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Plot-scale modelling to detect size, extent, and correlates of changes in tree defoliation in French high forests

Marco Ferretti [a,*], Manuel Nicolas [b], Giovanni Bacaro [a,c], Giorgio Brunialti [a], Marco Calderisi [a], Luc Croisé [b], Luisa Frati [a], Marc Lanier [b], Simona Maccherini [a,c], Elisa Santi [a], Erwin Ulrich [b]

[a] TerraData Environmetrics, Spin Off Company of the University of Siena, Via L. Bardelloni 19, 58025 Monterotondo M.mo, Grosseto, Italy
[b] Office National des Forêts, Département Recherche et Développement, Direction Technique et Commerciale Bois, Boulevard de Constance, 77300 Fontainebleau, France
[c] BIOCONNET, Biodiversity and Conservation Network, Department of Environmental Science "G. Sarfatti", University of Siena, Via P. A. Mattioli 4, 53100 Siena, Italy

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ABSTRACT

Tree crown defoliation data collected on 102 managed forest plots of the RENECOFOR programme in France were investigated to identify (i) short-term (annual) changes and medium term (1994–2009) trends, and (ii) possible correlates of such changes and trends. Methodological aspects (trees assessed, changes in methods and reporting units, observers, assessment dates) were considered. To account for the specificity of individual plots in terms of tree provenance, age, site condition and management regime, an individual plot approach was adopted. Results showed highly frequent, statistically significant and methodologically meaningful (>5% of the expected measurement error) annual defoliation changes, with pulses of increasing defoliation occurring in 1994–1997 (with a possible methodological bias), in 2002–2004 and 2008–2009. A meta-analysis of individual plot results revealed a significant overall increase, in defoliation over the examination period; when the potentially biased 1994–1996 data were excluded from the analysis, the increase in defoliation was also significant. Within this overall increasing trend, cases of stability (11–24% of the plots) or even decreasing defoliation (11–18%) were frequent. We used a Partial Least Square (PLS) regression to model defoliation on 87 plots where sufficient data was available for a standard set of predictors, including meteorology, nutrition, phenology, reported health problems, management regime and assessment methodology. The most frequent correlates of defoliation were precipitation-related variables (of the current and previous years), tree density and frequency of trees with reported health problems. Foliar nutrients, air temperature, assessment method and observers were never found to be important predictors. Within this general pattern, interactions among predictors varied on a plot basis, leading to divergent estimated effects for the same predictor. The adopted plot-based approach avoids the bias that affects traditional cross-sectional, correlative studies and makes it possible to estimate correlates of change at the scale of individual plots; it is therefore a powerful tool to identify response patterns that can be of value when considering (or re-considering) management options.

1. Introduction

Detecting and understanding changes in forest condition is important in terms of sustainability and adaptation of forests and forest management to environmental changes (Bolte et al., 2009; Wulff et al., 2012; Niinemets, 2010), with climate change being of particular concern (Allen et al., 2010; Carnicer et al., 2011). In Europe, anticipated climate change scenarios (e.g. IPCC, 2007; Meehl and Tebaldi, 2004) include increased frequency of heat waves, droughts, storms and related pathogen attacks that may all result in a loss of forest health and productivity and a reduction in the efficiency of terrestrial carbon sinks (e.g. Ciais et al., 2005). Concretely, forests "are exposed to a myriad of stress factors with varying strength and duration throughout their lifetime" (Niinemets, 2010). These multiple factors cause broad fluctuations in forest condition, and make it difficult to properly identify meaningful changes and trends and of the main factors associated to such changes, and to generalize the results obtained. While experiments with mature forests are subject to many constraints (e.g. Köhl et al., 1994), long-term large-scale forest monitoring provides consistent data series and is a powerful tool to investigate the role of biotic and abiotic factors on the development of forest conditions over time (e.g. Innes, 1995; Lindenmayer and Likens, 2009; Ferretti and Fischer, 2013); monitoring is therefore crucial to inform any adaptive management process

* Corresponding author. Tel./fax: +39 0566 916681.
E-mail address: ferretti@terradata.it (M. Ferretti).

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(Elzinga et al., 2001). During the 1990s, internationally co-ordinated intensive forest monitoring programmes (known as "Level II" monitoring, Lorenz and Fischer, 2013) were launched in most European countries under the auspices of the United Nations Economic Commission for Europe (UNECE) and with the support of the European Commission (EC). Intensive forest monitoring networks are series of permanent plots purposely selected to measure – at the same sites – forest response variables and a suite of possible driving factors (e.g. Ferretti, 2013). The potential of a monitoring network to provide the desired information rests on overall monitoring design, on the ability of the measured response variables to capture the phenomenon of concern, and on proper data evaluation (e.g. Innes, 1998; Percy and Ferretti, 2004; Wulff et al., 2012). In Europe, forest monitoring networks and response variables were established in the 1990s (Ferretti and Fischer, 2013). Regrettably, however, the question of data evaluation was almost completely disregarded at the time the intensive monitoring networks were being designed (Lindenmayer and Likens, 2009; Ferretti and Chiarucci, 2003). With the exception of Seidling (2007), evaluation approaches adopted for Level II data were based on spatial, cross-sectional (sensu Seidling, 2007) data aggregation (e.g. Zierl, 2002; Innes and Boswell, 1991; Innes and Whittaker, 1993; Klap et al., 2000; Ferretti et al., 2003, 2007; see also the review by Seidling, 2000). With this approach, data from different plots over a given region were averaged over a defined time frame and plots were used as cases in various statistical models to determine significant predictors of selected response variables at the biological and chemical level (e.g. tree defoliation, growth, nutrition). Unfortunately, this approach failed to consider that each Level II monitoring plot is a unique combination of various elements (trees, site, stand, past- and present disturbances, management, stressors, measurement errors) and that these factors need to be explicitly incorporated into the analysis. A few examples will suffice. Firstly, the development of the forest plot is punctuated by a number of planned (e.g. thinning) and random (e.g. storms and pest epidemics) disturbances, and the time passed after the disturbance is of great importance in determining forest condition and performance (e.g. Magnani et al., 2007). Past management operations were never taken into account in previous studies based on Level II plots, simply because the relevant information had not been incorporated into the database. Secondly, the suite of stressors that affect the condition of a given plot varies from plot to plot in terms of type, timing, strength, combination and duration (Niinemets, 2010) and the response pattern to such disturbances very much depends on specific plot characteristics (e.g. tree age, density and provenance). Thirdly, monitoring design at the plot level and reference standards may change from country to country (e.g. Ferretti et al., 2009), and within a country, observers and errors may vary from plot to plot and year to year. Finally, the co-occurrence of chance events and financial constraints preventing data collection may lead to unpredictable disturbances in the data series that often remain unreported (and are therefore not considered in the data analysis). In the end, a statistical analysis based on a cross-sectional approach carries an inherent risk of mixing different response patterns, different adaptation mechanisms and of incorporating noise from different sources of error. All together, this may lead to a substantial interpretation bias and threaten the ability of the monitoring programmes to respond to the questions they were designed for.

In our study, we acknowledged the specific nature of individual plots, and adopted an individual plot approach. For each individual plot, we considered a time series for one selected response variable (tree crown defoliation – see below and Section 2.3) and for a set of predictors (site, stand, nutrition, meteorology, phenology, methodology – see Section 2.4), and applied a set of statistical techniques to produce plot-wise results. We then combined the individual plot results to generalize the results while including the specificity of the response at the level of the individual plots.

Defoliation is a raw visual indicator of the relative amount of foliage on the tree crown compared with a reference standard. In France, an actual apparently non-defoliated living tree on the same or a nearby plot (same site and stand conditions) is taken as a reference (see Ulrich et al., 1994b and subsequent editions). Using defoliation as an indicator has been widely criticized in the past because of the inherent subjectivity of the assessment (e.g. Ferretti, 1998) and because of its unclear relationship with other, more objective indicators of tree condition such as tree growth (e.g. Innes, 1993). Subjectivity can, however, be controlled by adequate training and field checks (e.g. Ferretti et al., 1999) and a significant relationship between defoliation and growth has been demonstrated (e.g. Solberg, 1999; Solberg and Tveite, 2000; Ferretti et al., 2013a). Despite its inherent limitations, defoliation (and/or a similar proxy indicator such as crown density or transparency) is used to estimate tree condition in Europe and elsewhere (Ferretti and Fischer, 2013) and represents one of the indicator adopted to evaluate and report the sustainability of forest management (e.g. FOREST EUROPE, UNECE and FAO, 2011). The defoliation data in our study were collected by the French RENECOFOR intensive monitoring programme during the period 1994–2009. Two specific, explicit questions were of concern for this paper:

(i) Was there any statistically significant and meaningful change (between subsequent years) or trend (over 15 years) in defoliation during the period 1994–2009 at the RENECOFOR plots?
(ii) What is the relationship between biotic and abiotic stressors and defoliation across the same spatial (102 plots) and temporal (1994–2009) range?

Since the RENECOFOR plots are located in managed forest that undergo regular prescribed management operations, both questions are clearly of relevance in management terms and can provide insight into the response of managed forests to changing environmental factors. We therefore considered not only the set of variables customarily measured on the plots, but also the occurrence and extent of thinnings (in terms of tree density and basal area), the methodology and timing for tree condition assessment and the turnover of field observers.

Given the coverage of Level II monitoring programmes in Europe (ca. 35 countries), the substantial financial investments involved, and the importance of monitoring in providing data to assess the sustainability of forest management, we believe that our methodological approach and results can be of general interest throughout Europe, and perhaps even beyond.

2. Materials and methods

2.1. The RENECOFOR monitoring plots

The RENECOFOR was launched in 1992 and is based on a series of 102 specially selected permanent monitoring plots. The plots were selected in 1991 by taking into account the region, its main tree species, plot homogeneity in terms of site conditions, overall tree health status (only sites with a majority of trees in relatively good health were selected), management regime (only high forests), and stand age in relation to the management cycle (Ulrich et al., 1994a). All RENECOFOR plots are subject to management operations and planned thinnings have been carried out on most of the plots. The plots are located throughout France, cover a range of environmental conditions and include the main tree species