons represent trees. The greater the dot, the greater the number of the nests on a tree. Which of the two areas would you say that is in a greater risk because of the PPM?

AREA 1

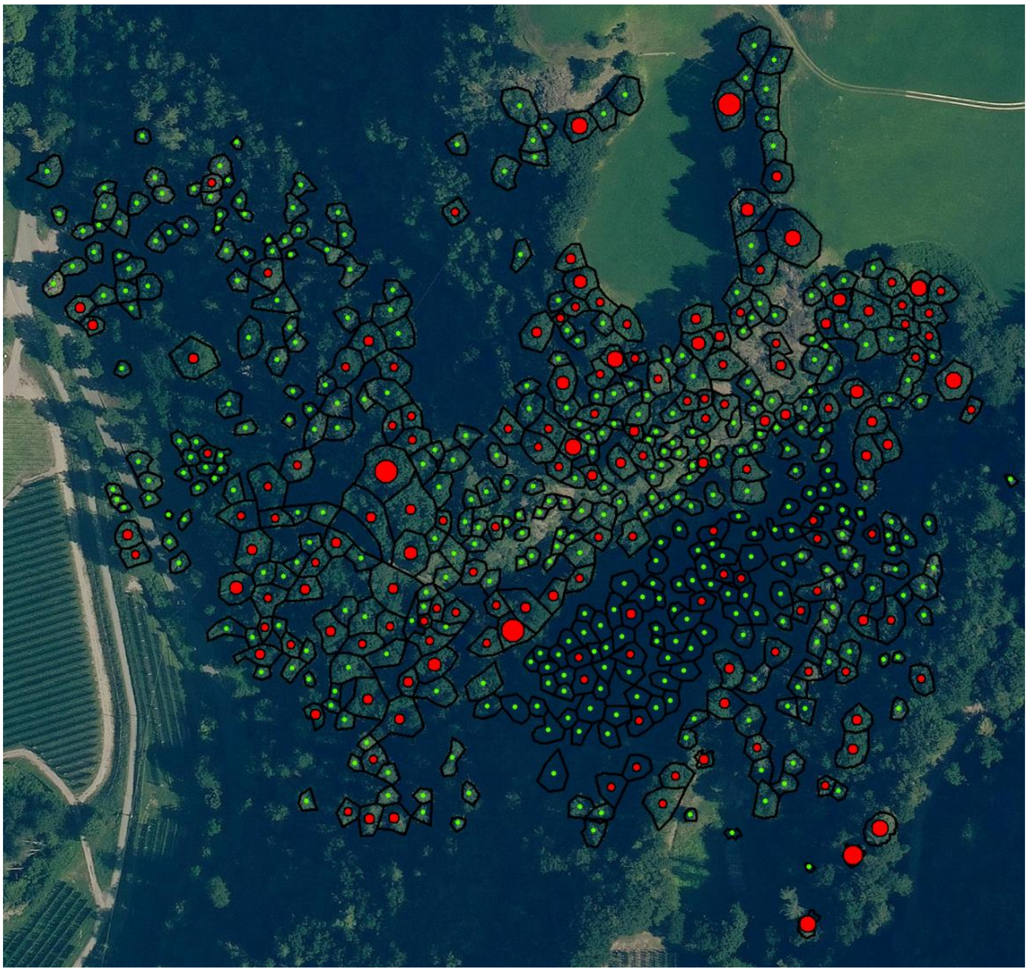


AREA 2



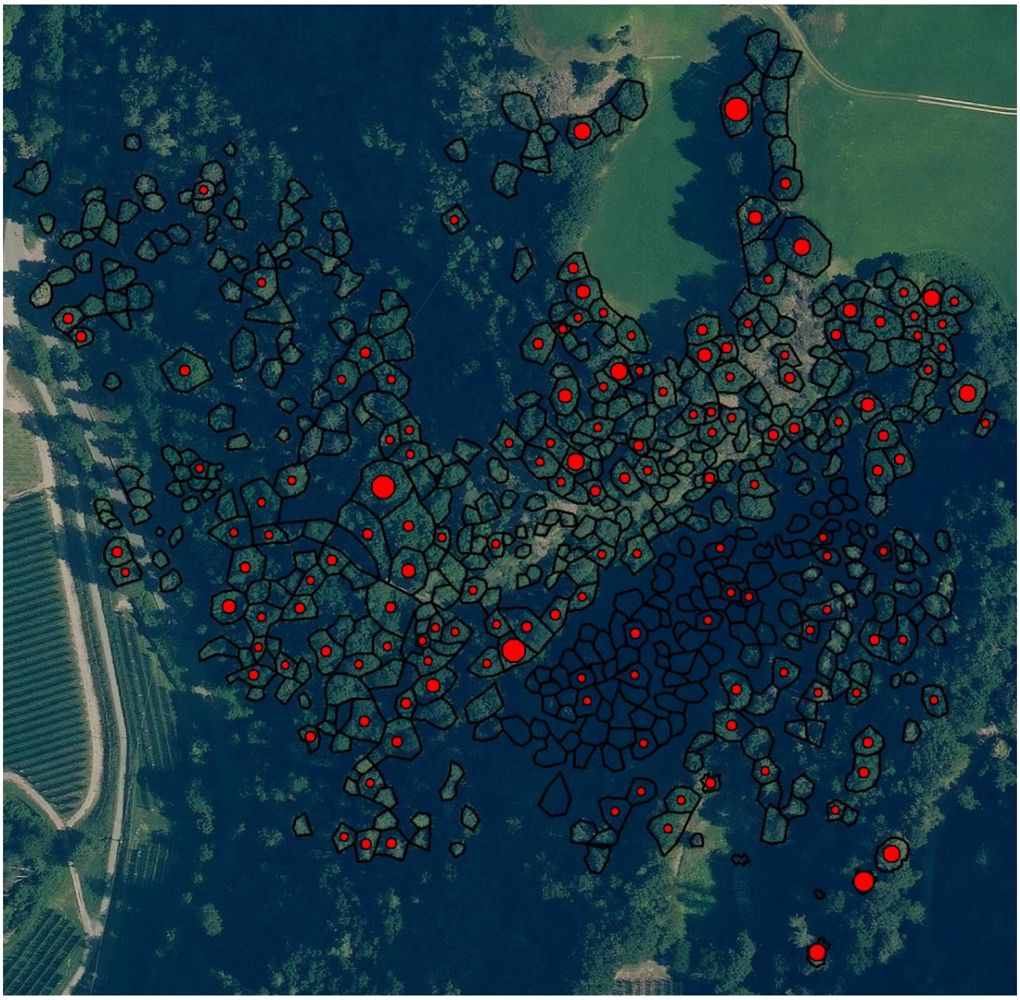
3.5 Please rate the following statement: Trees that have not infested by the PPM and there is no presence of a nest, should be marked with a green dot.

1. Strongly agree
2. Agree
3. Neither agree nor disagree
4. Disagree
5. Strongly disagree



3.6 Please rate the following statement: Trees that have not infested by the PPM and there is no presence of a nest, should be have no dot at all.

1. Strongly agree
2. Agree
3. Neither agree nor disagree
4. Disagree
5. Strongly disagree

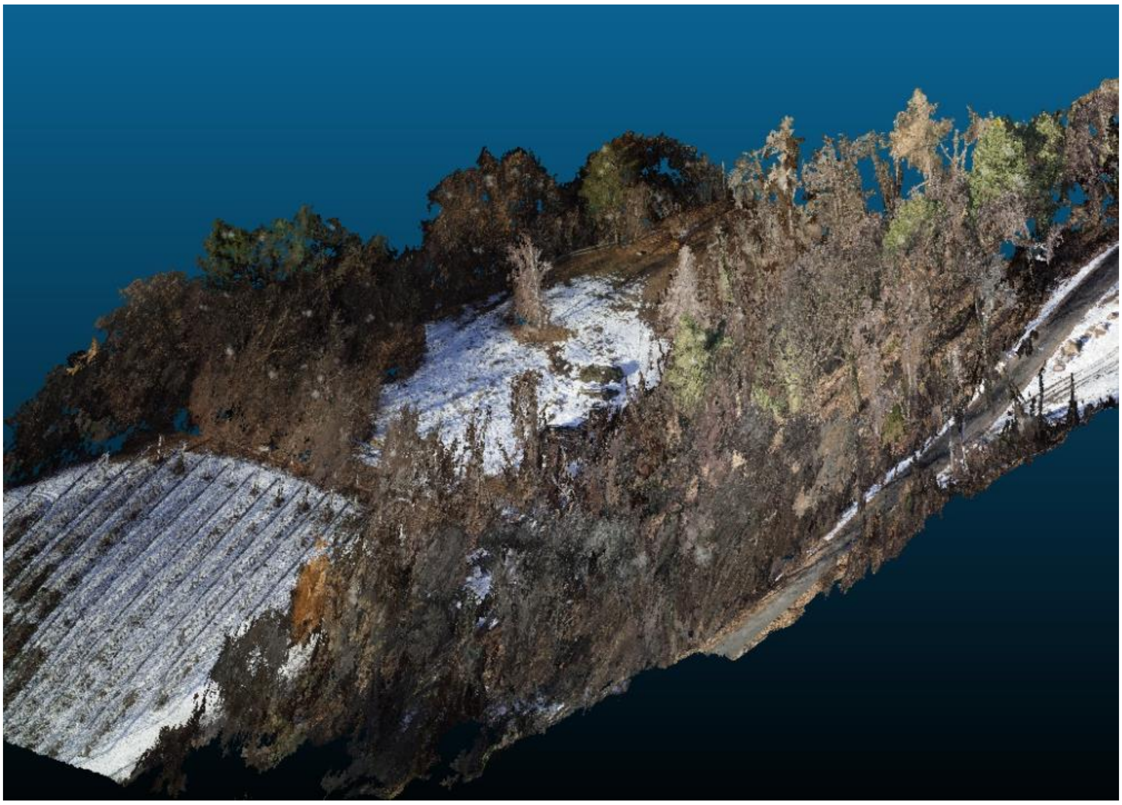


Section 4. Representation of Nests and Trees in 3D Environment.

In this section we present you a 3D model that we rendered by images we obtained with the use of an UAV and we visualized the nests that we located on the trees.

We have also built another 3d model of the province and we would like to know if 3d modeling and visualization contributes in better understanding the problem of the PPM expansion.

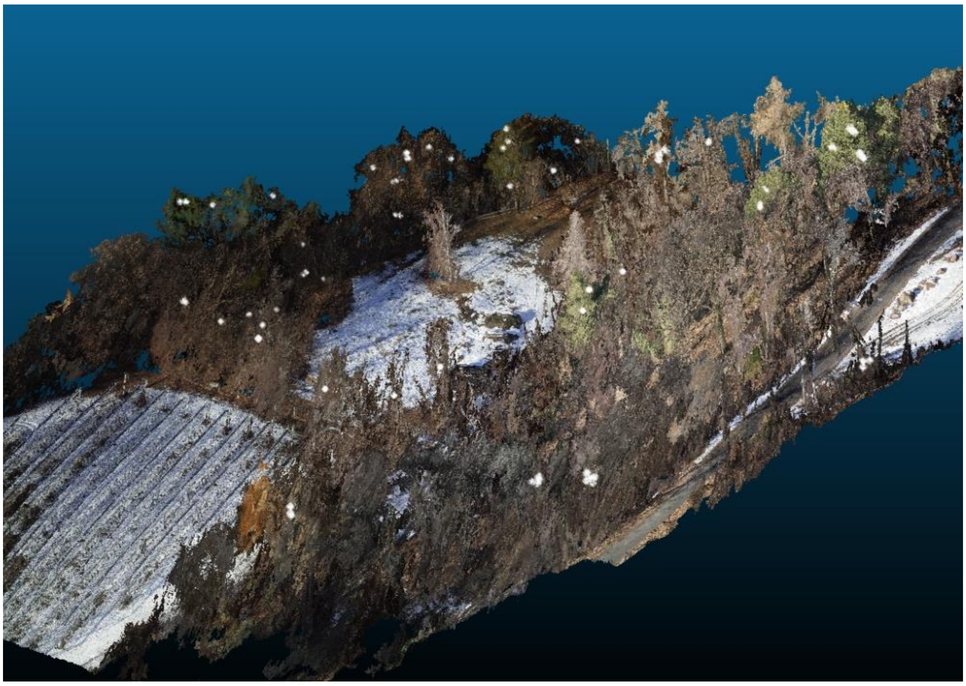
On the image below, we present you the area that we rendered for having a 3D model.



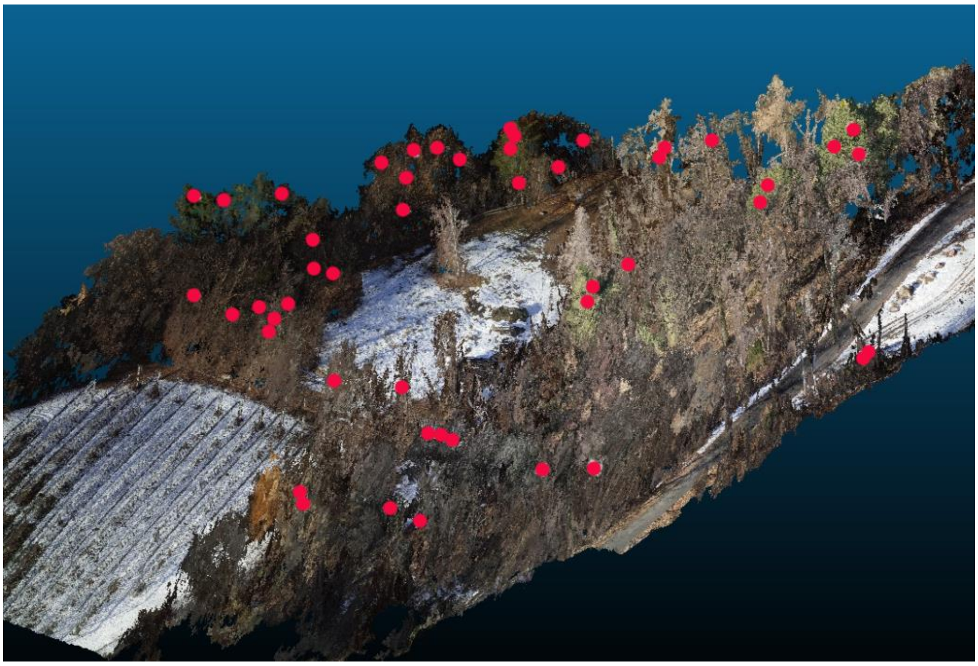
4.1 Can you clearly identify and locate the PPM nests?

1. Yes
2. No
3. Hard to say

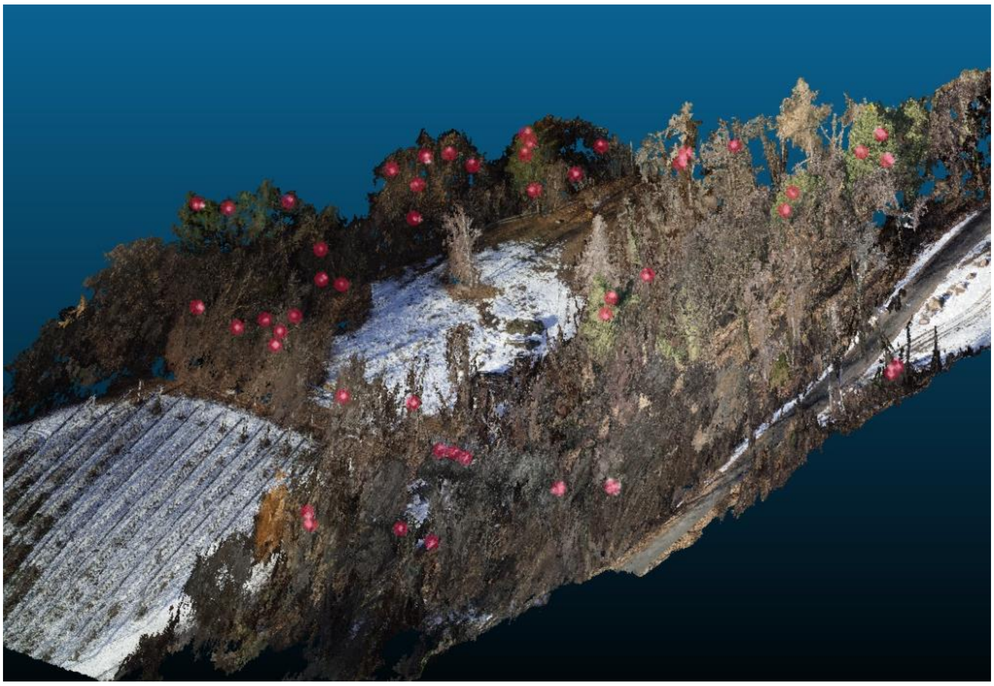
NESTS in WHITE EMPHASIZED



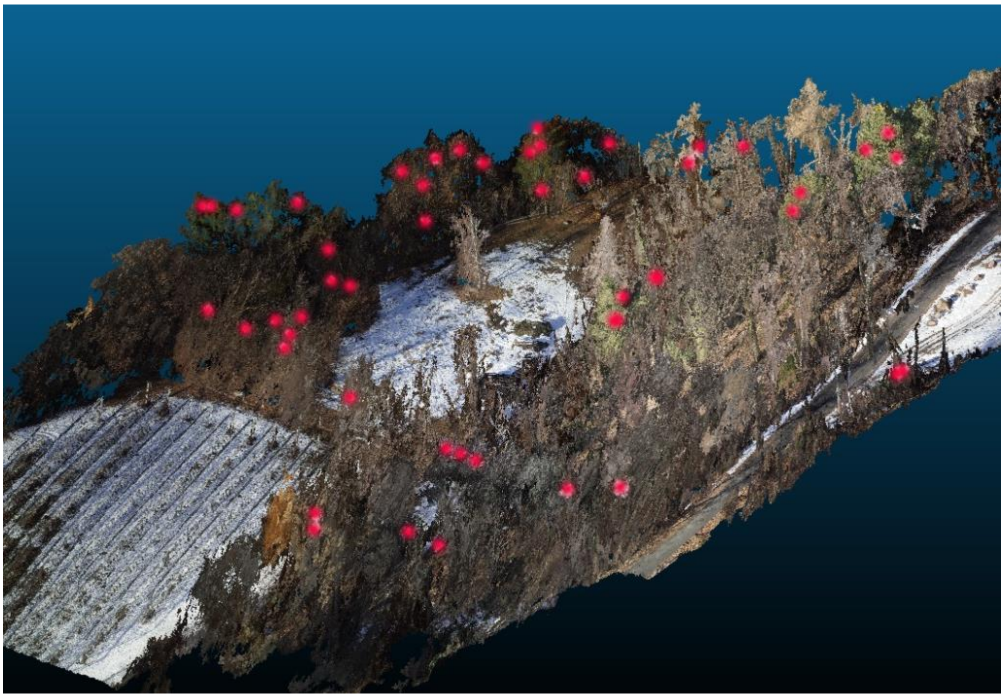
NESTS ILLUSTRATED AS RED DOTS (Hard Shape)



NESTS ILLUSTRATED AS RED DOTS with 70% TRANSPARENCY



NESTS ILLUSTRATED AS RED DOTS WITH REDUSED CRISPNESS



4.2 Please, rank the above presented illustrations of the nests based on how natural they fit with the forest, with 1 being the best.

- Nests emphasized with white color _______
- Nests illustrated as red dots strong silhouette _______
- Nests illustrated as red dots with 70% transparency _______
- Nests illustrated as red dots with reduced crispness _______

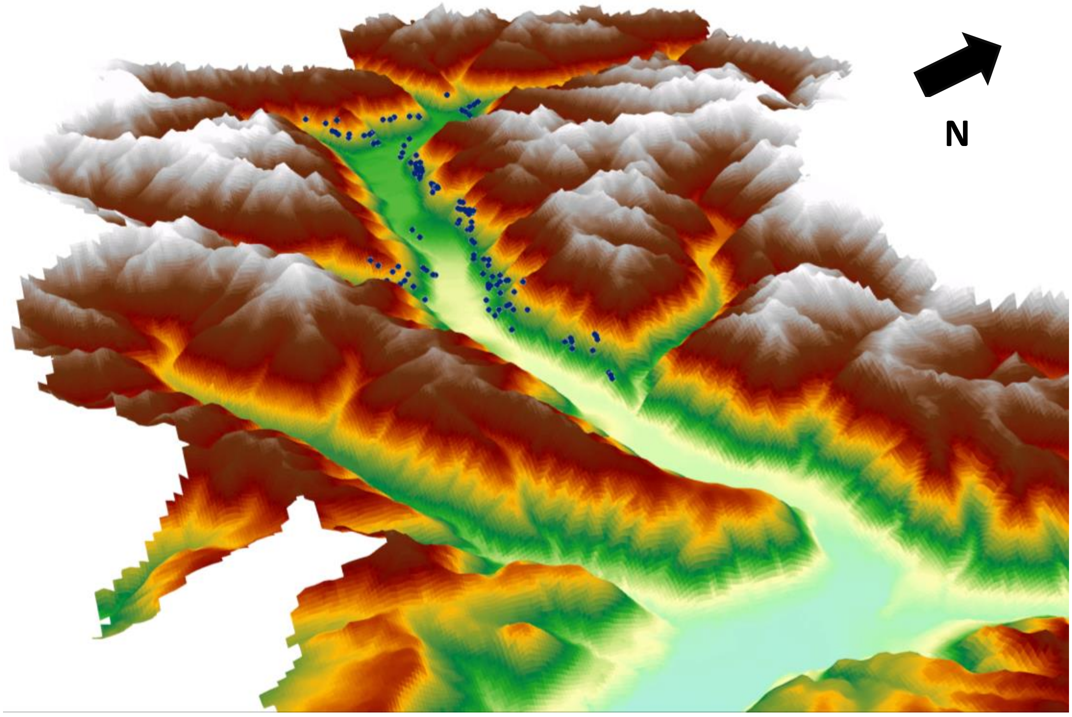
4.3 Please, rank the above presented illustrations of the nests based on how easy for your eyes to identify their location, with 1 being the best.

- Nests emphasized with white color _______
- Nests illustrated as red dots strong silhouette _______
- Nests illustrated as red dots with 70% transparency _______
- Nests illustrated as red dots with reduced crispness _______

4.4 Which one do you think is the best for you? Please rank your options with 1 being the best and write on the box below why you chose it.

- Nests emphasized with white color _______
- Nests illustrated as red dots strong silhouette _______
- Nests illustrated as red dots with 70% transparency _______
- Nests illustrated as red dots with reduced crispness _______

4.5 On the image below, we visualized confirmed cites that the presence of the PPM seems to be alarming (blue dots). As a forest scientist, what kind of information could you derive by just looking at this 3D Elevation model? Use the box below for your answer.



4.6 Now that you have an overview of the different visualization methods that we propose for a web-map to illustrate a population breakout of the PPM, please describe in few words how cartography contributes to manage and protect forests from the PPM threat.

THANK YOU FOR YOUR TIME AND YOUR CONTRIBUTION!

APPENDIX B: MICASENSE REDEDGE-M TECHNICAL SPECIFICATIONS

Figure 94: Micasense RedEdge-M camera (Aeromotus, 2022)

MicaSense RedEdge-M	
Weight:	170 g (Including DLS)
Dimensions:	9.4 cm x 6.3 cm x 4.6 cm (3.7” x 2.5” x 1.8”)
External Power:	4.2V-15.8V, 4 W nominal, 8W peak
Spectral Bands:	Narrowband: Blue, Green, Red, Red Edge, Near IR
Ground Sample Distance (GSD):	8.2 cm/pixel (per band) at 120 m (400 ft.) AGL
Capture Rate:	1 capture per second (all bands), 12-bit RAW
Wavelength (nm):	Blue (475 nm center ± 20 nm), green (560 nm ± 20 nm), red (668 nm center ± 10 nm), red edge (717 nm ± 10 nm), near-IR (840 nm ± 40 nm)

Table 7: MicaSense RedEdge-M Specifications

Source: *(Mavtech S.r.l., 2022)*

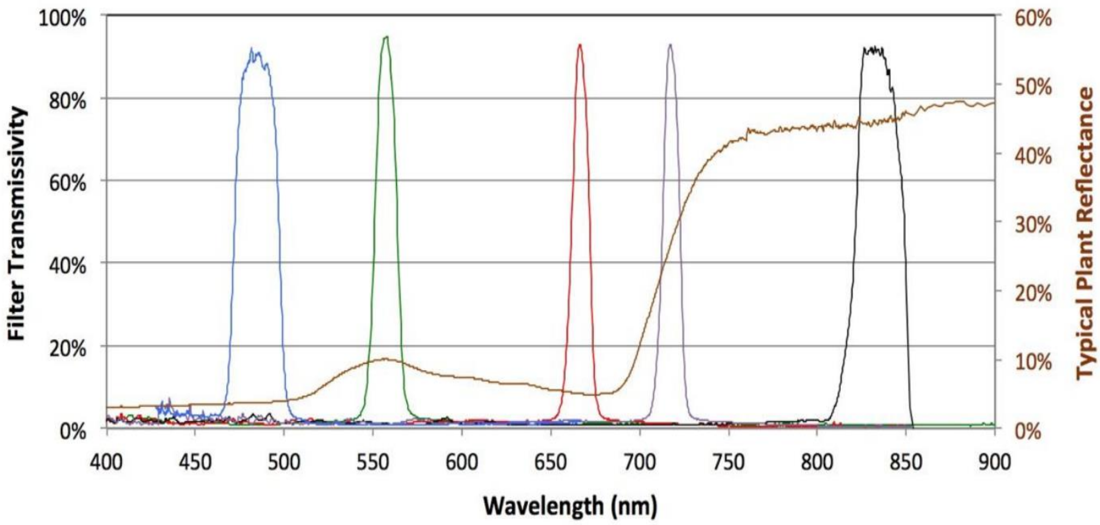


Figure 95: Typical plant reflectance and filter transmissivity wavelength (MicaSense Inc, 2017)

BAND NUMBER	BAND NAME	BAND NAME CENTER WAVELENGTH (nm)	BANDWIDTH FWHM (nm)
1	Blue	475	20
2	Green	560	20
3	Red	668	10
4	Near IR	840	40
5	Red Edge	717	10

Table 8: Band specifications of MicaSense RedEdge-M (MicaSense Inc, 2017)

REFERENCES

Adrián Cardil, Udayalakshmi Vepakomma, & Lluis Brotons. (2017). *Assessing Pine Processionary Moth Defoliation Using Unmanned Aerial Systems*.

Aeromotus. (2022). *Micasense RedEdge-M Multispectral Sensor*. AEROMOTUS. https://www.aeromotus.com/product/rededge-m/

Ahmad, F., & Goparaju, L. (2017). Assessment of Threats to Forest Ecosystems Using Geospatial Technology in Jharkhand State of India. *Current World Environment*, *12*(2), 355–365. https://doi.org/10.12944/CWE.12.2.19

Ampatzidis, Y., & Partel, V. (2019). UAV-Based High Throughput Phenotyping in Citrus Utilizing Multispectral Imaging and Artificial Intelligence. *Remote Sensing*, *11*, 410. https://doi.org/10.3390/rs11040410

Bade, B. (2020). *All you need to know about NDVI*. https://bikeshbade.com.np/tutorials/Detail/?title=All%20you%20need%20to%20know%20about%20NDVI&code=19

Bannari, A., Morin, D., Bonn, F., & Huete, A. R. (1995). A review of vegetation indices. *Remote Sensing Reviews*, *13*(1–2), 95–120. https://doi.org/10.1080/02757259509532298

Bartkowiak, P., Castelli, M., Crespi, A., Niedrist, G., Zanotelli, D., Colombo, R., & Notarnicola, C. (2022). Land Surface Temperature Reconstruction Under Long-Term Cloudy-Sky Conditions at 250 m Spatial Resolution: Case Study of Vinschgau/Venosta Valley in the European Alps. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *15*, 2037–2057. https://doi.org/10.1109/JSTARS.2022.3147356

Battisti, A., Avcı, M., Avtzis, D. N., Jamaa, M. L. B., Berardi, L., Berretima, W., Branco, M., Chakali, G., El Alaoui El Fels, M. A., & Frérot, B. (2015). Natural history of the processionary moths (Thaumetopoea spp.): New insights in relation to climate change. In *Processionary moths and climate change: An update* (pp. 15–79). Springer.

Battisti, A., Stastny, M., Netherer, S., Robinet, C., Schopf, A., Roques, A., & Larsson, S. (2005). Expansion of Geographic Range in the Pine Processionary Moth Caused by Increased Winter Temperatures. *Ecological Applications*, *15*(6), 2084–2096. https://doi.org/10.1890/04-1903

Bertin, J. (1983a). *Semiology of graphics*. University of Wisconsin press.

Bertin, J. (1983b). *Visual Representation from Semiology of Graphics*.

Brewer, C. A. (2005). Designing better maps. *A Guide for GIS Users*, *1*.

Buckley, A., & Field, K. (2011). *Making a Meaningful Map*. 4.

Buczkowski, A. (2015). *Beyond NDVI: What are vegetation indices, and how are they used in precision farming?* Geoawesomeness. https://geoawesomeness.com/eo-hub/beyond-ndvi-what-are-vegetation-indices-and-how-are-they-used-in-precision-farming/

Burg, J. P. (1975). *Maximum entropy spectral analysis.* Stanford University.

Caivano, J. L. (1990). *Visual texture as a semiotic system*.

Campbell, J. B., & Wynne, R. H. (2011). *Introduction to Remote Sensing, Fifth Edition*. Guilford Press.

Carter, G. A., & Knapp, A. K. (2001). Leaf optical properties in higher plants: Linking spectral characteristics to stress and chlorophyll concentration. *American Journal of Botany*, *88*(4), 677–684. https://doi.org/10.2307/2657068

Carus, S. (2004). Impact of defoliation by the pine processionary moth (Thaumetopoea pityocampa) on radial, height and volume growth of calabrian pine (Pinus brutia) trees in Turkey. *Phytoparasitica*, *32*(5), 459–469. https://doi.org/10.1007/BF02980440

Chen, D., & Stow, D. (2002). The Effect of Training Strategies on Supervised Classification at Different Spatial Resolutions. *Photogrammetric Engineering and Remote Sensing*, *68*.

Chen, Y., Wang, Q., Wang, Y., Duan, S.-B., Xu, M., & Li, Z.-L. (2016). A Spectral Signature Shape-Based Algorithm for Landsat Image Classification. *ISPRS International Journal of Geo-Information*, *5*(9), 154. https://doi.org/10.3390/ijgi5090154

Copernicus. (2022). *EU-DEM v1.1—Copernicus Land Monitoring Service* [Land item]. https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1

Crespi, A., Matiu, M., Bertoldi, G., Petitta, M., & Zebisch, M. (2020). *High-resolution daily series (1980—2018) and monthly climatologies (1981—2010) of mean temperature and precipitation for Trentino—South Tyrol (north-eastern Italian Alps)* [Data set]. PANGAEA. https://doi.org/10.1594/PANGAEA.924502

Dale, V. H., & Pearson, S. M. (1997). Quantifying habitat fragmentation due to land-use change in Amazonia. *WF Laurance and RO Bierregaard, Editors. Tropical Forest Remnants: Ecology, Management, and Conservation of Fragmented Communities. University of Chicago Press, Chicago, Illinois, USA*.

Durrant, T. H., De Rigo, D., & Caudullo, G. (2016). Pinus sylvestris in Europe: Distribution, habitat, usage and threats. *European Atlas of Forest Tree Species*, 132–133.

ESRI. (n.d.). *Making a Meaningful Map*. Retrieved November 25, 2022, from https://www.esri.com/news/arcuser/0911/making-a-map-meaningful.html

European Environment Agency. (2020). *Trends in annual temperature across Europe between 1990 and 2019—European Environment Agency* [Figure]. https://www.eea.europa.eu/data-and-maps/figures/trends-in-annual-temperature-across

European Environment Agency. (2022). *Italy shapefile—European Environment Agency* [Data File]. https://www.eea.europa.eu/data-and-maps/data/eea-reference-grids-2/gis-files/italy-shapefile

Fang, H., & Liang, S. (2014). Leaf Area Index Models. In *Encyclopedia of Ecology*. https://doi.org/10.1016/B978-0-12-409548-9.09076-X

Forest Research. (2022). Pine processionary moth (Thaumetopoea pityocampa). *Forest Research*. https://www.forestresearch.gov.uk/tools-and-resources/fthr/pest-and-disease-resources/pine-processionary-moth-thaumetopoea-pityocampa/

Gikunda, A. (2021, October 17). *17 Differences between Passive and Active Remote Sensing*. https://grindgis.com/remote-sensing/17-differences-between-passive-and-active-remote-sensing

GISGeography. (2014, May 2). *Image Classification Techniques in Remote Sensing*. GIS Geography. https://gisgeography.com/image-classification-techniques-remote-sensing/

GISGeography. (2015, February 9). *Passive vs Active Sensors in Remote Sensing*. GIS Geography. https://gisgeography.com/passive-active-sensors-remote-sensing/

GISGeography. (2017, May 9). *What is NDVI (Normalized Difference Vegetation Index)?* GIS Geography. https://gisgeography.com/ndvi-normalized-difference-vegetation-index/

GISGeography. (2018, July 16). *Dot Distribution vs Graduated Symbols vs Proportional Symbol Maps*. GIS Geography. https://gisgeography.com/dot-distribution-graduated-symbols-proportional-symbol-maps/

Hoch, G., Toffolo, E. P., Netherer, S., Battisti, A., & Schopf, A. (2009). Survival at low temperature of larvae of the pine processionary moth Thaumetopoea pityocampa from an area of range expansion. *Agricultural and Forest Entomology*, *11*(3), 313–320. https://doi.org/10.1111/j.1461-9563.2009.00431.x

Hódar, J. A., Castro, J., & Zamora, R. (2003). Pine processionary caterpillar Thaumetopoea pityocampa as a new threat for relict Mediterranean Scots pine forests under climatic warming. *Biological Conservation*, *110*(1), 123–129.

Homayouni, S., & Roux, M. (2004). *Hyperspectral Iamge Analysis for material mapping using spectral matching*. https://www.semanticscholar.org/paper/HYPERSPECTRAL-IMAGE-ANALYSIS-FOR-MATERIAL-MAPPING-Homayouni-Roux/ac06f2744eebe70a06e8d5e9a32fc4998c8eeccc

Hubert-Moy, L., Cotonnec, A., Le Du, L., Chardin, A., & Perez, P. (2001). A Comparison of Parametric Classification Procedures of Remotely Sensed Data Applied on Different Landscape Units. *Remote Sensing of Environment*, *75*(2), 174–187. https://doi.org/10.1016/S0034-4257(00)00165-6

Huchon, H., & Demolin, G. (1970). La bioécologie de la Processionnaire du pin: Dispersion potentielle, dispersion actuelle. *Revue Forestière Française*, *22*(S), 220–234.

ICA. (2003). *A Strategic Plan for the International Cartographic Association 2003-2011*. 18.

Ioseliani, N. (2021). *Visualizing Decision-Relevant Map Layers to Support Travel Planning*.

Jactel, H., Barbaro, L., Battisti, A., Bosc, A., Branco, M., Brockerhoff, E., Castagneyrol, B., Dulaurent, A.-M., Hódar, J. A., Jacquet, J.-S., Mateus, E., Paiva, M.-R., Roques, A., Samalens, J.-C., Santos, H., & Schlyter, F. (2015). Insect – Tree Interactions in Thaumetopoea pityocampa. In A. Roques (Ed.), *Processionary Moths and Climate Change: An Update* (pp. 265–310). Springer Netherlands. https://doi.org/10.1007/978-94-017-9340-7_6

Jones, H. G., Archer, N., Rotenberg, E., & Casa, R. (2003). Radiation measurement for plant ecophysiology. *Journal of Experimental Botany*, *54*(384), 879–889. https://doi.org/10.1093/jxb/erg116

Kachhwaha, T. S. (1983). Spectral signatures obtained from Landsat digital data for forest vegetation and land-use mapping in India. *Photogrammetric Engineering and Remote Sensing*, *49*(5), 685–689.

Kerdelhué, C., Zane, L., Simonato, M., Salvato, P., Rousselet, J., Roques, A., & Battisti, A. (2009). Quaternary history and contemporary patterns in a currently expanding species. *BMC Evolutionary Biology*, *9*, 220. https://doi.org/10.1186/1471-2148-9-220

Kraak, J. M., & Ormeling, F. (1998). Kartografia, wizualizacja danych przestrzennych, Warszawa: Wydawnictwo Naukowe PWN. *Search In*, 113–130.

Kraak, M.-J., Roth, R. E., Ricker, B., Kagawa, A., & Le Sourd, G. (2021). *Mapping for a sustainable world*.

Landgrebe, D. A. (2003). *Signal Theory Methods in Multispectral Remote Sensing*. John Wiley & Sons.

Lechner, A. M., Foody, G. M., & Boyd, D. S. (2020). Applications in remote sensing to forest ecology and management. *One Earth*, *2*(5), 405–412.

Lu, D., & Weng, Q. (2007). A survey of image classification methods and techniques for improving classification performance. *International Journal of Remote Sensing*, *28*(5), 823–870. https://doi.org/10.1080/01431160600746456

MacEachren, A. M. (1992). Visualizing uncertain information. *Cartographic Perspectives*, *13*, 10–19.

MacEachren, A. M. (1995). *How maps work: Representation, visualization, and design*. Guilford Press.

MacEachren, A. M., Roth, R. E., O'Brien, J., Li, B., Swingley, D., & Gahegan, M. (2012). Visual semiotics & uncertainty visualization: An empirical study. *IEEE Transactions on Visualization and Computer Graphics*, *18*(12), 2496–2505.

Mai, T. (2015, May 6). *What are passive and active sensors?* NASA; Brian Dunbar. http://www.nasa.gov/directorates/heo/scan/communications/outreach/funfacts/txt_passive_active.html

Malthus, T. J., & Madeira, A. C. (1993). High resolution spectroradiometry: Spectral reflectance of field bean leaves infected by Botrytis fabae. *Remote Sensing of Environment*, *45*(1), 107–116. https://doi.org/10.1016/0034-4257(93)90086-D

Mather, P. M., & Koch, M. (2004). *Computer Processing of Remotely-Sensed Images: An Introduction—Paul M. Mather, Magaly Koch—Google Books*. https://books.google.gr/books?hl=en&lr=&id=GWhvDMNh1hAC&oi=fnd&pg=PT8&ots=rmc83FkSKo&sig=8N2cTgwiKF_Ge1MWGSZsG3J29OU&redir_esc=y#v=onepage&q&f=false

Matsushita, B., Yang, W., Chen, J., Yuyichi, O., & Guoyu, Q. (2007). Sensitivity of the Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI) to Topographic Effects: A Case Study in High-Density Cypress Forest. *Sensors*, *7*. https://doi.org/10.3390/s7112636

Mavtech S.r.l. (2022). *MAVTech S.r.l. | MICASENSE REDEDGE-M™*. https://www.mavtech.eu/en/products/micasense-rededge-m/

McLeod, B. A. (2021). *Precision Mapping of Apple Proliferation using Multi-and Hyperspectral Data*.

Melesse, A. M., Weng, Q., Thenkabail, P. S., & Senay, G. B. (2007). Remote Sensing Sensors and Applications in Environmental Resources Mapping and Modelling. *Sensors*, *7*(12), Article 12. https://doi.org/10.3390/s7123209

MicaSense Inc. (2017). *MicaSense RedEdge-M Multispectral Camera*. https://support.micasense.com/hc/en-us/article_attachments/115004168274/RedEdge-M_User_Manual.pdf

Mohd, H. I., Pakhriazad, H., & Shahrin, M. (2009). Evaluating supervised and unsupervised techniques for land cover mapping using remote sensing data. *Geografia : Malaysian Journal of Society and Space*, *5*(1), Article 1.

Nadipally, M. (2019). Optimization of Methods for Image-Texture Segmentation Using Ant Colony Optimization. In D. J. Hemanth, D. Gupta, & V. Emilia Balas (Eds.), *Intelligent Data Analysis for Biomedical Applications* (pp. 21–47). Academic Press. https://doi.org/10.1016/B978-0-12-815553-0.00002-1

NASA. (2012). *Reflected Near-Infrared Waves | Science Mission Directorate*. https://science.nasa.gov/ems/08_nearinfraredwaves

NASA Science. (2019, August 23). *What is Remote Sensing?* [Backgrounder]. Earthdata; Earth Science Data Systems, NASA. http://www.earthdata.nasa.gov/learn/backgrounders/remote-sensing

Navalgund, R. R., Jayaraman, V., & Roy, P. S. (2007). Remote sensing applications: An overview. *CURRENT SCIENCE*, *93*(12).

Nelson, E. (2000). The impact of bivariate symbol design on task performance in a map setting. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *37*(4), 61–78.

Nie, Y., Kafatos, M., & Wood, K. (2001). Estimating soil-type pattern from supervised and unsupervised classification: Case study in Cuprite, Nevada. *Project Report*, 28.

Nivala, A.-M., & Sarjakoski, L. T. (2005). Adapting map symbols for mobile users. *Proc. of the International Cartographic Conference*, 9–16.

Padma, S., & Sanjeevi, S. (2014). Jeffries Matusita based mixed-measure for improved spectral matching in hyperspectral image analysis. *International*

Journal of Applied Earth Observation and Geoinformation, *32*, 138–151. https://doi.org/10.1016/j.jag.2014.04.001

Pal, M., & Mather, P. M. (2006). Some issues in the classification of DAIS hyperspectral data. *International Journal of Remote Sensing*, *27*(14), 2895–2916. https://doi.org/10.1080/01431160500185227

Paulo Raposo & John P. Wilson. (2017). *Scale and Generalization | GIS&T Body of Knowledge*. http://gistbok.ucgis.org/bok-topics/scale-and-generalization-1

Pettorelli, N., Vik, J. O., Mysterud, A., Gaillard, J.-M., Tucker, C. J., & Stenseth, N. Chr. (2005). Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution*, *20*(9), 503–510. https://doi.org/10.1016/j.tree.2005.05.011

Praciak, A., Pasiecznik, N., Sheil, D., Van Heist, M., Sassen, M., Correia, C. S., Dixon, C., Fyson, G., Rushford, K., & Teeling, C. (2013). *The CABI encyclopedia of forest trees (CABI, Oxfordshire, UK)*.

Raposo, P. (2017). Scale and Generalization. *Geographic Information Science & Technology Body of Knowledge*, *2017*(Q4). https://doi.org/10.22224/gistbok/2017.4.3

Reddy, C. S., Khuroo, A. A., Krishna, P. H., Saranya, K. R. L., Jha, C. S., & Dadhwal, V. K. (2014). Threat evaluation for biodiversity conservation of forest ecosystems using geospatial techniques: A case study of Odisha, India. *Ecological Engineering*, *69*, 287–303.

Régolini, M., Castagneyrol, B., Dulaurent-Mercadal, A.-M., Piou, D., Samalens, J.-C., & Jactel, H. (2014). Effect of host tree density and apparency on the probability of attack by the pine processionary moth. *Forest Ecology and Management*, *334*, 185–192. https://doi.org/10.1016/j.foreco.2014.08.038

Ricciardi, L., Giorgianni, C., Briguglio, G., Gangemi, S., & Spatari, G. (2021). Processionary caterpillar reactions in Southern Italy forestry workers: Description of three cases. *Clinical and Molecular Allergy*, *19*(1), 15. https://doi.org/10.1186/s12948-021-00155-8

Robinet, C., & Roques, A. (2010). Direct impacts of recent climate warming on insect populations. *Integrative Zoology*, *5*(2), 132–142.

Roques, A. (2015). *Processionary moths and climate change: An update* (Vol. 427). Springer.

Roth, R. E. (2017). Visual variables. *International Encyclopedia of Geography: People, the Earth, Environment and Technology*, 1–11.

Rustamov, R. B., Hasanova, S., & Zeynalova, M. H. (2018). *Multi-purposeful Application of Geospatial Data*. BoD – Books on Demand.

SARE. (2018). *Correlating Nitrogen Application Rates in Sugarcane With Low-Cost Normalized Difference Vegetation Index (NDVI)*.

Soleon. (n.d.). *Pest control | Soleon—We make your project fly*. Retrieved January 4, 2023, from https://www.soleon.it/en/projekts/pest-control

Tappeiner, U., Marsoner, T., & Niedrist, G. (2021). *Landwirtschaftsreport zur Nachhaltigkeit Südtirol 2020*.

Toth, C., & Jóźków, G. (2016). Remote sensing platforms and sensors: A survey. *ISPRS Journal of Photogrammetry and Remote Sensing*, *115*, 22–36. https://doi.org/10.1016/j.isprsjprs.2015.10.004

USGS. (2018). *NDVI, the Foundation for Remote Sensing Phenology | U.S. Geological Survey*. https://www.usgs.gov/special-topics/remote-sensing-phenology/science/ndvi-foundation-remote-sensing-phenology

USGS. (2022). *What is remote sensing and what is it used for? | U.S. Geological Survey*. https://www.usgs.gov/faqs/what-remote-sensing-and-what-it-used

Wang, P., Chen, P., Yuan, Y., Liu, D., Huang, Z., Hou, X., & Cottrell, G. (2018). Understanding Convolution for Semantic Segmentation. *2018 IEEE Winter Conference on Applications of Computer Vision (WACV)*, 1451–1460. https://doi.org/10.1109/WACV.2018.00163

Watts, D. (2008). *Pine processionary moth {Thaumetopoea pityocampa} on pine tree*. https://www.naturepl.com/stock-photo/pine-processionary-moth-thaumetopoea-pityocampa-on-pine-tree-s-europe/search/detail-0_01092761.html

Weibel, R. (1997). Generalization of spatial data: Principles and selected algorithms. In M. van Kreveld, J. Nievergelt, T. Roos, & P. Widmayer (Eds.), *Algorithmic Foundations of Geographic Information Systems* (pp. 99–152). Springer. https://doi.org/10.1007/3-540-63818-0_5

Weng, Q. (2011). *Advances in Environmental Remote Sensing: Sensors, Algorithms, and Applications*. CRC Press.

West, J., Bravo, C., Oberti, R., Lemaire, D., Moshou, D., & McCartney, H. (2003). The Potential of Optical Canopy Measurement for Targeted Control of Field Crop Diseases. *Annual Review of Phytopathology*, *41*, 593–614. https://doi.org/10.1146/annurev.phyto.41.121702.103726

World Resources Institute. (1992). *Global Biodiversity Strategy*. https://www.wri.org/research/global-biodiversity-strategy

Yuan, Y., & Hu, X. (2016). Random forest and objected-based classification for forest pest extraction from UAV aerial imagery. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *41*, 1093.

Żyszkowska, W. (2016). Visual features of cartographic representation in map perception. *Polish Cartographical Review*, *48*. https://doi.org/10.1515/pcr-2016-0003

Adrián Cardil, Udayalakshmi Vepakomma, & Lluis Brotons. (2017). *Assessing Pine Processionary Moth Defoliation Using Unmanned Aerial Systems*.

Aeromotus. (2022). *Micasense RedEdge-M Multispectral Sensor*. AEROMOTUS. https://www.aeromotus.com/product/rededge-m/

Ahmad, F., & Goparaju, L. (2017). Assessment of Threats to Forest Ecosystems Using Geospatial Technology in Jharkhand State of India. *Current World Environment*, *12*(2), 355–365. https://doi.org/10.12944/CWE.12.2.19

Ampatzidis, Y., & Partel, V. (2019). UAV-Based High Throughput Phenotyping in Citrus Utilizing Multispectral Imaging and Artificial Intelligence. *Remote Sensing*, *11*, 410. https://doi.org/10.3390/rs11040410

Bade, B. (2020). *All you need to know about NDVI*. https://bikeshbade.com.np/tutorials/Detail/?title=All%20you%20need%20to%20know%20about%20NDVI&code=19

Bannari, A., Morin, D., Bonn, F., & Huete, A. R. (1995). A review of vegetation indices. *Remote Sensing Reviews*, *13*(1–2), 95–120. https://doi.org/10.1080/02757259509532298

Bartkowiak, P., Castelli, M., Crespi, A., Niedrist, G., Zanotelli, D., Colombo, R., & Notarnicola, C. (2022). Land Surface Temperature Reconstruction Under Long-Term Cloudy-Sky Conditions at 250 m Spatial Resolution: Case Study of Vinschgau/Venosta Valley in the European Alps. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *15*, 2037–2057. https://doi.org/10.1109/JSTARS.2022.3147356

Battisti, A., Avcı, M., Avtzis, D. N., Jamaa, M. L. B., Berardi, L., Berretima, W., Branco, M., Chakali, G., El Alaoui El Fels, M. A., & Frérot, B. (2015). Natural history of the processionary moths (Thaumetopoea spp.): New insights in relation to climate change. In *Processionary moths and climate change: An update* (pp. 15–79). Springer.

Battisti, A., Stastny, M., Netherer, S., Robinet, C., Schopf, A., Roques, A., & Larsson, S. (2005). Expansion of Geographic Range in the Pine Processionary Moth Caused by Increased Winter Temperatures. *Ecological Applications*, *15*(6), 2084–2096. https://doi.org/10.1890/04-1903

Bertin, J. (1983a). *Semiology of graphics*. University of Wisconsin press.

Bertin, J. (1983b). *Visual Representation from Semiology of Graphics*.

Brewer, C. A. (2005). Designing better maps. *A Guide for GIS Users*, *1*.

Buckley, A., & Field, K. (2011). *Making a Meaningful Map*. 4.

Buczkowski, A. (2015). *Beyond NDVI: What are vegetation indices, and how are they used in precision farming?* Geoawesomeness. https://geoawesomeness.com/eo-hub/beyond-ndvi-what-are-vegetation-indices-and-how-are-they-used-in-precision-farming/

Burg, J. P. (1975). *Maximum entropy spectral analysis.* Stanford University.

Caivano, J. L. (1990). *Visual texture as a semiotic system*.

Campbell, J. B., & Wynne, R. H. (2011). *Introduction to Remote Sensing, Fifth Edition*. Guilford Press.

Carter, G. A., & Knapp, A. K. (2001). Leaf optical properties in higher plants: Linking spectral characteristics to stress and chlorophyll concentration. *American Journal of Botany*, *88*(4), 677–684. https://doi.org/10.2307/2657068

Carus, S. (2004). Impact of defoliation by the pine processionary moth (Thaumetopoea pityocampa) on radial, height and volume growth of calabrian pine (Pinus brutia) trees in Turkey. *Phytoparasitica*, *32*(5), 459–469. https://doi.org/10.1007/BF02980440

Chen, D., & Stow, D. (2002). The Effect of Training Strategies on Supervised Classification at Different Spatial Resolutions. *Photogrammetric Engineering and Remote Sensing*, *68*.

Chen, Y., Wang, Q., Wang, Y., Duan, S.-B., Xu, M., & Li, Z.-L. (2016). A Spectral Signature Shape-Based Algorithm for Landsat Image Classification. *ISPRS International Journal of Geo-Information*, *5*(9), 154. https://doi.org/10.3390/ijgi5090154

Copernicus. (2022). *EU-DEM v1.1—Copernicus Land Monitoring Service* [Land item]. https://land.copernicus.eu/imagery-in-situ/eu-dem/eu-dem-v1.1

Crespi, A., Matiu, M., Bertoldi, G., Petitta, M., & Zebisch, M. (2020). *High-resolution daily series (1980—2018) and monthly climatologies (1981—2010) of mean temperature and precipitation for Trentino—South Tyrol (north-eastern Italian Alps)* [Data set]. PANGAEA. https://doi.org/10.1594/PANGAEA.924502

Dale, V. H., & Pearson, S. M. (1997). Quantifying habitat fragmentation due to land-use change in Amazonia. *WF Laurance and RO Bierregaard, Editors. Tropical Forest Remnants: Ecology, Management, and Conservation of Fragmented Communities. University of Chicago Press, Chicago, Illinois, USA*.

Durrant, T. H., De Rigo, D., & Caudullo, G. (2016). Pinus sylvestris in Europe: Distribution, habitat, usage and threats. *European Atlas of Forest Tree Species*, 132–133.

ESRI. (n.d.). *Making a Meaningful Map*. Retrieved November 25, 2022, from https://www.esri.com/news/arcuser/0911/making-a-map-meaningful.html

European Environment Agency. (2020). *Trends in annual temperature across Europe between 1990 and 2019—European Environment Agency* [Figure]. https://www.eea.europa.eu/data-and-maps/figures/trends-in-annual-temperature-across

European Environment Agency. (2022). *Italy shapefile—European Environment Agency* [Data File]. https://www.eea.europa.eu/data-and-maps/data/eea-reference-grids-2/gis-files/italy-shapefile

Fang, H., & Liang, S. (2014). Leaf Area Index Models. In *Encyclopedia of Ecology*. https://doi.org/10.1016/B978-0-12-409548-9.09076-X

Forest Research. (2022). Pine processionary moth (Thaumetopoea pityocampa). *Forest Research*. https://www.forestresearch.gov.uk/tools-and-resources/fthr/pest-and-disease-resources/pine-processionary-moth-thaumetopoea-pityocampa/

Gikunda, A. (2021, October 17). *17 Differences between Passive and Active Remote Sensing*. https://grindgis.com/remote-sensing/17-differences-between-passive-and-active-remote-sensing

GISGeography. (2014, May 2). *Image Classification Techniques in Remote Sensing*. GIS Geography. https://gisgeography.com/image-classification-techniques-remote-sensing/

GISGeography. (2015, February 9). *Passive vs Active Sensors in Remote Sensing*. GIS Geography. https://gisgeography.com/passive-active-sensors-remote-sensing/

GISGeography. (2017, May 9). *What is NDVI (Normalized Difference Vegetation Index)?* GIS Geography. https://gisgeography.com/ndvi-normalized-difference-vegetation-index/

GISGeography. (2018, July 16). *Dot Distribution vs Graduated Symbols vs Proportional Symbol Maps*. GIS Geography. https://gisgeography.com/dot-distribution-graduated-symbols-proportional-symbol-maps/

Hoch, G., Toffolo, E. P., Netherer, S., Battisti, A., & Schopf, A. (2009). Survival at low temperature of larvae of the pine processionary moth Thaumetopoea pityocampa from an area of range expansion. *Agricultural and Forest Entomology*, *11*(3), 313–320. https://doi.org/10.1111/j.1461-9563.2009.00431.x

Hódar, J. A., Castro, J., & Zamora, R. (2003). Pine processionary caterpillar Thaumetopoea pityocampa as a new threat for relict Mediterranean Scots pine forests under climatic warming. *Biological Conservation*, *110*(1), 123–129.

Homayouni, S., & Roux, M. (2004). *Hyperspectral Iamge Analysis for material mapping using spectral matching*. https://www.semanticscholar.org/paper/HYPERSPECTRAL-IMAGE-ANALYSIS-FOR-MATERIAL-MAPPING-Homayouni-Roux/ac06f2744eebe70a06e8d5e9a32fc4998c8eeccc

Hubert-Moy, L., Cotonnec, A., Le Du, L., Chardin, A., & Perez, P. (2001). A Comparison of Parametric Classification Procedures of Remotely Sensed Data Applied on Different Landscape Units. *Remote Sensing of Environment*, *75*(2), 174–187. https://doi.org/10.1016/S0034-4257(00)00165-6

Huchon, H., & Demolin, G. (1970). La bioécologie de la Processionnaire du pin: Dispersion potentielle, dispersion actuelle. *Revue Forestière Française*, *22*(S), 220–234.

ICA. (2003). *A Strategic Plan for the International Cartographic Association 2003-2011*. 18.

Ioseliani, N. (2021). *Visualizing Decision-Relevant Map Layers to Support Travel Planning*.

Jactel, H., Barbaro, L., Battisti, A., Bosc, A., Branco, M., Brockerhoff, E., Castagneyrol, B., Dulaurent, A.-M., Hódar, J. A., Jacquet, J.-S., Mateus, E., Paiva, M.-R., Roques, A., Samalens, J.-C., Santos, H., & Schlyter, F. (2015). Insect – Tree Interactions in Thaumetopoea pityocampa. In A. Roques (Ed.), *Processionary Moths and Climate Change: An Update* (pp. 265–310). Springer Netherlands. https://doi.org/10.1007/978-94-017-9340-7_6

Jones, H. G., Archer, N., Rotenberg, E., & Casa, R. (2003). Radiation measurement for plant ecophysiology. *Journal of Experimental Botany*, *54*(384), 879–889. https://doi.org/10.1093/jxb/erg116

Kachhwaha, T. S. (1983). Spectral signatures obtained from Landsat digital data for forest vegetation and land-use mapping in India. *Photogrammetric Engineering and Remote Sensing*, *49*(5), 685–689.

Kerdelhué, C., Zane, L., Simonato, M., Salvato, P., Rousselet, J., Roques, A., & Battisti, A. (2009). Quaternary history and contemporary patterns in a currently expanding species. *BMC Evolutionary Biology*, *9*, 220. https://doi.org/10.1186/1471-2148-9-220

Kraak, J. M., & Ormeling, F. (1998). Kartografia, wizualizacja danych przestrzennych, Warszawa: Wydawnictwo Naukowe PWN. *Search In*, 113–130.

Kraak, M.-J., Roth, R. E., Ricker, B., Kagawa, A., & Le Sourd, G. (2021). *Mapping for a sustainable world*.

Landgrebe, D. A. (2003). *Signal Theory Methods in Multispectral Remote Sensing*. John Wiley & Sons.

Lechner, A. M., Foody, G. M., & Boyd, D. S. (2020). Applications in remote sensing to forest ecology and management. *One Earth*, *2*(5), 405–412.

Lu, D., & Weng, Q. (2007). A survey of image classification methods and techniques for improving classification performance. *International Journal of Remote Sensing*, *28*(5), 823–870. https://doi.org/10.1080/01431160600746456

MacEachren, A. M. (1992). Visualizing uncertain information. *Cartographic Perspectives*, *13*, 10–19.

MacEachren, A. M. (1995). *How maps work: Representation, visualization, and design*. Guilford Press.

MacEachren, A. M., Roth, R. E., O'Brien, J., Li, B., Swingley, D., & Gahegan, M. (2012). Visual semiotics & uncertainty visualization: An empirical study. *IEEE Transactions on Visualization and Computer Graphics*, *18*(12), 2496–2505.

Mai, T. (2015, May 6). *What are passive and active sensors?* NASA; Brian Dunbar. http://www.nasa.gov/directorates/heo/scan/communications/outreach/funfacts/txt_passive_active.html

Malthus, T. J., & Madeira, A. C. (1993). High resolution spectroradiometry: Spectral reflectance of field bean leaves infected by Botrytis fabae. *Remote Sensing of Environment*, *45*(1), 107–116. https://doi.org/10.1016/0034-4257(93)90086-D

Mather, P. M., & Koch, M. (2004). *Computer Processing of Remotely-Sensed Images: An Introduction—Paul M. Mather, Magaly Koch—Google Books*. https://books.google.gr/books?hl=en&lr=&id=GWhvDMNh1hAC&oi=fnd&pg=PT8&ots=rmc83FkSKo&sig=8N2cTgwiKF_Ge1MWGSZsG3J29OU&redir_esc=y#v=onepage&q&f=false

Matsushita, B., Yang, W., Chen, J., Yuyichi, O., & Guoyu, Q. (2007). Sensitivity of the Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI) to Topographic Effects: A Case Study in High-Density Cypress Forest. *Sensors*, *7*. https://doi.org/10.3390/s7112636

Mavtech S.r.l. (2022). *MAVTech S.r.l. | MICASENSE REDEDGE-M™*. https://www.mavtech.eu/en/products/micasense-rededge-m/

McLeod, B. A. (2021). *Precision Mapping of Apple Proliferation using Multi-and Hyperspectral Data*.

Melesse, A. M., Weng, Q., Thenkabail, P. S., & Senay, G. B. (2007). Remote Sensing Sensors and Applications in Environmental Resources Mapping and Modelling. *Sensors*, *7*(12), Article 12. https://doi.org/10.3390/s7123209

MicaSense Inc. (2017). *MicaSense RedEdge-M Multispectral Camera*. https://support.micasense.com/hc/en-us/article_attachments/115004168274/RedEdge-M_User_Manual.pdf

Mohd, H. I., Pakhriazad, H., & Shahrin, M. (2009). Evaluating supervised and unsupervised techniques for land cover mapping using remote sensing data. *Geografia : Malaysian Journal of Society and Space*, *5*(1), Article 1.

Nadipally, M. (2019). Optimization of Methods for Image-Texture Segmentation Using Ant Colony Optimization. In D. J. Hemanth, D. Gupta, & V. Emilia Balas (Eds.), *Intelligent Data Analysis for Biomedical Applications* (pp. 21–47). Academic Press. https://doi.org/10.1016/B978-0-12-815553-0.00002-1

NASA. (2012). *Reflected Near-Infrared Waves | Science Mission Directorate*. https://science.nasa.gov/ems/08_nearinfraredwaves

NASA Science. (2019, August 23). *What is Remote Sensing?* [Backgrounder]. Earthdata; Earth Science Data Systems, NASA. http://www.earthdata.nasa.gov/learn/backgrounders/remote-sensing

Navalgund, R. R., Jayaraman, V., & Roy, P. S. (2007). Remote sensing applications: An overview. *CURRENT SCIENCE*, *93*(12).

Nelson, E. (2000). The impact of bivariate symbol design on task performance in a map setting. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *37*(4), 61–78.

Nie, Y., Kafatos, M., & Wood, K. (2001). Estimating soil-type pattern from supervised and unsupervised classification: Case study in Cuprite, Nevada. *Project Report*, 28.

Nivala, A.-M., & Sarjakoski, L. T. (2005). Adapting map symbols for mobile users. *Proc. of the International Cartographic Conference*, 9–16.

Padma, S., & Sanjeevi, S. (2014). Jeffries Matusita based mixed-measure for improved spectral matching in hyperspectral image analysis. *International Journal of Applied Earth Observation and Geoinformation*, *32*, 138–151. https://doi.org/10.1016/j.jag.2014.04.001

Pal, M., & Mather, P. M. (2006). Some issues in the classification of DAIS hyperspectral data. *International Journal of Remote Sensing*, *27*(14), 2895–2916. https://doi.org/10.1080/01431160500185227

Paulo Raposo & John P. Wilson. (2017). *Scale and Generalization | GIS&T Body of Knowledge*. http://gistbok.ucgis.org/bok-topics/scale-and-generalization-1

Pettorelli, N., Vik, J. O., Mysterud, A., Gaillard, J.-M., Tucker, C. J., & Stenseth, N. Chr. (2005). Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution*, *20*(9), 503–510. https://doi.org/10.1016/j.tree.2005.05.011

Praciak, A., Pasiecznik, N., Sheil, D., Van Heist, M., Sassen, M., Correia, C. S., Dixon, C., Fyson, G., Rushford, K., & Teeling, C. (2013). *The CABI encyclopedia of forest trees (CABI, Oxfordshire, UK)*.

Raposo, P. (2017). Scale and Generalization. *Geographic Information Science & Technology Body of Knowledge*, *2017*(Q4). https://doi.org/10.22224/gistbok/2017.4.3

Reddy, C. S., Khuroo, A. A., Krishna, P. H., Saranya, K. R. L., Jha, C. S., & Dadhwal, V. K. (2014). Threat evaluation for biodiversity conservation of forest ecosystems using geospatial techniques: A case study of Odisha, India. *Ecological Engineering*, *69*, 287–303.

Régolini, M., Castagneyrol, B., Dulaurent-Mercadal, A.-M., Piou, D., Samalens, J.-C., & Jactel, H. (2014). Effect of host tree density and apparency on the probability of attack by the pine processionary moth. *Forest Ecology and Management*, *334*, 185–192. https://doi.org/10.1016/j.foreco.2014.08.038

Ricciardi, L., Giorgianni, C., Briguglio, G., Gangemi, S., & Spatari, G. (2021). Processionary caterpillar reactions in Southern Italy forestry workers: Description of three cases. *Clinical and Molecular Allergy*, *19*(1), 15. https://doi.org/10.1186/s12948-021-00155-8

Robinet, C., & Roques, A. (2010). Direct impacts of recent climate warming on insect populations. *Integrative Zoology*, *5*(2), 132–142.

Roques, A. (2015). *Processionary moths and climate change: An update* (Vol. 427). Springer.

Roth, R. E. (2017). Visual variables. *International Encyclopedia of Geography: People, the Earth, Environment and Technology*, 1–11.

Rustamov, R. B., Hasanova, S., & Zeynalova, M. H. (2018). *Multi-purposeful Application of Geospatial Data*. BoD – Books on Demand.

SARE. (2018). *Correlating Nitrogen Application Rates in Sugarcane With Low-Cost Normalized Difference Vegetation Index (NDVI)*.

Soleon. (n.d.). *Pest control | Soleon—We make your project fly*. Retrieved January 4, 2023, from https://www.soleon.it/en/projekts/pest-control

Tappeiner, U., Marsoner, T., & Niedrist, G. (2021). *Landwirtschaftsreport zur Nachhaltigkeit Südtirol 2020*.

Toth, C., & Jóźków, G. (2016). Remote sensing platforms and sensors: A survey. *ISPRS Journal of Photogrammetry and Remote Sensing*, *115*, 22–36. https://doi.org/10.1016/j.isprsjprs.2015.10.004

USGS. (2018). *NDVI, the Foundation for Remote Sensing Phenology | U.S. Geological Survey*. https://www.usgs.gov/special-topics/remote-sensing-phenology/science/ndvi-foundation-remote-sensing-phenology

USGS. (2022). *What is remote sensing and what is it used for? | U.S. Geological Survey*. https://www.usgs.gov/faqs/what-remote-sensing-and-what-it-used

Wang, P., Chen, P., Yuan, Y., Liu, D., Huang, Z., Hou, X., & Cottrell, G. (2018). Understanding Convolution for Semantic Segmentation. *2018 IEEE Winter Conference on Applications of Computer Vision (WACV)*, 1451–1460. https://doi.org/10.1109/WACV.2018.00163

Watts, D. (2008). *Pine processionary moth {Thaumetopoea pityocampa} on pine tree*. https://www.naturepl.com/stock-photo/pine-processionary-moth-thaumetopoea-pityocampa-on-pine-tree-s-europe/search/detail-0_01092761.html

Weibel, R. (1997). Generalization of spatial data: Principles and selected algorithms. In M. van Kreveld, J. Nievergelt, T. Roos, & P. Widmayer (Eds.), *Algorithmic Foundations of Geographic Information Systems* (pp. 99–152). Springer. https://doi.org/10.1007/3-540-63818-0_5

Weng, Q. (2011). *Advances in Environmental Remote Sensing: Sensors, Algorithms, and Applications*. CRC Press.

West, J., Bravo, C., Oberti, R., Lemaire, D., Moshou, D., & McCartney, H. (2003). The Potential of Optical Canopy Measurement for Targeted Control of Field Crop Diseases. *Annual Review of Phytopathology*, *41*, 593–614. https://doi.org/10.1146/annurev.phyto.41.121702.103726

World Resources Institute. (1992). *Global Biodiversity Strategy*. https://www.wri.org/research/global-biodiversity-strategy

Yuan, Y., & Hu, X. (2016). Random forest and objected-based classification for forest pest extraction from UAV aerial imagery. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *41*, 1093.

Żyszkowska, W. (2016). Visual features of cartographic representation in map perception. *Polish Cartographical Review*, *48*. https://doi.org/10.1515/pcr-2016-0003