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## Modelling spatial distributions of alpine vegetation: A graph theory approach to delineate ecologically-consistent species assemblages

A. Mikolajczak<sup>a</sup>, D. Maréchal<sup>b</sup>, T. Sanz<sup>a</sup>, M. Isenmann<sup>a</sup>, V. Thierion<sup>b</sup>, S. Luque<sup>b,c,\*</sup>

<sup>a</sup> CBNA, National Botanical Conservatory of the Alps, 148 rue Pasteur, 73000 Chambéry, France

<sup>b</sup> Irstea – National Research Institute of Science and Technology for Environment and Agriculture, UR EMGR Mountain Ecosystems Unit, Grenoble, France

<sup>c</sup> University of St Andrews, School of Biology, St Andrews, Fife KY16 9ST, Scotland UK

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### ABSTRACT

Safeguarding biodiversity has been one of the most important issues on the environmental and forest policies agenda since the 1990s. The problem remains in terms of decisions and knowledge on where to set appropriate conservation targets. Hence, we need detailed and reliable information about habitat structure and composition and methods for estimating this information over the whole spatial domain. In answer to this target, in France, the Ministry of Ecology launched an ambitious project to map the terrestrial vegetation at a scale of 1:25,000 known as CarHAB. This project initiated in 2011, will be used as a strategic spatial planning tool in answer to key issues in relation to biodiversity, conservation, green infrastructures and to report on the conservation status of habitats and species of community interest.

We use species–distribution models (SDMs) to identify areas that are ecologically suitable for the presence of species based on specific habitat characteristics. Available techniques using graph theory enable identification of groups of species (assemblages) based on ecological affinities. Species co-occurrences (present within the same assessment plot), revealing a shared ecological niche, are analysed using algorithms derived from graph theory in order to define different nodes of species affinities. Thus, the resulting assemblages are based on ecological similarities. Hence, these assemblages are used to develop models of the potential distribution of alpine vegetation communities. The BIOMOD platform is used to facilitate the simultaneous implementation of different modelling approaches that can be compared in order to choose the most suitable and accurate for each species assemblage obtained from graph theory. Using the different relevant spatially explicit results provides a more comprehensive vision of the communities' spatial distributions.

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### 1. Introduction

Predictive models of species distributions are being increasingly used to address questions related to the ecology, biogeography, and conservation of species (see Peterson, 2007). Detailed knowledge of ecological and geographic distributions of species and vegetation is fundamental for conservation planning and forecasting (Ferrier et al., 2002; Funk and Richardson, 2002; Rushton et al., 2004) and for understanding ecological factors of spatial patterns of biodiversity (Brown and Lomolino, 1998; Graham and Hijmans, 2006; Ricklefs, 2004; Rosenzweig, 1995).

In the framework of the French national project CarHAB, this research aims at exploring the potential of predictive vegetation modelling to improve and support detailed vegetation mapping. CarHAB project aims at mapping natural and semi-natural vegetation of the

French territory at a scale of 1:25,000 (EEA, 2014). It addresses three major challenges based on stakeholders needs: i) to provide a comprehensive inventory of vegetation and habitats, ii) to assess their conservation status and iii) to provide the baselines for related planning and conservation projects. Vegetation mapping relies on achieving base-map learning about the physiognomic and environmental characteristics of vegetation. These base-maps are aimed at providing support for the extrapolation of phytosociological surveys conducted in the field before the completion of the final vegetation maps based on remote sensing data derived from different satellites. The work presented was tested in a complex mountainous environment in the French Alps (Isere Department). In all, the approach developed opens innovative ways towards a replicable classification scheme for vegetation mapping over open environments based on graph theory to delineate ecologically-consistent species assemblages to be modelled.

### 2. Background and study area

The study area is a testing ground on a crystalline mountain range (Belledonne, Grandes-Rousses, Ecrins, Oisans; Fig. 1), extending to

\* Corresponding author at: Irstea – National Research Institute of Science and Technology for Environment and Agriculture, UR EMGR Mountain Ecosystems Unit, Grenoble, France.

E-mail address: [Sandra.luque@irstea.fr](mailto:Sandra.luque@irstea.fr) (S. Luque).

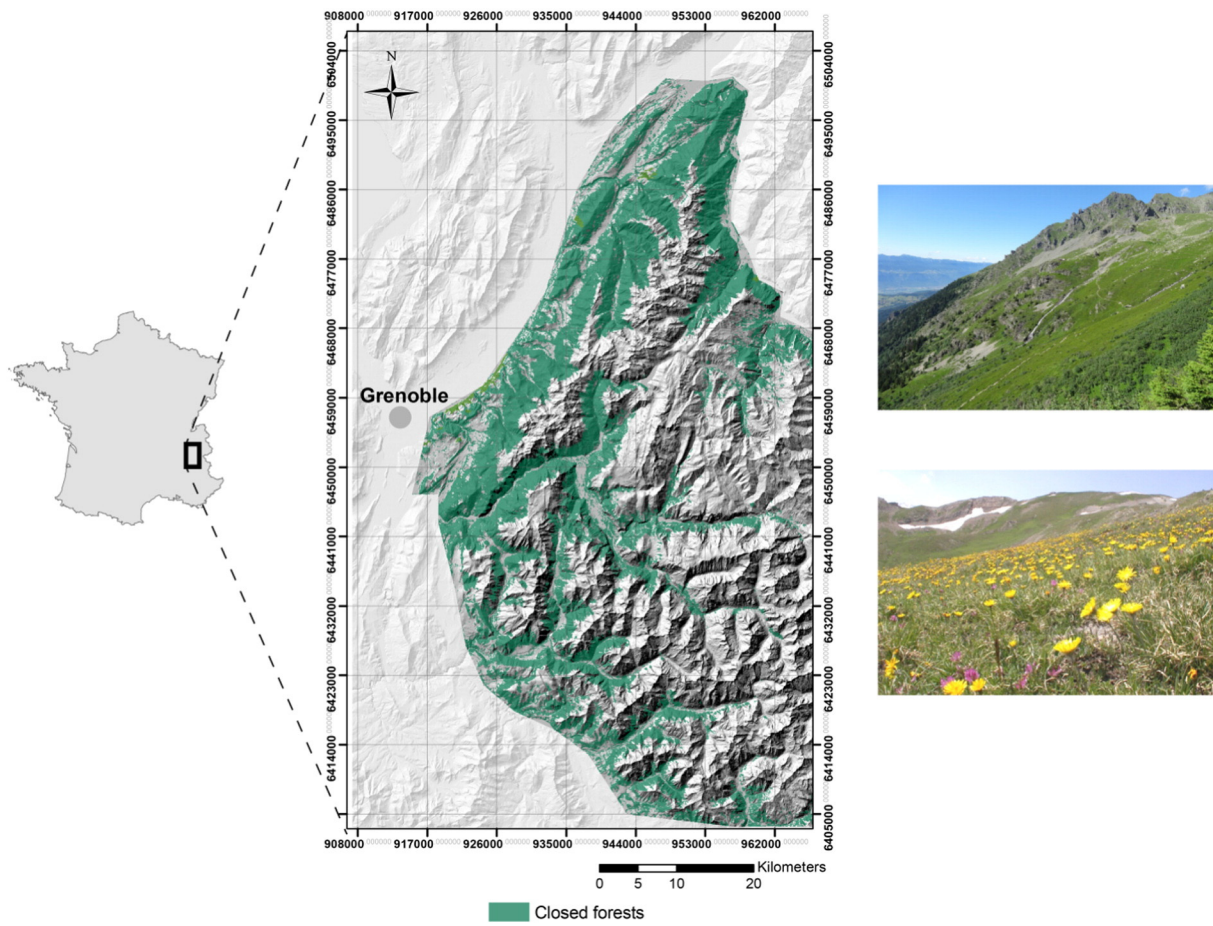


Fig. 1. Belledonne, Grandes-Rousses, Ecrins, Oisans — mountain range located in the Isère French Department.

5000 km<sup>2</sup> and located in the Isère French Department. The area is dominated by siliceous grasslands from sub-alpine and alpine belts ranging from 1500 to more than 3000 m above sea level — the timberline being at about 2200 m. Sub- and alpine grasslands show a great diversity according to ecological factors, such as temperature, elevation and solar radiation. Topographic position at the alpine belt is a key factor because it influences snow cover duration, which is known to determine plants' ecophysiology and adaptation. Micro-topography and consequent rapid changes of environmental conditions in space and time are also important features of alpine glacier-shaped landscapes that strongly influence the plant community properties.

### 3. Methods

#### 3.1. Graph theory to uncover species assemblage patterns

Graph theory has recently gained much attention in various fields of science. In the ecological sciences, it was first used to analyse webs of real biological interactions, such as food-webs, gene and protein networks and pollination networks (Proulx et al., 2005). The first application of graph theory to vegetation-plot data (species \* sites table) was conducted by Yarrington (1973) to test the homogeneity of phytosociological tables. Dale (1977a,b) suggested later that graph theory could be used to detect plant species interactions in temperate forests at different scales. The method enables the properties and behaviour of networks to be quantified and visualized with friendly graphical outputs.

A graph is a mathematical object corresponding to a network. It is composed of a set of units, called nodes, connected by edges. A module is a subset of highly-connected nodes with looser connections to the rest of the graph (Fig. 2B). The nodes can represent units at most levels

of the biological hierarchy (e.g. from genes to proteins, from individuals in a population to species in a community). Edges usually represent interactions between nodes. The co-occurrence of species that is derived from vegetation-plot data represents a sort of statistical interaction. Depending on the scale of the dataset (plot size and extent), the co-occurrence species can be linked to different kinds of ecological processes that graph theory can help to explain. Dale (1977a,b) showed facilitation patterns in forests with very fine-scale data. Fine-scale data like in this study are relevant to look at the ecological requirements of species (niche). Yet large-scale data could be used to reveal *nestedness* and other biogeography-related patterns of communities' species composition.

Here the goal is to delineate alpine-grasslands plants' assemblages based on the ecological requirements of species in order to use ecological gradients to model assemblages' distribution patterns. We start with the hypothesis that all species have specific habitat requirements, which can be described by habitat factors. These factors are inter-related to critical habitat characteristics, e.g. to those of vegetation and soil, but also areas surrounding the habitat (e.g. the spatial structure of landscape elements). The assemblages were then defined by applying a graph theory approach to a dataset of 4280 phytosociological vegetation plots corresponding to acidophilus sub- and alpine grasslands, collected by the National Botanical Conservatory of the Alps (CBNA). Information within plots includes location and plant species list (abundance) occurring within vegetation' stands. Our concern was to elaborate species assemblages (or modules) that are not constrained by phyto-sociological principles but based on the species co-occurrence at the monitoring plot level.

The co-occurrences between pairs of species were derived from the vegetation-plot dataset. They were then translated into a graph where

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