Workflow to improve the forest management of *Eucalyptus globulus* stands affected by *Gonipterus scutellatus* in Galicia (Spain) using remote sensing and GIS

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ABSTRACT

In Spain there are more than 500,000 ha of Eucalyptus plantations. These represent 3,5% of the national forest and the 25% of the timber harvested. Galicia monocultures of *Eucalyptus globulus* Labill. plantations cover 177,679 ha, and mixed stands of eucalyptus cover 200,000 ha more. This high productivity has been powered by the absence of pests and pathogens. However, since 1991 the health and productivity of these stands has been threatened by the Eucalyptus snout beetle (*Gonipterus scutellatus* Gyll.), which causes a severe defoliation to eucalyptus stands in Galicia.

The aim of this paper is to establish a workflow to locate the areas affected by the defoliator, and determinate the basics patterns of spatial distribution, in order to predict future hot spots and develop more integrated pests management. This information will be part of a wider Information System, develop to improve the forest management and monitoring of these stands. The damaged area and the level of defoliation will be mapped using satellite imagery. The additional information of stand conditions, such as site index, climate and microclimatic conditions, digital terrain model, dendrometric and dasometric variables, will be integrated also in a Geographical Information System.

Keywords: remote sensing, GIS, defoliation, *Eucalyptus globulus*, forest management

1. INTRODUCTION

Eucalyptus plantations (around 500,000 ha) are the most productive forest stands in Spain. While the mean annual increment in the productive forests in the Iberic peninsula is 2.5 m^3/ha·year, the mean for eucalyptus plantations is around 7.5 m^3/ha·year[1]. Of the nearly 600 Eucalyptus species (most of them native to Australia and Tasmania), only eighty appear in this region, all of them as non native trees. Considering its extent and the utility of its wood, *Eucalyptus globulus* Labill. has become the most important species. The chemical composition of its wood is higher in holocellulose and pentosans than in other eucalyptus used in the pulp and paper industry, and also higher than birch, which is the principal input in the Scandinavian short-fiber pulp industry. The current demand for white pulp in the European Union (EU) has exceeded the 4 million tons/year, and is supported in a 40% by Eucalyptus pulp from Spain and Portugal[1].

Its location is mainly limited to the North and Northwest of Spain (from the Basque Country to Galicia), areas in the south west of Spain (Huelva), and to Portugal, due to its climatic requirements[2]: humid climates, without frost periods, and with an uniformly distributed annual precipitation over 700 mm. These plantations comprise the 25% of the total harvested wood each year in Spain (77% if only leaf broad trees are considered[3] and the 45% in Portugal[1]. As settled by the I National Forest Inventory (1965-74) and the II National Forest Inventory (1986-96) Eucalyptus stocks have increased 56% in Spain, which means 26 million m^3 in 1996[4,5] (data from the III National Forest Inventory are not already available for all the regions in Spain).

Regarding stocks (around 23 million m^3 in pure stands according to the III National Forest Inventory) and extension (about 400,000 ha), Galicia is the most representative area for Eucalyptus plantations in Spain. Concerning wood

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production, *Eucalyptus globulus* reaches an annual increment of 3 million m^3/year, which means nearly the 23% of the total in Galicia. If mixed eucalyptus stands are considered, this increment would represent nearly the 45% of the timber volume increment in this area[3]. This high productivity results, as eucalyptus are well adapted to the climatic and soil conditions in this area. The yield is higher for eucalyptus than the other species, achieving average values of 13-17m^3/ha·year, and is possible to reach 30 m^3/ha·year on the best terrain[6]. According to the "Forestry Plan for Galicia"[7] 245,000 ha of pure stands are forecasted for 2032, as well as, a growth rate of 5 million m^3/year. Currently there is evidence that these estimations are low.

Data provided by the Third National Forest Inventory (1997-2006) highlights the great importance of Galicia's woodland, revealing that there has been a sustainable management in the period 1987-1998, so that more timber was attained despite continued harvesting[8]. However, more than 120,000 eucalyptus plantation's owners in Galicia involve a high atomization of the property and considerable management difficulties. The high growth rate, the simple silviculture (it does no need to be pruned or thinned and it coppices do not need to replant after harvesting) and the frugality of this species, combined with a highly demanded wood, have been the enticing factors for a land owner when deciding planting Eucalyptus in Galicia. Hence, many stands are in non suitable sites, where pests and diseases are more likely to appear, due to the higher susceptibility of the trees. The rotation age corresponding to the maximum mean annual increment is around 12 years[3], although new and higher rotation ages are being considered in order to obtain more profitable wood products. After the clearcut eucalyptus stands can self regenerate up to for times, then their vigor decreases and a new plantation is recommended. Around 6,000 ha are annually afforested with *Eucalyptus globulus* but it is necessary to indicate that in the campaign 98/99 this species was subsidized in restrictive conditions, although in many cases it was used without any subvention[6]. This species is planted up to 500 m in altitude, higher *Eucalyptus nitens* Maiden is used. Large eucalyptus monoculture areas are a result of the mosaic of smaller plantations with different owners, ages, origin (plantation/regeneration) and stand densities.

The integral value of eucalyptus stands in Galicia is estimated in 10,000 million €, taking into account the productive, recreational and environmental value. The principal one is the productive value (more than 6,000 million €), but their contribution to Carbon sequestration and to Oxygen production should not be forgotten[9]. The importance of eucalyptus in this area is not only based on Eucalyptus globulus wood and fibers fine quality, but also its fast growth, its high adaptability, frugality, natural pruning and, until the 90's, the absence of important pests or diseases[1].

Nevertheless, since 1991 the high productivity of this species has been threatened by the outbreaks of the Eucalyptus snout beetle (*Gonipterus scutellatus* Gyll.), found at first time in Lorizán (Pontevedra, Galicia)[10]. However, other beetles (e.g. *Ctenarytaina eucalypti* Maskell, *Phoracantha semipunctata* Fabricius) and diseases (e.g. fungi as *Mycosphaerella* spp.) affect Eucalyptus stands in Galicia, the most harmful has been the snout beetle[1], concerning its proliferation and the extent of its effects over the trees.

This is a weevil (family *Curculionidae*) native to south-east Australia, where it is a rare insect that feeds exclusively Eucalyptus (mostly *Eucalyptus globulus*), although attacks on apple trees have been reported[11]. It remained largely ignored until it was found in South Africa in 1916, where populations reached pest status in the southern half of the continent in only 30 years. It appeared in 1925 in South America (Argentina), and quick spread towards the North, reaching California (USA) in 1995 and Chile in 1997[12]. In Spain its spread has also been fast (around 100 km/year in some areas), and it has been detected in the other northern regions of Spain and in Portugal, reaching the South of Portugal in 2003[13]. The speed of spread has to do with the absence of natural enemies, and the lack of an ecological balance between the populations. Damages are quite worrying and research has been focused mainly in the biological cycle[10,11] and how to control it following the integrated pest management guidelines.

In these latitudes the snout beetle can produce up to three generations per year, with a mean production of 700-800 eggs/female. The second generation adult outbreak happens in middle February, eating shoots and tender leaves, which causes a characteristic festoon. The larvae are also very harmful for the tree because of their voracity. Larvae damage the epidermis on both sides of the leaf. Both phases are very active, and cause intense defoliation, which means significant losses in forest productivity. Some authors estimate that growth is reduced 30% in the worst cases[14], resulting in an economic loss of 7 million €/year in Galicia[15].

Previous inventories in Galicia (in 1997 and in 2001) show that more than 10% of the area with eucalyptus is affected by severe defoliation (more than 90% of the upper third tree crown is affected in those stands), while only about 20% is free from defoliation or it is considered slight defoliation (0-10% defoliation). The area affected by the highest degree of infestation has even increased from 19% to 27% if data are compared[13].

These damages have tried to be minimized using biological control, which can be defined as the maintenance of the density of a pest population under a threshold using its natural enemies, which are usually introduced from the pest native area[12,16]. In 1926 a parasitoid of Gonipterus eggs was found in its natural area, the mymarid *Anaphes nitens* Girault. The parasitoid was subsequently been introduced in South Africa. Due to its success, the parasitoid has since been employed in other areas with the same problem (New Zealand, Zimbabwe, Mauritius, Italy…)[11]. In Galicia the first campaigns with *Anaphes nitens* started in 1994 and the results can be considered very successful, however it is not always possible to apply this control[12].

In order to coordinate all the efforts and to control the pest in a sustainable way for the medium term, a special plan has been developed by the regional government (Xunta de Galicia) since 2001 ("Plan estratéxico de Loita Integrada Contra o *Gonipterus scutellatus*")[13]. The aim is to gather information about the status and dynamics of the pest and report ancillary information about the biology of Gonipterus and Anaphes, as well as their relationships with eucalyptus and site quality. The objectives are locating the damaged areas, evaluating the damage, and assessing the percentage of parasitizing with *Anaphes nitens* in the forests, so that the most suitable areas to use *Anaphes nitens* and those areas where this kind of control is not feasible will be identified. To achieve it a permanent and continuous pest inventory is being developed, so that distribution and dynamics, as well as biological cycles, can be known. This field inventory is done using a 4·4 km grid in eucalyptus stands and it is carried out monthly. Each plot is selected by accessibility and height (trees have to be not too high, so that measurements in the shoots can be done: defoliation, larvae number…). However, this results in a bias in the data as far many adult stands are not sampled. In each plot 10 trees are measured and the degree of defoliation, number of larvae of *Anaphes nitens*, etc. collected. Defoliation measures are based on a visual key, but different observers assess the defoliation depending on the Forestry District the plot belongs to.

The results point out that some areas are repeatedly attacked by Gonipterus, despite of the success of the biological control done with *Anaphes nitens.* In some areas Anaphes populations survive from one year to the next one, and artificial introductions become useless. Differences in Gonipterus's behaviour have been also found between the stands on the coastal area, where up to three generations per year are produced, whereas in and continental stands only one brood appears each year. Damage is highest in spring, and if winter is very cold and windy Anaphes populations will be small, the biological control will be successful later, thus the harm will rise. However, in summer and autumn the parasitoid control the pest once its population is established. Nonetheless, for one individual tree defoliation is more marked in July and August[17], maybe because the growth rate of Eucalyptus interferes in the way defoliation is showed, and in spring high damages can be hidden by growth rates in the tree. Where the biological control is not possible because the degree of infection is too high (it means more than 80% of the eucalyptus stand is affected by severe defoliation)[13] pesticides are being effectively used (e.g. flufenoxuron). Until now, no resistant stems of *Eucalyptus globulus* have been found[11].

Another study[10] confirms that eucalyptus stands placed in unsuitable sites, or those where preparatory works before afforestation and/or silvicultural labours are not properly done, will suffer severe damage. The most affected stands seem to be in areas over 300 m a.s.l., over poor and/or shallow soils and on southern aspect. These results are not based on large statistical research and need to be verified. However, all these studies suggest that the most important factors to regulate the weevil's cycle are supposed to be climate, tree vigour and *Anaphes nitens*[12].

Maybe most *Gonipterus scutellatus* outbreaks cannot be prevented, but damage can be managed by forest restructuring. This will undoubtedly become a more important strategy for reducing weevil damage in the future, as costs and environmental concerns about insecticide use increase. It is presently uncertain whether our activities are creating forest landscapes that will be more resistant to pathogens, or are creating a habitat for potential future epidemics. These relationships between stand characteristics and weevil damage allow the use of silviculture and forest management to reduce the incidence of the most damaged stand types across the landscape. That is the main reason to develop a Forest Monitoring System, where not only defoliation (forest health), but also silvicultural, dasometrical, dendrometrical, climate and soil data are assembled.

Forest Health Monitoring (FHM) systems are quite common in other areas such as North America. In Canada the Forest Health information systems (also known as forest health tracking systems or databases) have been developed to serve several operational needs. Some systems have been designed for single purposes (i.e. project tracking) while others serve multiple needs (i.e. performance measurement). Their complexity ranges from spreadsheets to highly complex databases integrated with other land management data. The major objectives of a database (primarily for bark beetle management purposes) are: strategic planning (to determine where resources are best allocated to achieve specific management objectives while incorporating other management constraints), performance monitoring (database are used to determine if the strategies are being adequately met), project tracking (tracking of infestations from initial detection to treatment (if any) and keeping statistics on what was accomplished), predicting infestation growth, interfacing with inventory data to determine the impacts on timber supply in the short and long-term, and evaluating efficacy of management practices. With spatial data linkages, these databases can also be used to determine operability and assign harvest priorities[18]. Currently nine of these systems are operative in Canada.

In the Western Interior of USA, a program to determine the status, changes, and trends in forest conditions on an annual basis has been developed. It is used to assess the resilience of ecosystems to disturbances and has been implemented at four levels: detection monitoring, evaluation monitoring, intensive site monitoring, and research on monitoring techniques[19]. Data come from a permanent plot network and aerial surveys.

In Europe the *International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests* (ICP Forests) was launched in 1985 under the Convention on Long-Range Transboundary Air Pollution of the United Nations Economic Commission for Europe (UNECE) due to the growing public awareness of possible adverse effects of air pollution on forests. ICP Forests monitors the forest condition in Europe, using two different monitoring intensity levels in cooperation with the European Union. The first grid (called *Level I*) was established in 1986. Since then it has annually been monitoring the crown condition on a systematic transnational grid of 16 x 16 km throughout Europe, complemented by assessments on national grids of varying densities. Between 1992 and 1996 also soil condition and the foliar nutrient status were assessed. The second monitoring intensity level (called *Level II*) has been inplace since 1994 in selected forest ecosystems in Europe. On these plots, soil and soil solution chemistry, foliar nutrient status, increment, meteorological condition, ground vegetation and deposition of air pollutants are measured in addition to the annual crown condition assessments[20]. Some plots of this grid are in Galicia and in the area with weevil outbreaks, but neither the plot density nor the timeliness are enough to integrate these data in an effective and practical monitoring system. Measurements using field inventory methods are done once or twice a year, using a visual key to assess defoliation. Defoliation measures are relative because they are gathered by comparison with the tree which looks the healthiest in the plot. It involves a set of non comparable data between plots.

One good example of using GIS for forest health management in Germany is the “Referenz-GIS Nationalpark Bayerischer Wald”, which had been built up and developed from 1996 to 2002 by the chair of Geoinformationsystems of the Technical University of Munich in cooperation with the institutions “Bayerische Staatsforstverwaltung” (Bavarian forestry administration) and “Bayerische Vermessungsverwaltung” (Bavarian surveying administration)[21]. This large geographic data pool of about 20 Gbytes of size provides a basis of research for a modern technique of analysis for the Bavarian forestry administration and the appending national park administration “Bayerischer Wald” including extensive possibilities to have a scientific look at the current problems of the national park like bark beetle spread and increase in dead woods. The fact that the damage to forests depends on physical, biological, geological, meteorological and climatic conditions and also on time, presents numerous starting-points to evaluate the modelling ability of modern GIS and database techniques. Expanded metadata structures for heterogeneous, geo-spatial databases, climatic questions and object relational modeling techniques in GIS occupy further central positions[21]. The data pool of the Referenz-GIS Nationalpark Bayerischer Wald currently comprises 591 ESRI Shapefiles (2D and 3D), 225 raster datasets (mainly saved as TIFFs), 18 ESRI GRIDs and 4 ESRI TINs. Attribute data like forest inventory output, daily climate measurements taken since 1947, multimedia data (videos, pictures, sounds) and general parcelling entries is saved in several Microsoft Access databases. All these files and databases reside in a logical folder structure, which provides a clear overview of their data sources, data types, object domains and geographic extents. All the information has been gathered using field inventory or already existent databases. The Referenz-GIS follows the principle of the georelational model as geographic features and attribute data are linked by common identifiers via ODBC interface[22]. Mortality and regeneration maps have been demanded by the forest managers in order to design a strategy which helps improve the natural regeneration process.

Although the special plan developed by the regional government ("Plan estratéxico de Loita Integrada Contra o *Gonipterus scutellatus*") can be considered somehow a kind of forest health monitoring plan, an objective, accurate, timely and efficient Forest Monitoring System for the eucalyptus stands affected by weevil outbreaks is necessary. The need for an objective, accurate, consistency and timely method to detect defoliated Eucalyptus stands arises, and remote sensing should be considered. Changes in foliage characteristics are potentially detectable with remote sensing instruments because the physical components that comprise a leaf interact with the electromagnetic spectrum. Not only changes in pigments, leaf moisture or in the structure of the leaf mesophyll can be detected, but also the presence or absence of leaves (defoliation) may be detectable. The latter is possible because the leaf as a whole has a higher spectral reflectance compared to the tree branches[23]. Most of the research in forest defoliation has been done using coarse spatial resolution imagery, mainly Landsat and SPOT imagery. They have been for a long time the only affordable imagery with a spatial, spectral, temporal and radiometric resolution to fulfil the researcher's requirements.

As an example of forest monitoring using remote sensing tools, the survey of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) effects in British Columbia is considered. Provincial and local scale are settled to distinguish between tactical and strategic planning in order to control the pest. At the provincial scale aerial overview sketch mapping is used, however the use of a satellite image (e.g. Landsat imagery) is used to improve spatial placement of sketched attacked polygons by providing a geographic context has been proposed[24]. At a local scale the use of large scale air photos for tactical planning is employed. The data collected by satellite sensors provides information for both tactical and strategic planning, because these data and their subsequent analyses enable the construction of landscape level datasets that have high positional and attribute accuracy. High resolution imagery has been also successfully proposed for the detection of red-attack stage mountain pine beetle infestations[25]. These data can also provide context for the targeted acquisition of more detailed information where necessary, decreasing the costs.

Most of the studies developed in Central Europe, concerning remote sensing and forest damage, are focused on "forest decline"[26,27,28,29,30]. This phrase is used to describe the slow, progressive deterioration in health and vigor in the forests, including metabolic changes, regeneration problems, discoloration, changes in growth patterns, defoliation (mainly needle loss) and, some times, the death of the tree, due to a complex interaction of biotic and/or abiotic factors[30]. The methods employed by these authors have been adapted after to defoliated areas due to insect outbreaks[31]. On the other hand, many land change detection methods have been applied to forest areas[32,33,34] and they can be used for insect defoliation detection. However, some critical aspects have to be taken into account, because they can lead to a erroneous result[35]: the spectral variability among living trees can be higher than for living and dead trees. For instance, the spectral reflectance of an object can be different just due to the date of acquisition; geometric missregistration can induce false change values, and change magnitude has to be high enough to be detected. Due to its robustness and simplicity "image differencing"[36] and "ratio differencing"[37] can be highlighted. More sophisticated methods are those which make image transformations, for instance the Gramm-Schmidt transformation[38], the principal component analysis (GONG, 1993) or the Tasseled Cap transformation[33]. Other employed models are the Li-Strahler geometrical-optical canopy model[35], the change-vector analysis[39], or the linear mixture model[40]. Variations in the Leaf Area Index (LAI) are currently being effectively used as defoliation estimators[41,47].

Previous works has produced quite accurate classifications for damaged areas using a single image[42], but the best results are generally achieved by analysing multitemporal imagery[43]. Insect defoliation is a hot spot in forest damage detected using remote sensing, but in most cases the results cannot be considered as satisfactory, as usually no more than three defoliation levels (severe, medium and slight) were assessed, with an accuracy around 70-80%, being particularly difficult to detect slight defoliation[29,35]. In Spain the most remarkable study in this field is the one for monitoring *Thaumatopoea pytiocampa* Den.&Schiffin pine stands in Andalucía using IRS-WIFS imagery. Using the NIR band and three defoliation classes, according to the error matrix an accuracy of 50% is reached[44].

Research in this field has been focused on needle-trees, and detecting insect defoliation in Eucalyptus stands in Europe is quite a new issue. Areas where Eucalyptus is a native tree are not affected by insect outbreaks, and forest monitoring is focused in other topics such as timber volume, productivity or deforestation[45].

The aim of this study is to propose and describe a workflow in order to generate an objective, accurate, timely and efficient Forest Monitoring System for the eucalyptus stands affected by weevil outbreaks in Galicia. This system should locate the affected areas, find the infestation patterns and the relationships with other characteristics of the forest stand or the site, and result in a map of locations at high risk of insect outbreaks. GIS and remote sensing have strong potential to meet these requirements.

2. STUDY AREA

Galicia covers an area of nearly three millions hectares. Of this area the 69.67% is forest land, and 48.18% is forestry-wooded land[6]. The most frequent species in Galician forest are *Pinus pinaster* Ait. (390,000 ha), *Quercus robur* L. (195,000 ha), *Eucalyptus globulus* (177,000 ha), mixed-forest of *P. pinaster* and *E. globulus* (159,000 ha), and *Quercus pyrenaica* Willd. (101,000 ha). The total growing stocks in Galicia are 135 253 945 m^3, being mainly of *Pinus pinaster* and *Eucalyptus* spp. These afforestations cover more than the 70% of the forestry wooded-land[3].

In Galicia, in the coastal area, the mean annual precipitation is about 1,000 mm, depending on the considered area. This range of rainfall, an average temperature of 13ºC and the lack of long periods with frost, result in large areas of Galicia that are suitable for eucalyptus plantations[2]. Currently 400,000 ha represent 30% of the forested area in Galicia, distributed mainly along the coastal area in the following proportions: 56% in A Coruña, 24% in Pontevedra, 19% in Lugo and less than 1% in Ourense[1].

A target area of about 300 km^2 in Pontevedra in the Morrazo's peninsula has been selected for this study (Fig. 1). Its location has been selected because the weevil outbreaks have been important since the beginning, and it is where it was first detected.

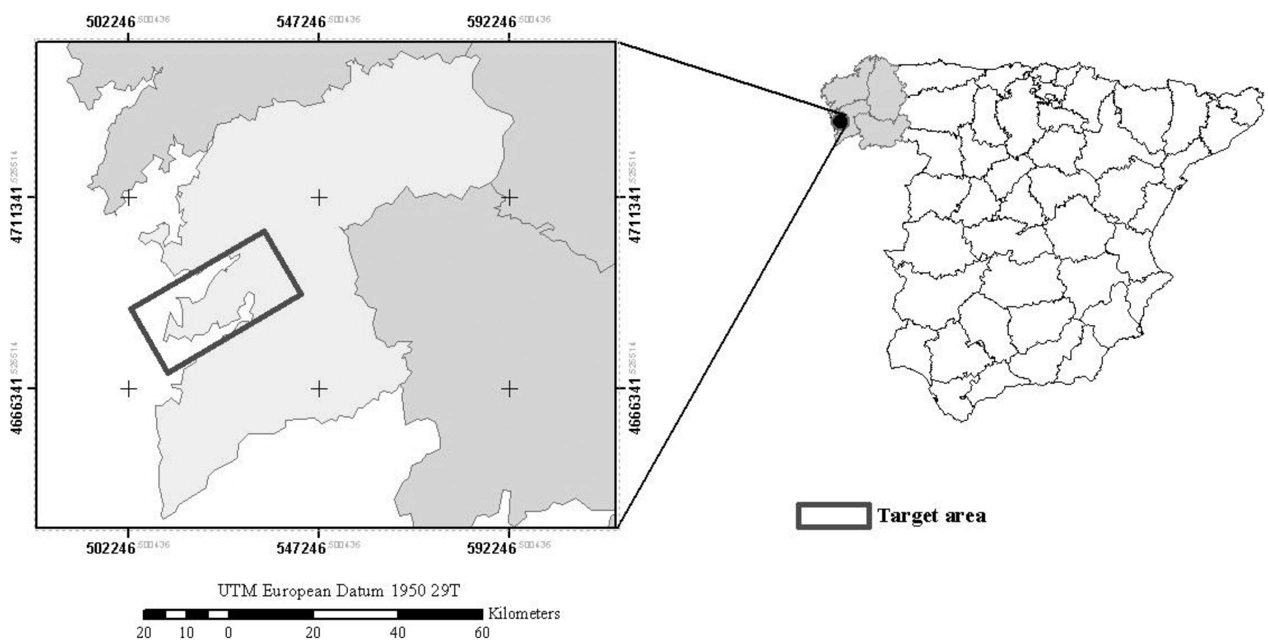

Figure 1. Target area location.

3. METHODOLOGY

For the workflow, the following criteria have been taken into account and applied to the data and characteristics of the study area. The method includes six basic phases to be fulfilled by the workflow: 1. Goals establishment, 2. Inputs (data collection and management), 3. Processing, 4. Outputs, and 5. Feedback. This workflow is supposed to be a set of interconnected "boxes", where information and processes interact in order to achieve the Forest Monitoring System for the eucalyptus stands affected by weevil outbreaks in the target area. Several "boxes" might not be filled now, because of the lack of suitable data, budget… but the designed workflow should provide the possibility of filling them when it would be feasible (e.g. using high resolution instead of medium resolution imagery).

3.1. Goals establishment

The first step in the workflow was determining the goals to achieve. For this study four critical questions have to be addressed: Where are the weevil outbreaks? Why those locations? What should be done: biological control, silvicultural treatments, chemical treatments? Which are the most unsuitable areas for new plantations regarding this pest?
These goals have to be clearly described in the workflow. As well, the outputs (format, scale, accuracy…) necessary for forestry administration, the private owners and all the other stakeholders should be identified. The workflow can be less output-dependent if these requirements are flexible.

3.2. Inputs (data collection and management)

Prior to data collection, data requirements necessary to meet the identified goals and outputs should be considered. In the workflow different kind of satellite imagery, field data, and forest inventory data has to be combined to optimize the results. The high cost of field inventory data, point out the importance of a careful data selection. This workflow is designed to use remote sensing data for defoliation assessments, as well as ancillary data such as forest stand data or topographic data. Depending on the available data, the workflow outputs will be different. For instance, if topographic maps 1:50,000 and coarse resolution imagery are used, detailed outbreak mapping cannot be expected. Data availability, costs, and timeliness have to be considered when selecting data collection methods.
To facilitate data consolidation and minimize processing time, the data standardization of all data inputs is required. All the attributes have to be included in the database, and a data quality matrix is applied to verify the standards are taken into account. This forest information system tracks data collected from the aerial detection to ground detection phases, tracks the proposed actions for each infected area and follows the progress of the management proposals.

3.3. Processing

This step deal with transforming raw data into information. This means image analyses, thematic/spatial queries, and a complete integration of all the information in the system. The specific analyses depend however on the imagery and the forest stand information gathered. The workflow presented here deals with specific data, however conversions can be introduced regarding the particular requirements of some satellite imagery or new information acquisition. In this paper, processing is more a result than methodology. Ancillary data from the developed GIS is used to achieve a more accurate classification of defoliated areas using satellite imagery. Remote sensing is the selected source to detect and monitor eucalyptus stands affected by the weevil.

3.4. Outputs

Outputs are directly related to goals. Following the recommendations of the Ministry of Forests (Canada)[18], which indicate the typical outputs for an information system in a Forest Health System, the next kind of outputs can be expected:

a. Summary maps and tables depicting the spatial distribution of the outbreaks and the affected stands. These maps are suitable for planning to define actions and responsibilities. Different scales can be obtained.
b. Reports about spread patterns and maps for visualizing these patterns.
c. Reports and maps with technical solutions for the different stands, suggesting the most suitable method: biological control, silvicultural and/or chemical treatments. Biological control requires information about where and when the outbreaks appear. Chemical treatments will be only suggested after taking into consideration: the degree of damage, stand location (e.g. proximity to inhabited areas), expectable effectiveness, and environmental impact.

Each of these outputs requires formats to be established (i.e., map, table and report templates). Generating the required maps, tables and reports should be a semi-automated process if steps 1 to 3 are followed. The full utility and value of an information system is revealed at this point.

3.5. Feedback and update

The utility of the outputs has to be checked in field by the stakeholders (e.g. forestry administration, owner) and new requirements can be pointed out. Changes in the scale, the way to present the recommendations can be modified regarding the new requests. It means a redesign or readjust in the workflow, always necessary to optimize it.

This monitoring system has to be updated at least once a year. The frequency depends on the possibility of acquiring satellite imagery and the necessary data.

4. RESULTS

Once the advantages and disadvantages of using remote sensing to identify defoliated areas are settled, a forest management and monitoring system which integrates remote sensing and GIS is proposed. Biological control, silviculture, chemical treatments and their planning are considered as outputs for this system. The workflow is shown at Fig. 2.
The system has two different and connected components: the integrated pest management part and the resources estimation (timber volume) component. This workflow is focused on the first one, while the later is still under development, but based on the same information system and remote sensing data.

4.1. Inputs and processes

The first step is detecting defoliated areas using remote sensing, as an objective, accurate, consistent and affordable method. Taking into account the eucalyptus stands characteristics (evergreen broadleaf stands, nearly monoespecific, currently without silvicultural practices), the biological cycle of the insect (number of generations per year, effective biological control with *Anaphes nitens*, most visible damage period), costs and the project potential area extent, multispectral medium spatial resolution imagery are proposed as input data. Landsat 5 (July 2004) and SPOT (July 2004) will be employed. Depending on the results multitemporal data will be acquired in order to do multitemporal analyses and try to identify patterns. One available ASTER image (2001) would be tested; if the results are satisfactory acquisition of ASTER images in the future would be considered. High resolution IKONOS imagery is proposed to be used in a sub area, in order to test their performance. Data fusion with aerial NIR photographs of 2001 will be done in order to achieve a more accurate classification. All these data will be georeferenced using 1:5,000 digital topographic maps. This cartographic information wild be also used to register all the information which will be a part of the GIS.

Topographic maps are used not only as a geographical reference, but also to generate a Digital Terrain Model (DTM), which will be used do obtain a slope and an aspect maps. Combining imagery metadata and the DTM a shadows map will be calculated. These attributes will be used during the imagery classification process, if suitable. All data will also be part of the GIS.

A set of ground data is required to make the imagery classification and also to try to explain the “Why there?” question. These ground data have different sources and different mensuration methods have been used. Forest stand parameters such as species or timber volume, come from the Third National Forest Inventory (IFN3) (data from 1998-99) and the grid established by ENCE (a pulp and paper company). Attribute data about defoliation can be obtained from the ICP European network, the network developed by the Phytopathologic Station of Areeiro (Pontevedra) and the one established by the Forestry Research Centre of Lourizán (Pontevedra). These are not current data and they do not match to the imagery acquisition dates, so that they cannot be used in this study. However, for other areas of Galicia they may be suitable, and that is why they are included in the workflow. All these data have to be registered with GPS in a consistent format.

Due to the lack of current data to be used as ground truth data for defoliation, a new network is designed to gather suitable data. More than 200 plots are measured following a 1x1 km grid, coincident with one used during the III IFN, and in each plot dasometric, dendrometric variables are collected, in order to stratify data depending on age, canopy or stand structure, GPS position and physiographic variables are also recorded, as well as understory data. The main parameter is, however, defoliation, which is measured following a special standard developed. The measures are done by one single team, so that subjectivity is minimized. Different defoliation levels are established considering not only the outbreaks, but also the canopy structure. Site index information is derived from this dataset. A new table with spatial information is created in the database that records the specific information collected during these ground surveys and it is included in the GIS.

Soil information from existing digital maps, climatic maps, or information about the areas where Anaphes nitens populations have been released, are included in the GIS as ancillary information to be used when trying to explain the detected outbreak patterns.

Each of the datasets has to fulfill the data quality requirements, and follow a metadata/lineage standard, in order to know its accuracy and its suitability and limitations for the proposed analyses.

For imagery classification to identify the defoliated areas, a mask with the existent eucalyptus stands according to the III IFN is applied. Then classic per pixel classifications and object oriented classifications are used. Data as topographic variables, shadows and dasometric variables are used to improve the results, as proposed by several authors[29,46]. To validate the classification and to obtain a reliable accuracy assessment an independent defoliation subset from the ground survey data is used.

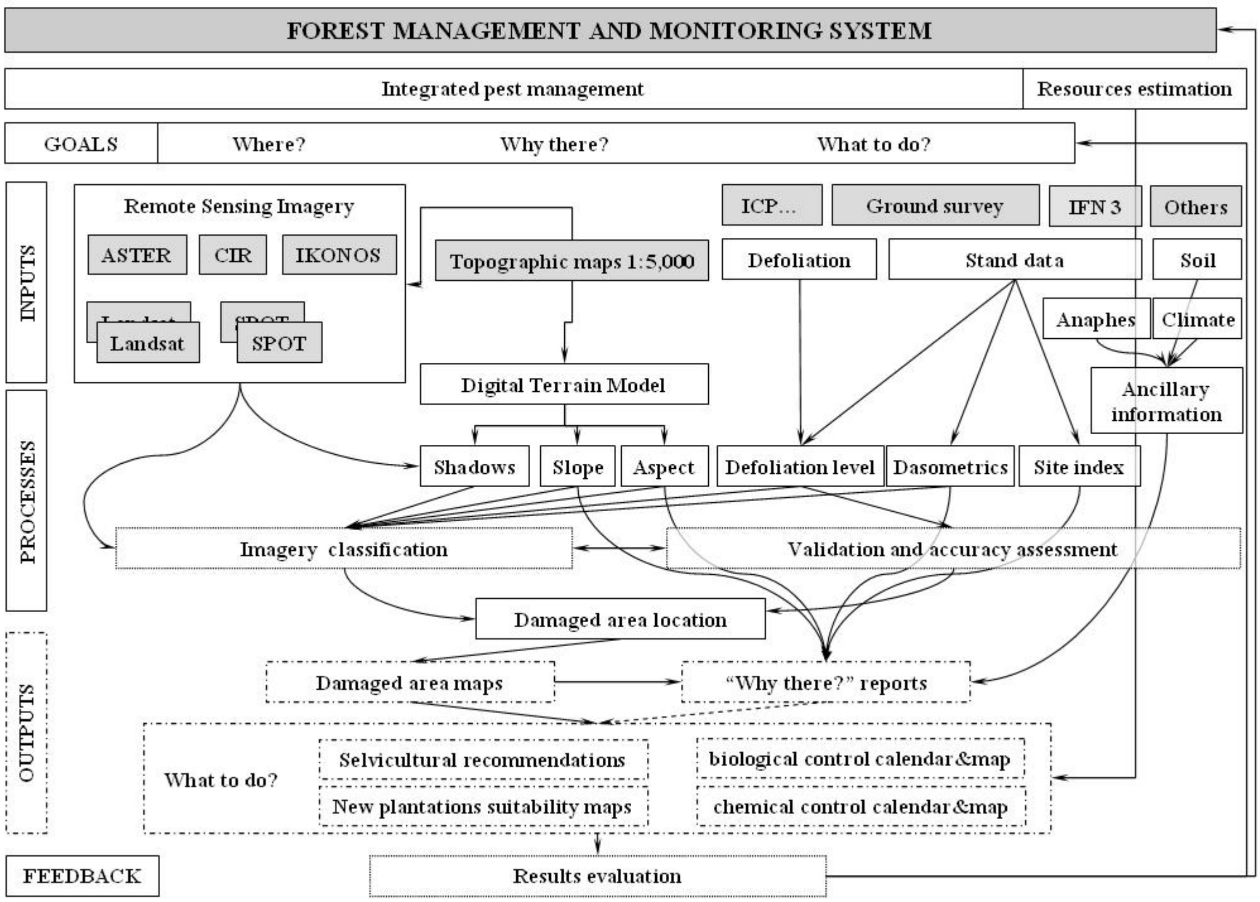

Figure 2. Forest management and monitoring system workflow.

4.2. Outputs

Once the classification is validated and damaged areas are located using remotely sensed imagery, the system's first output is achieved: the damaged area maps. These can be directly used by the administration for inventory purposes and to quantify how large are the areas affected by the outbreaks.

The second output is obtained after combining the damaged area maps and information about physiographic variables, dasometric variables, site index and ancillary information regarding soils, climate, etc. This data fusion is the first step in investigating “Why there?” and explaining the detected patterns.

The third output is actually a set of outputs, gathering practical recommendations that take into account the damaged area maps and the “Why there?” reports, as well as the resource estimations. Depending on the economical value, the suitability for forest production, the site index, the degree of infection, the outbreaks’ frequency, the efficiency, and the environmental impact of the treatment in the area, then new plantations suitability maps are developed, silvicultural recommendations for current/new plantations are reported, and a calendar and a map to apply biological or chemical control are built up.

4.3. Feedback

At the end of the year the results are evaluated, with consideration of their applicability. Feedback from the administration and from the plantations’ owners is requested, in order to modify the goals, methods and/or outputs. Questions as: friendly format, understandable reports, and specific and useful recommendations are critical to achieve a successful forest and management system.

5. CONCLUSIONS

A reliable, accurate, and effective Forest Management and Monitoring System has to be based on a workflow where remote sensing imagery, forest stand parameters and complementary data are integrated in a GIS.

The success of this system depends on the ability to detect defoliation using satellite imagery. Without remotely sensed data costs will be unaffordable to reach a suitable accuracy.

Depending on the spatial resolution of the satellite imagery employed, management at different scales is possible. Temporal resolution should also be considered, as well as climatic conditions during the image acquisition.

All data have to fulfill the established accuracy requirement, and metadata have to be carefully development, in order to know the limitations and the applicability of the data and the results.

The use of complementary information about outbreaks frequency, the suitability for forest production, economical value, site index, degree of infection, the efficiency and the environmental impact of the treatment in the area, maps where owners visualize locations less suitable and profitable for eucalyptus plantation should be developed. If this information is taken into account it would ensure that eucalyptus plantations are only located in the most suitable places or, at least, in the most profitable ones considering pests.

Actions over current plantations can be also planned, such as silvicultural recommendations adapted to the site index, or planning the biological/chemical treatments. Objective criteria are the base for these recommendations, so that technical decisions are reported.

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