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Poster contributions
Large area mapping and monitoring

**EUCALYPTUS HEALTH MONITORING SYSTEM BASED ON
REMOTE SENSING AND GIS FOR PLANTATIONS AFFECTED BY
WEEVIL OUTBREAKS IN GALICIA (NORTHWEST SPAIN)**

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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 study is to propose and describe an objective, accurate, timely and efficient Eucalyptus Health Monitoring System for plantations affected by weevil outbreaks in Galicia by means of remote sensing techniques and a geographic information system. The main goal is locating the areas where pest outbreaks affect health status and productivity in *Eucalyptus globulus* in Galicia. In those areas a more intensive health assessment/monitoring survey should be considered. The interest is focused on detecting those areas where damages caused by defoliation are severe enough to not to be compensated by the high growth rates in these plantations or where the growth rates are slowed down. Thus, the areas identified by the proposed model are suggested areas to monitor by field survey, as part of a multistage or multiphase sampling. Hence, field work is led to those stands with a high likelihood of being infested, increasing sampling efficiency and decreasing sampling pressure, which results in lower costs.

Keywords: remote sensing, GIS, process-based model, defoliation, *Eucalyptus globulus*, forest health

1 INTRODUCTION

In Spain *Eucalyptus* plantations cover 500,000 ha and considering its extent and the utility of its wood, *Eucalyptus globulus* has become the most important species. *Eucalyptus globulus* location is mainly limited to the North and Northwest (Galicia, Asturias, Cantabria) and to some areas in the Southwest due to its climatic requirements (González-Río *et al.*, 2004): 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 (MMA, 2004)). According to the 3rd National Forest Inventory (1997-2006) in Galicia there are 429,000 ha of mixed stands where *E. globulus* is the primary species and 178,000 ha of pure *E. globulus* stands (12% of the total forest area) (MMA, 2004). Furthermore, *Eucalyptus globulus* plantations are the most productive forest stands in Spain. While the mean annual increment in the productive forests in the Iberian Peninsula is 2.5 m³/ha-year, the mean for eucalyptus plantations is around 7.5 m³/ha-year (Toval, 2002).

Regarding stocks (around 23 million m³ in pure stands according to the 3rd National Forest Inventory) and extension, Galicia is the most representative area for Eucalyptus plantations in Spain. Concerning wood production, *E. globulus* reaches an annual increment of 3 million m³/year, which means nearly the 28% of the total in Galicia. The yield is also higher for eucalyptus than for the other species, achieving average values of 13-17 m³/ha-year, and is possible to reach 30 m³/ha-year on the best terrain (Roís, 2004). 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. Nevertheless, since 1991 the high productivity of this species has been threatened by the outbreaks of the

Eucalyptus snout beetle (*Gonipterus scutellatus*, family *Curculionidae*), found at first time in Pontevedra (Mansilla & Pérez, 1996). However, other beetles and diseases affect Eucalyptus stands in Galicia, the most harmful has been the snout beetle, concerning its proliferation and the extent of its effects over the trees.

Gonipterus scutellatus is native to south-east Australia and it had a rapid spread in Spain (around 100 km/year in some areas), being detected in the other northern regions of Spain and in Portugal, and reaching the South of Portugal in 2003 (Xunta de Galicia, 2004). The speed of spread has to do with the absence of natural enemies, and the lack of an ecological balance between the populations. In these latitudes the snout beetle can produce up to three generations per year and both larvae and adult phases are very active, causing intense defoliation by eating shoots and tender leaves, which means significant losses in forest productivity. These damages have tried to be minimized using the mymarid *Anaphes nitens* Girault, a parasitoid of *Gonipterus* eggs, for biological control. In Galicia the first campaigns with *Anaphes nitens* started in 1994 and the results can be considered very successful. Where the biological control is not possible because the degree of infection is too high, a pesticide is being effectively used. For one individual tree defoliation is more marked in July and August (Ruiz *et al.*, 2002), 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. According to the Pan European forest monitoring system defoliation increased during the period 2002-2004 in *Eucalyptus globulus* plots mostly due to an augment of damaged caused by *Gonipterus scutellatus*. In 2004, 88% of *Eucalyptus globulus* plots showed defoliation, most of them (59%) in a slight degree; besides, the moderate class increased in comparison to 2002 and 2003.

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 Eucalyptus Health Monitoring System (EHMS), where not only defoliation (forest health), but also silvicultural, dasometrical, dendrometrical, climate and soil data are assembled.

Although it is not generalized the use of a systematic system in place to collect or report information and incorporate it into decision making regarding monitoring insects and diseases, fuel loading, stand density, and other stress indicators to maintain forest health, several forest health monitoring systems have been developed by the governments or the local agencies in areas like Europe, Canada, the United States or Australia. The implementation of these forest health assessment programs has met with mixed success, and the main reasons have been attributed to a lack of understanding as to what is meant by forest health and/or varying definitions of forest health depending on management perspectives, budget constraints in forest management, a poor integration of health monitoring programs with other forestry management operations and to limitations associated with the qualitative, visual and subjective assessment of forest health (Stone *et al.*, 2000).

The aim of this study is to propose and describe an objective, accurate, timely and efficient Eucalyptus Forest Monitoring System for the eucalyptus stands affected by weevil outbreaks in Galicia using remote sensing and Geographic Information Systems (GIS).

2 STUDY AREA

Galicia is in the North West of Spain and covers an area of nearly three millions hectares. Of this area the 69.67% is forest land, and 48.18% is forestry-wooded land⁶. 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 m³, being mainly of *Pinus pinaster* and *Eucalyptus* spp. These afforestations cover more than the 70% of the forestry wooded-land (MMA, 2004). In Galicia, in the coastal area, the mean annual precipitation is about 1,000 mm, depending on the considered area. A target area of about 300 km² in Pontevedra in the Morrazo's peninsula has been selected for this study. Its location has been selected because the weevil outbreaks have been important since the beginning, and it is where it was first detected.

3 PROPOSED EUCALYPTUS HEALTH MONITORING SYSTEM

A forest management and monitoring system for eucalyptus plantations which integrates remote sensing and GIS is proposed. There is a critical need to consistently map and monitor the spatial location and dynamics of insect defoliation to provide information for prescribing pest management practices and to assess their impacts on eucalypts health and productivity. The workflow is shown at Fig. 1. This system provides decision support to forest managers by identifying areas of concern, recommending areas to monitor and recommending areas to treat using biological control, silvicultural treatments, chemical treatments.

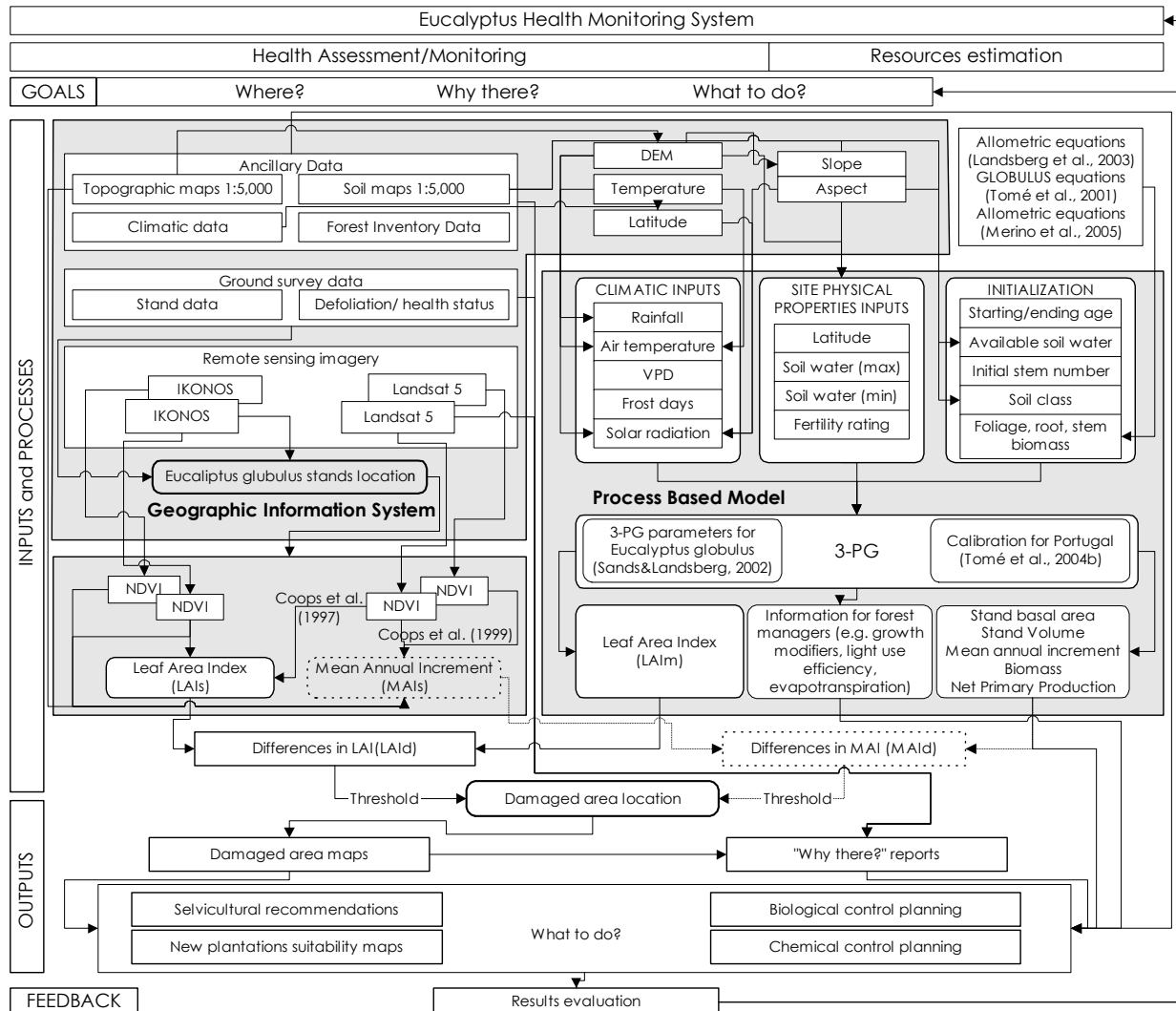


Figure 1. Proposed Eucalyptus Health Monitoring System

The main goal is, as described before, locating the areas where pest outbreaks affect health status and productivity in *Eucalyptus globulus* in Galicia. In those areas a more intensive health assessment/monitoring survey should be considered. The proposed monitoring system is designed for *Gonipterus scutellatus* outbreaks, but it is possible to detect other disturbances which disturb eucalyptus growth (e.g. abiotic damages, diseases). The interest is focused on detecting those areas where damages caused by defoliation are severe enough to not to be compensated by the high growth rates in these plantations or where the growth rates are slowed down. The areas of concern where disturbances are identified are not straightforward identified as defoliated areas by the weevil, because is not reliable assessing causal agents merely from remote sensing imagery (Ciesla, 2000). Thus, the areas identified by the proposed model are suggested areas to monitor by field survey, as part of a multistage or multiphase sampling (Wulder & Dymond, 2004). Hence, field work is led to those stands with a high likelihood of being infested, increasing sampling efficiency and decreasing sampling pressure, which results in lower costs.

3.1 INPUTS AND PROCESSES

The proposed Eucalyptus Health Monitoring System is developed for *Eucalyptus globulus* stands, so that their locations have to be known and stored in a Geographic Information System (GIS). If updated and reliable maps from forest inventory are available, they can be used and straightforwardly integrated in the GIS. Otherwise, *Eucalyptus globulus* stands are identified and mapped using remote sensing imagery.

One of the most important factors governing the use of remote sensing for assessing insect damage, including defoliation, is timing (Ciesla, 2000). Damages in eucalyptus stands canopy due to snout weevil are not permanent, because often the high *E. globulus* growth rate and postdefoliation compensatory growth make the likelihood of insect defoliation exceeding foliar production decrease, ensuring rapid recovery after defoliation (Loch & Floyd, 2001). Only severely and repeatedly attacked areas look permanently defoliated. Thus, attacked areas can be masked by posterior refoliation and sometimes the effect of defoliation is only showed as a slow down in growth or growth rate lower than the expected. It makes difficult to define a suitable bio-window to monitor defoliation using remote sensing, and suggest the low suitability of using change detection techniques, because changes in biomass are often too slight to be detected. Although refoliation would not have been expected to produce very high Leaf Area Index (LAI) values, its occurrence raises issues that the timing and magnitude of the second flush are very important from the perspectives of defining the bio-window when remote sensing can be applied for detection of defoliation, and assessing the impact of defoliation on C uptake and productivity (Hall *et al.*, 2003). Thus, another approach is proposed to monitor healthy status in eucalypt stands, by comparing LAI estimated by remote sensing (LAIs) and LAI estimated by means of a process based model (LAI_m). Thus, in defoliated stands actual LAI (LAIs) will be smaller than LAI predicted by a process based model (LAI_m). Considering this approach, not only likely currently defoliated areas are detected, but also areas where there is or there has been disturbances (e.g. weevil outbreaks, frost) which have modified LAI evolution.

A timely and cost affordable assessment of LAI in a large area is not possible by ground-based measurements, so that remote sensing techniques are proposed for its estimation. Coops *et al.* (1997) compared field LAI to the Normalized Difference Vegetation Index (NDVI) and the Simple Ratio (SR) derived from Landsat MSS data in Eucalyptus mixed hardwood forest in south-eastern Australia. Linear relationships were shown to be appropriate to relate both transformations to the LAI data with r^2 values of 0.71 and 0.53 respectively. Therefore, the predictive regression relationship of the form $LAI = a + b(NDVI)$ ($r=0.84$) developed by Coops *et al.* (1997) is integrated in the proposed model to estimate LAI from NDVI derived from Landsat 5 imagery (LAIs). In order to achieve more accurate results, the equation parameters should be calibrated for Galicia using field data. If higher spatial accuracy determining actual LAI is required, high spatial resolution satellite data (IKONOS) is proposed to be used.

Process based models can determine stand parameters such as stand basal area, stand volume, Mean Annual Increment (MAI), biomass or Leaf Area Index (LAI) taking into account variations in soil or weather conditions (Landsberg *et al.*, 2003). Regarding its simplicity the process-based forest growth model called 3-PG, developed by Landsberg and Waring (1997) is included in the Eucalyptus Health Monitoring System to estimate LAI. The parameters necessary to drive the 3-PG model in *Eucalyptus globulus* stands in Galicia are already available (Sands and Landsberg, 2002), and the results are likely to improve by using the calibration developed for Portuguese stands (Tomé *et al.*, 2004b). Basic climatic data in the GIS are monthly temperature (maximum and minimum) and rainfall records from nearby weather stations. Vapor Pressure Deficit (VPD) is estimated straightforwardly by the 3-PG model using the maximum and minimum monthly temperature values. A Digital Elevation Model is used to calculate soil variables and to topographically correct radiation and temperature data, as proposed by Coops and Waring (2001) and Tickle *et al.* (2001). Soil water holding capacity is primarily a function of texture, permeability, and soil depth (Almeida *et al.*, 2004), and estimates are based on soil physical properties and soil depth (from available soil maps) and chemical analysis when available, as done by Landsberg *et al.* (2003). Soil fertility is inferred from mineralogy classes available from soil maps, which provide broad indications of the fertility of the major soil types (Coops & Waring, 2001). Slope and topographic parameters are used in the modeling of soils properties at landscape scale, as proposed by Tickle *et al.* (2001). Initial values of available soil water can be estimated by using the Williams *et al.* (1992; in: Tickle *et al.*, 2001) pedotransfer functions. Initial values of foliage, stem and root mass, appropriate to the age of the stand at the beginning of a run are also required; specific biomass

equations depending on diameter at breast height, height and basal area are available for *Eucalyptus globulus* in Galicia to predict these biomass fractions (Merino *et al.*, 2005). If height data are not available, allometric equations for *Eucalyptus globulus* developed by Landsberg *et al.* (2003) can be used. Foliage, root and stem biomass can be also estimated from the equations of the GLOBULUS stand model for *Eucalyptus globulus* plantations in Portugal (Tomé *et al.*, 2004a).

The main outputs of 3-PG model (leaf area index, mean annual increment, stand basal area, stand volume, foliage biomass) are showed as layers in the GIS, achieving values for all areas with Eucalyptus stands. Therefore LAI values are predicted through the model (LAI_m) can be compared with actual LAI values derived from satellite imagery. When the difference (LAI_d) is negative, LAI predicted by the model is larger than the estimated using satellite imagery; thus, the first output of the system is achieved after selecting a threshold to differentiate areas where the differences are so large that they can be due to defoliation. The differences are ranked and showed in a map, so that areas where differences in LAI are larger are more likely to be damaged areas. Some spatial context will be needed in to separate differences in LAI due to insect infestation versus changes due to other factors such as harvesting. Mean Annual Increment (MAI) is proposed as additional criterion in order to achieve consistent results because severe health issues are reflected in growth and changes in growth rate can be an effect of pest/diseases pressure (De Jong, 1995). Mean Annual Increment can be predicted using 3-PG model (MAI_m), using the same data as for predicting LAI (see above). Differences in MAI predicted by the 3-PG model (MAI_m) and from satellite (MAI_s) will highlight those areas where the growth patterns are/have been disturbed.

One of the outputs of the Eucalyptus Health Monitoring System is reporting if defoliation is related to stands parameters, spatial data (topographic variables, climatic data) and/or spectral response, so that “Why there” reports are generated. The method is calibrated and validated with ground survey data, topographic data and medium spatial resolution imagery stored in GIS layers. Due to the lack of current defoliation data registered enough geometric accuracy, a network was 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 were 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.

3.2 OUTPUT

Once the 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 likely to be affected by the outbreaks. However, the EHMS does not attempt to identify causal agents by the solely use of remote sensing imagery, an component of the operational system will be a supportive ground-based program. Hence, when necessary, more intensive surveys will use as reference these damaged area maps.

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 information from the growth model regarding 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. Chemical treatments will be suggested after considering the degree of damage, stand location, expectable effectiveness, and likely environmental impact.

3.3 FEEDBACK

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

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