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Identification and spatial extent of understory plant species requiring vegetation control to ensure tree regeneration in French forests

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Abstract

Key message: Fifteen species are most susceptible to require vegetation control during tree regeneration in the range of our study. Among these 15 species, *Rubus fruticosus*, *Pteridium aquilinum*, and *Molinia caerulea* cover each more than 300,000 ha of open-canopy forests.

Context: Vegetation control, i.e., the reduction of competitive species cover, is often required to promote tree seedling establishment during the forest regeneration stage. The necessity to control understory vegetation largely depends on the species to be controlled. In order to plan forest renewal operations, it is critical to identify which species require vegetation control during the regeneration stage and to quantify the forest area affected by these species.

Aims: We aimed at identifying the main species requiring vegetation control and at estimating the forest area they cover at the national level.

Methods: Using National Forest Inventory data, we created four indicators based on two levels of plant cover, cross-referenced with two levels of canopy opening, and compared them to the outcome of a survey of forest manager practices.

Results: The best indicator was the one that represented the proportion of forests with open canopy where the species was present with a large cover in the understory. In non-Mediterranean France, according to the indicator, a total of 15 species were found to frequently require vegetation control during the tree regeneration stage. *Pteridium aquilinum*, *Molinia caerulea*, and *Rubus fruticosus* were the main species, and each covered more than 300,000 ha of forest with open canopies, representing about 13% of the total forest area with open canopies outside of the Mediterranean area.

Conclusions: Forests covered by species requiring vegetation control according to forest managers represent a large share of the forest area undergoing regeneration. This study provides the first list of species that require vegetation control based on a methodological protocol that makes it possible to calculate the area associated with each species.

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1 Introduction

Forest understory plant species may have adverse effects on tree regeneration (De Lombaerde et al. 2021; Wagner et al. 2006) by slowing down or stopping the regeneration process for a time period that ranges from a few years up to more than a century in some extreme cases (Mallik 2003; Royo and Carson 2006; Thrippleton et al. 2018; Thrippleton et al. 2016). Understory species interact with crop tree seedlings through competition for light, water or nutrients, allelopathy, or the creation of a physical barrier, which may have adverse effects on tree seedling development (Fernandez 2019; Mallik 2003; Ssali et al. 2018). A wide range of vegetation control methods (i.e., the reduction of competitive species cover to promote crop tree species growth and survival), including mechanical site preparation, herbicide application, manual cutting, and prescribed burning, were developed to reduce the cover of competitive plant species and to facilitate crop tree regeneration.

Regardless of the method used, vegetation control always induces environmental and financial costs. The negative impacts of herbicides on soil and water quality as well as on biodiversity are well documented, and, as a result, herbicides are less and less used around the world (Guynn Jr et al. 2004). Mechanical site preparation, often used as an alternative to herbicides, may have adverse effects on soil structure and long-term fertility (Aust et al. 2004; Collet et al. 2021; Sutinen et al. 2019) as well as on plant communities (Newmaster et al. 2007). Similarly, other vegetation control methods also disturb the vegetation and the soil and have been shown to have long-term environmental impacts (McCarthy et al. 2011). Economic analyses show that although most vegetation control methods are economically viable, they usually represent a large share of the overall regeneration costs. Consequently, reducing these costs is a critical step in the development of cost-effective forest management practices (Bell et al. 1997; Homagain et al. 2011). Serious debates are now taking place concerning the vegetation control operations that should be performed to enable successful regeneration while reducing their environmental impacts, at an acceptable economic cost (Espelta et al. 2003). In each regenerating forest stand, decisions to control the vegetation as well as the choice of the appropriate method depend on management objectives, site characteristics, and understory plant species to be controlled (Richardson et al. 2006). Decision-support tools to assess the need to control the vegetation, which suggest appropriate methods to be applied and provide estimations of the associated costs, are available in many forest regions around the world (Richardson et al. 2006). These approaches primarily target the forest stand scale and require a full diagnosis based on a description of vegetation type, site characteristics, and management objectives.

Policies, incentives, and practical guidelines that influence the choice of methods to be used are defined at large spatial scales — regional, national, or continental — and determine the overall technical, economic, and environmental impacts of forest vegetation management. This guidance depends on the analysis of the same characteristics (vegetation, site, management objectives) used for decision-support tools developed at the stand scale but, instead, applied at a larger spatial scale. However, most diagnostic approaches developed at the stand scale cannot be used at a larger scale, and new approaches are required. A first step is to perform a vegetation diagnosis method at regional or national scale that could (1) identify the understory plant species that may substantially reduce the establishment and growth of young trees and (2) quantify the forest area where these plant species may be problematic for tree regeneration. Based on the vegetation diagnosis and additional information about site types and management objectives, the next steps would be to define vegetation control methods that may be applied on each vegetation type and to quantify their overall impact at a large spatial scale, given the environmental and economic impacts of these methods.

Previous attempts to identify species requiring vegetation control were based on literature searches (De Lombaerde et al. 2018) or expert knowledge (Frochot et al. 2002; Gjerstad and Barber 1987; Newton et al. 1987; Walstad et al. 1987), but did not make it possible to quantify their spatial extent. Estimating the spatial extent requires large-scale quantitative data on the distribution of understory plant species, which may be provided by National Forest Inventory (NFI) programs. In many countries, NFI data include understory vegetation and ecological attributes of forests (Tomppo et al. 2010), potentially making it possible to study plant species likely to require vegetation control. In addition, analyses based on NFI data may be easily applied at different geographical scales, from small forest regions to countries. They are based on sampling protocols that reduce sampling biases, even at large geographical scales. In many countries, NFI data are already available and do not require additional data collection. Finally, NFI data were designed to derive quantitative estimates of various forest characteristics and can be used to estimate the surface areas of forest stands covered by different understory plant species. However, in many NFI programs, data contain little information about management objectives and silvicultural operations performed in the stand, which may limit the options necessary to analyze the need to perform vegetation control operations in the studied stand types.

The approach based on expert knowledge may be used to assess silvicultural objectives through local knowledge and personal expertise (Raymond et al. 2010). Such expert knowledge may range from informal personal communication to formal surveys of large groups of forest managers and may form an appropriate basis if implemented with a representative sampling of management units (Biemer and Lars 2003). However, expert surveys present several limits inherent to the methodology (e.g., time and cost, low response rate if the survey is not appropriately designed, potential biases in the analysis), which reduce their use and potential applications. To overcome the limitations of both of these methods, NFI data may be combined with stakeholder surveys that take technical considerations into account (Hegetschweiler et al. 2020).

The objective of our study was to identify which understory plant species are most frequently controlled by forest managers at large (regional or national) geographic scales and to estimate the forest area affected by these species. Using French forests as a case study, we ran a survey to identify understory plant species that require vegetation control according to forest managers, we correlated NFI data with the survey results, and we used NFI data to quantify the forest area affected by each understory plant species.

2 Methods

2.1 Study area

In Metropolitan France, forests cover 16.8 million ha, representing 31% of the total area of France (IGN 2019). They are located in Atlantic, continental, Mediterranean, and mountainous climatic areas. Their latitude and longitude ranges as well as climatic averages data are given in Dumas et al. (Dumas et al. 2022, Table 1). Soil types range from extremely poor sandy soils to rich loamy or clay soils.

In our study, French forests were pooled into six large regions: North Atlantic, South Atlantic, subatlantic-lowland, subatlantic-mountainous, continental, and Mediterranean regions that were defined by regrouping small ecological regions used by the French National Institute of Geographic and Forest Information (IGN 2011). Pooling into large regions was necessary when implementing the survey described in Section 2.4.1, in order to use sampling regions that were large enough to encompass the spatial extent of units run by forest managers.

2.2 Plant species and groups

All plant species in the NFI database were pooled into nine groups: (1) *Poaceae*, *Cyperaceae*, and *Juncaceae*, hereafter referred to as “graminoids” (labeled “Gra” in figures); (2) ligneous species less than 8 m at maximum height (Julve 1998), excluding *Ericaceae* species, hereafter referred to as “shrubs” (“Shr”); (3) species of the genus *Rubus* (“Rub”); (4) vines (“Vin”); (5) *Ericaceae*, referred to as “Ericaceous” (“Eri”); (6) ferns (“Fer”); (7) bryophytes, hereafter referred to as “mosses” (“Mos”); (8) trees over 8 m at maximum height (Julve 1998), including crop-tree species, hereafter referred to as “trees” (“Tre”); and (9) other species that were all forbs, hereafter referred to as “forbs” (“For”). Invasive species outside their natural range were excluded from the study because, according to preliminary analyses, they cover small areas in French forests, and their geographical distribution significantly changed over the period covered by the NFI inventories used in our study.

2.3 General approach

We developed a three-step approach to identify the understory species that are controlled to enable forest regeneration and to estimate the forest area impacted by these species (Fig. 1):

> Step 1: Using a preliminary list of 29 species thought to require vegetation control during the tree regeneration stage (Appendix Table 4) according to a preliminary analysis that selected the species frequently showing high cover and potentially hindering tree regeneration, using NFI data (Box I *in* Dumas et al. 2022), we performed the following two analyses: (a) a survey among forest managers to identify and rank the main understory plant species that require vegetation control operations in order to enable successful forest regeneration and (b) the construction of four indicators of the need to control understory plant species in order to enable successful forest regeneration, which were based on two levels of species cover crossed with two levels of canopy cover and which used NFI data.
>
> Step 2: Among the NFI indicators that were built in step 1, we selected the indicator that was best correlated with the survey results.
>
> Step 3: We applied the indicator that best correlated to survey results in step 2, on the 100 most frequent species with a large cover in the NFI database to (a) establish the final list of the main understory species requiring vegetation control during the tree regeneration stage and (b) estimate the forest area affected by each of these species.

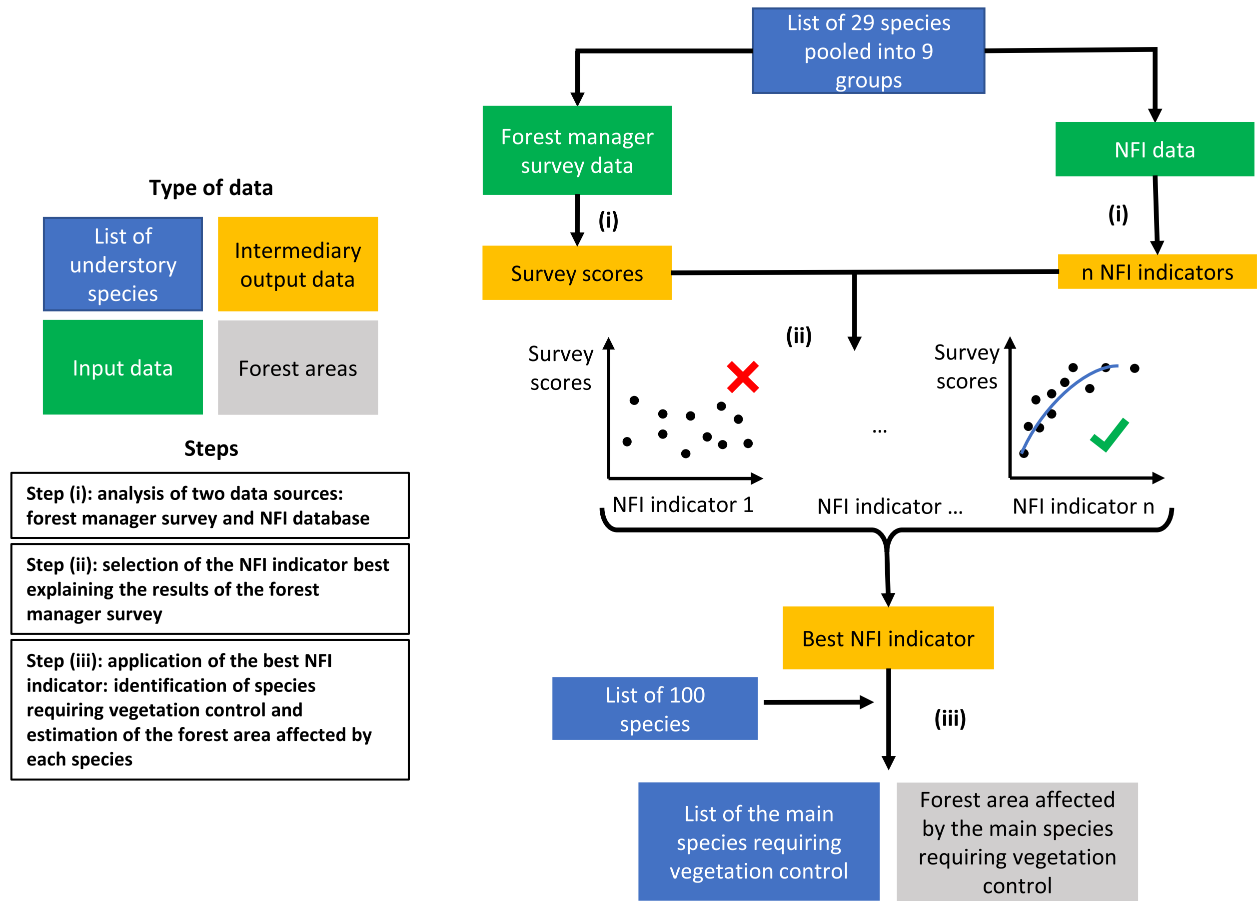

Fig. 1 Workflow of the study. The three steps correspond to the steps described in the "Methods" section

Three lists of species were used throughout our study:

- A preliminary list of species potentially requiring vegetation control during the tree regeneration stage (Appendix Table 4). It was built to initiate the work and, in particular, to select the species to be included in the survey of forest managers. We estimated that a maximum number of 30 species could be used in the survey so as to limit the time needed by the respondents to answer the survey. The list was based on a preliminary analysis presented in the Supplementary Materials (Box 1 *in* Dumas et al. 2022). It contained 29 species.
- List of the 100 species most frequently showing a high cover in the NFI plots or requiring vegetation control during the tree regeneration stage according to the expert survey (Appendix Table 4). The list was used to apply the best NFI indicator on a larger set of species and to identify understory species requiring vegetation control during the regeneration stage.
- The final list of species requiring vegetation control during the tree regeneration stage, selected according to our best indicator applied to the 100-species list.

2.4 Data acquisition

2.4.1 Survey of forest managers

We conducted a survey aimed at (1) identifying, in each study region, the understory plant species that forest managers consider most often as requiring species control operations to facilitate forest regeneration and (2) estimating, for each understory plant species, the frequency at which forest managers control the species over the duration of the entire regeneration phase. Data from this survey are available in Dumas et al. (2022). A Web-based anonymous questionnaire was sent to key contact persons in forest organizations across all French regions, who then forwarded it to forest managers within their organization. The survey was sent to the *Office National des Forêts* (ONF, French organism that manages public forests), the *Groupement des Coopératives Forestières*

(GCF, group of forest cooperatives that manage private forests), and to the *Centre Régionaux de la Propriété Forestière* (CRPF, public organisms that advise and train private stakeholders). The size of the population that received the questionnaire is unknown. In total, 126 forest managers responded to the questionnaire between July and September 2020. The responses were distributed in all regions defined in the survey.

The survey was divided into five sections: (1) geographical location of the respondent, (2) overall frequency of vegetation control operations, (3) frequency of vegetation control operations for each of the nine groups of plant species defined above, (4) frequency of vegetation control operations for each of the 29 preselected plant species, and (5) other plant species that have to be controlled during the stand renewal stage. The respondent was asked to identify species not listed in the survey (i.e., not included in the 29 preselected species) that required vegetation control in her/his region. There were four possible answers for each question in Section 3: "rarely or never," "sometimes," "frequently or very frequently," and "do not know or do not know the species." Answers for each question in Sections 2 and 4 were the same as for Section 3 except that "do not know or do not know the species" was replaced by "do not know."

2.4.2 NFI data

We used French NFI data collected from 2006 to 2018 at 79,695 field plots. The inventory is a survey organized in space and time according to a systematic global 1 km × 1 km sampling grid (Hervé 2016), where each inventory plot is surveyed once. Each year, an annual grid consisting of 1/10 of the global grid cells covering the entire territory is used as the basis for a new NFI sample. The raw field data gathered at each sampled point include stand and soil characteristics, as well as a comprehensive flora survey. Data are freely available on the French NFI website: https://inventaire-forestier.ign.fr/dataIFN/.

At each sample point, the floristic composition of the understory was surveyed in a 700-m^2 circular plot centered on the sample point. The understory layer comprised bryophytes and vascular plants, including all herbaceous and shrub individuals, and trees whose diameter at breast height was less than 7.5 cm. It must be noted that recorded tree species comprised both crop species and non-crop species, including species that may hinder crop tree regeneration. It was not possible to separate these different types of tree species because the inventory did not provide any information about silvicultural objectives. Cover was visually estimated for each identified plant species using a scale adapted from Braun-Blanquet (1932) with the following classes of species cover: 0: 0%; 1:]0–5%]; 2:]5–25%]; 3:]25–50%]; 4:]50–75%]; 5:]75–100%].

The forest canopy was described in a 2000-m^2 circular plot centered on the plot used for floristic composition and considered all trees with a diameter at breast height greater or equal to 7.5 cm. The percentage of the plot area covered by the tree canopy that was considered to be in full light (i.e., that was not overtopped by the foliage of another plant species) was visually estimated for each tree species on a 10%-increment scale. For each plot, the total full-light canopy cover rate (hereafter referred to as "canopy cover") was computed as the sum, for all tree species present on the plot, of full-light canopy cover percentages. By definition, canopy cover was comprised between 0 and 100%. The date of the last thinning was not recorded, and it was therefore impossible to estimate relationships between the age of canopy opening and plant cover.

2.5 Data analysis

2.5.1 Step 1: Analysis of the forest manager survey

The answers of each respondent for each species, each species group, and overall vegetation were transformed into a quantitative score using a Likert scale (Croasmun and Ostrom 2011; Likert 1932), in this case, a discrete scale ranging from 0 to 1, in order to create quantitative indices of control intensities. "Rarely or never" was transformed into 0, "sometimes" into 0.5, and "frequently or very frequently" into 1. "Do not know" and "do not know or do know the species" were transformed into 0 since unknown species were mostly species that were absent in the respondent region (e.g., *Erica arborea* in continental regions) or species that forest managers very rarely control (e.g., moss species). For each question (each species, group of species, or all vegetation in general), a score was computed for each study region as the mean response value over all respondents in the region. In Section 5 of the survey (other plant species that have to be controlled during the stand renewal stage), forest managers were asked to indicate all species requiring vegetation control that were not included on the preliminary list of 29 species, and to define how often they were controlled. Since not all forest managers indicated the same supplementary species, we were not able to calculate a numerical score for each supplementary species in each region. Instead, for each supplementary species, we only recorded the number of forest managers who added it in this section.

Survey reliability was checked by calculating Cronbach's alpha that measured the consistency of survey scores for all vegetation, all groups, and all species within each region (Cronbach 1951). We obtained a value of 0.83, indicating that the forest manager responses were consistent within each region.

Plant species were sorted into three classes according to their survey scores: (i) species requiring frequent vegetation control, which included species with an average survey score across all regions above 0.5, and supplementary species added by more than 20% of the respondents; (ii) species requiring intermediate vegetation control, which included species with an average survey score across all regions below 0.5 and with a survey score above 0.25 in at least one region, and supplementary species added by 5 to 20% of the respondents; and (iii) species requiring occasional or no vegetation control, which included all others species.

2.5.2 Step 1: Analysis of NFI data and definition of the NFI indicators

We aimed at creating NFI indicators that would be applied to each understory plant species and that would be correlated with the frequency at which forest managers perform vegetation management operations to control the species.

We expressed NFI indicators using the cover of the understory plant species (PC) (two threshold levels: the presence, i.e., $PC > 0\%$ or high cover, i.e. $PC > 50\%$) crossed with the cover of forest canopy (CC) (two threshold levels: all cover values, i.e., $CC \leq 100\%$ or low cover i.e. $CC < 50\%$). We chose understory plant cover as a first criterion since it largely reflects the plant's ability to compete with other plants (Gaudet and Keddy 1988). We used plant presence as a first threshold level because plants requiring vegetation control during the tree regeneration stage are necessarily plants that are commonly found in the study region, and, conversely, rare plants are not a major concern in terms of vegetation control (Gaston 1996). We used high plant cover as a second threshold level because understory species that most hinder tree regeneration tend to create almost monospecific plant layers and, hence, to show high cover. Such monospecific layers of a competitive species are more competitive towards tree regeneration than multispecies understories (Becker 1972; Royo and Carson 2006). Conversely, plants with a small cover usually have a lower competitive ability (Gaudet and Keddy 1988). We chose forest canopy cover as a second criterion since canopy closure affects the light level in the understory and regulates plant species ability to compete with other species (De Lombaerde et al. 2019; Verheyen et al. 2012). We used the first threshold level (all canopy cover), which included all forest stands, as a basis for comparison. We used the second threshold level (low canopy cover) because the highest competitive effects of understory plants on tree regeneration are generally observed after canopy opening (Royo and Carson 2006), and most species that compete strongly with tree seedlings are quickly able to take advantage of canopy opening to outgrow other species (Balandier et al. 2006; Becker 1972; Royo and Carson 2006). Open-canopy plots corresponded to plots that had been opened either by thinning or by natural disturbance and provided light conditions favorable to tree seedling establishment and understory plant growth. We aimed at creating four indicators obtained by crossing the two criteria (each with two levels):

i) The percentage of plots where the plant species (or group of species) was present, among all plots
ii) The percentage of plots where the plant species (or group of species) had a high cover, among all plots
iii) The percentage of plots where the plant species (or group of species) was present, among open-canopy plots
iv) The percentage of plots where the plant species (or group of species) had a high cover, among open-canopy plots

The indicators were computed for each understory plant species. They were based on an estimation of the forest area that met the two criteria for the species considered and were developed as follows.

First, forest areas associated with inventory plots showing different combinations of plant species cover and canopy cover were computed using a NFI routine that enables us to compute area-related estimates of forests that meet the desired criteria (Hervé 2016). For each NFI plot and each plant species or group i, two Boolean variables based on plant cover were added: (1) a first variable distinguishing plots where plant species or group i was either present or absent and (2) a second variable distinguishing plots where plant species or group i was either present with a high (> 50%) or with a low (≤ 50%) plant cover. For individual plant species, plant cover was directly extracted for each species from species cover measured in the plot. For plant groups, plant cover was computed for each group as the maximum species cover over all species belonging to the group measured in the plot. A third Boolean variable based on canopy cover, distinguishing whether plots showed low canopy cover, was created. For each of the five regions, a series of area estimates were computed using these three Boolean variables (Table 1).

Second, four NFI indicators were created to estimate the frequency of vegetation control operations required for each understory plant. The four NFI indicators, computed for each understory plant species or for each plant group i crossed two criteria: plant cover and canopy cover (Table 2). The indicators expressed the percentage of the forest area with two levels of canopy cover (either all forests, i.e., forests with a canopy cover ≤ 100% or open forests with a canopy cover < 50%) where plant species or groups of plant species i were either present (plant

Table 1 Area estimates used to calculate the various NFI indicators; PC_i indicate the plant cover (plant species or group *i*), CC the canopy cover, and A the forest area (ha), in region *j*

Estimate	Definition
$A_{CC\leq100,j}$	Total forest area, in all canopy cover conditions ($CC \leq 100\%$)
$A_{PC_i>0,CC\leq100,j}$	Forest area where plant group or species *i* was present ($PC > 0\%$) in all canopy cover conditions ($CC \leq 100\%$)
$A_{PC_i>50,CC\leq100,j}$	Forest area where plant cover of group or species *i* was high ($PC > 50\%$) in all canopy cover conditions ($CC \leq 100\%$)
$A_{CC<50,j}$	Forest area where canopy cover was less than 50% ($CC < 50\%$)
$A_{PC_i>0,CC<50,j}$	Forest area where plant group or species *i* was present ($PC > 0\%$) and canopy cover was less than 50% ($CC < 50\%$)
$A_{PC_i>50,CC<50,j}$	Forest area where plant cover of group or species *i* was high ($PC > 50\%$) and canopy cover was less than 50% ($CC < 50\%$)

cover > 0%) or present with a high cover (plant cover > 50%). Each of the four indicators was calculated for each of the 29 plant species and for each of the nine plant groups using understory plant cover assessed in the NFI inventory plots. All indicators were separately computed in each of the six study regions.

2.5.3 Step 2: Selection of the NFI indicator best explaining forest manager survey results

In this step, we selected the NFI indicator from among the four previous ones that best explained the scores of the manager survey across the different plant species and plant groups and across the study regions. The predictive power of the four indicators was assessed by regressing species indicators against the survey scores. The relationships between indicators and survey scores were nonlinear. They were investigated for the nine groups and for the 29 preselected species using a nonlinear function:

$$y_i = \Phi_1 + \Phi_2 \exp^{\Phi_3 x_i} \quad (1)$$

where the response y_i was the average survey score for the 29 species or the nine groups in each of the five studied regions i (y_i was therefore a continuous variable), the explanatory variable x the indicator tested, and Φ_1, Φ_2, and Φ_3 parameters to be estimated (Pinheiro and Bates 2000). We tested the addition of plant group as a random factor into the model. However, due to the small number of repetitions, incorporating plant group did not significantly improve the model. Finally, we selected the indicator with the best Spearman's rank correlation coefficient (r_s) between the survey score and the indicator for plant groups and species.

2.5.4 Step 3: Identification of species requiring vegetation control with the best NFI indicator and estimation of the forest area affected by each species

In this step, we identified the main species requiring vegetation control during the tree regeneration stage and estimated the associated forest area at the scale of France. We first applied the best NFI indicator selected in step 2 to each of the 100 species most frequently found with a large cover in the NFI plots.

Two threshold values that split the species into three classes were determined: species requiring (i) frequent, (ii) intermediate, or (iii) no vegetation control. The two thresholds were determined using the receiver Operating Characteristic (ROC) curve method (Robin et al. 2011), such that the classes obtained were closest to the classification using the survey scores as defined in Section 2.5.1, i.e., species requiring frequent, intermediate, occasional, or no vegetation control.

The total forest area affected by each understory species was determined as the forest area with high species cover and open canopy at the scale of France ($\sum_j A_{PC_i>50,CC<50,j}$,where j denoted the region and i the plant species). It should be noted that the total area requiring vegetation control during the tree regeneration stage cannot be estimated by summing the areas of each individual species since several species requiring vegetation control may be present in a plot at the same time.

Table 2 Four indicators of the frequency of the vegetation control operations required for understory species, based on the forest area estimates defined in Table 1. In the following formulas, *i* corresponds to the plant species or group and *j* to the region

Forest	Plant species or plant group *i*	
	Present (plant cover > 0%)	Present with a high cover (plant cover > 50%)
All forests (plots with canopy cover ≤ 100%)	$\%A_{PC>0,CC\leq100\,i,j} = \frac{100\times A_{PC_i>0,CC\leq100,j}}{A_{CC\leq100,j}}$	$\%A_{PC>50,CC\leq100\,i,j} = \frac{100\times A_{PC_i>50,CC\leq100,j}}{A_{CC\leq100,j}}$
Open forests (plots with canopy cover < 50%)	$\%A_{PC>0,CC<50\,i,j} = \frac{100\times A_{PC_i>0,CC<50,j}}{A_{CC<50,j}}$	$\%A_{PC>50,CC<50\,i,j} = \frac{100\times A_{PC_i>50,CC<50,j}}{A_{CC<50,j}}$

All analyses were conducted using R 4.0.2 (R Core Team 2020). Data was processed using the data.table package (Dowle and Srinivasan 2021), nonlinear regressions were run using the nlme package (Pinheiro et al. 2020), and ROC curves were calculated using the pROC package (Robin et al. 2011).

3 Results

3.1 Survey of forest managers

A total of 126 forest managers responded to the survey (Fig. 2), for an average response rate of 0.81 respondents per 100,000 ha of forest. The lowest number of respondents were obtained for the North Atlantic and Mediterranean regions (7 and 5 respondents, respectively). In the sparsely forested North Atlantic region, it corresponded to 1.10 respondents per 100,000 ha of forests, which was the second highest value across all regions. In the Mediterranean region however, it corresponded to 0.18 respondents per 100,000 ha of forest, which was at least 70% lower than the values observed in all other regions. Regardless of plant species or plant group, global intervention scores ranged between 0.40 in the Mediterranean region and 1.00 in the North Atlantic region where vegetation control during the forest renewal stage was very frequent. All regions but the Mediterranean displayed average intervention rates above 0.50, with a North Atlantic to Mediterranean gradient of decreasing values.

A low response rate, combined with a low intervention score, suggested that vegetation control to ensure tree regeneration was not a major concern in the Mediterranean region. It was therefore removed from later analyses.

Intervention scores for plant groups ranged from an average of 0.78 for *Rubus* species down to 0.01 for mosses (Fig. 3a). *Rubus* species as well as trees, ferns, shrubs, and graminoids displayed average intervention scores higher than 0.5 (corresponding to "sometimes" in the survey), while vines, ericaceous, and forbs displayed values between 0.25 and 0.5.

Average intervention scores for individual species varied from 0 for *Quercus coccifera* L. to 0.82 for *Rubus fruticosus* aggr. (Fig. 3b). Out of the 29 species, nine (*Rubus fruticosus*, *Pteridium aquilinum* (L.) Kuhn, *Corylus avellana* L., *Cytisus scoparius* (L.) Link, *Fagus sylvatica* L., *Molinia caerulea* (L.) Moench, *Castanea sativa* Mill., *Prunus spinosa* L., and *Calluna vulgaris* (L.) Hull) had a score of above 0.25 in at least one region. These species belonged to the following groups: *Rubus* (one species), ferns (one species), trees (three species), graminoids (one species), shrubs (two species), and ericaceous (one species). No forb or moss exceeded this threshold value.

Only four species had an average survey score above 0.5, namely *Rubus fruticosus*, *Pteridium aquilinum*, *Corylus avellana*, and *Cytisus scoparius*. These species belonged to the following groups: *Rubus* (one species), ferns (one species), trees (one species), and shrubs (one species).

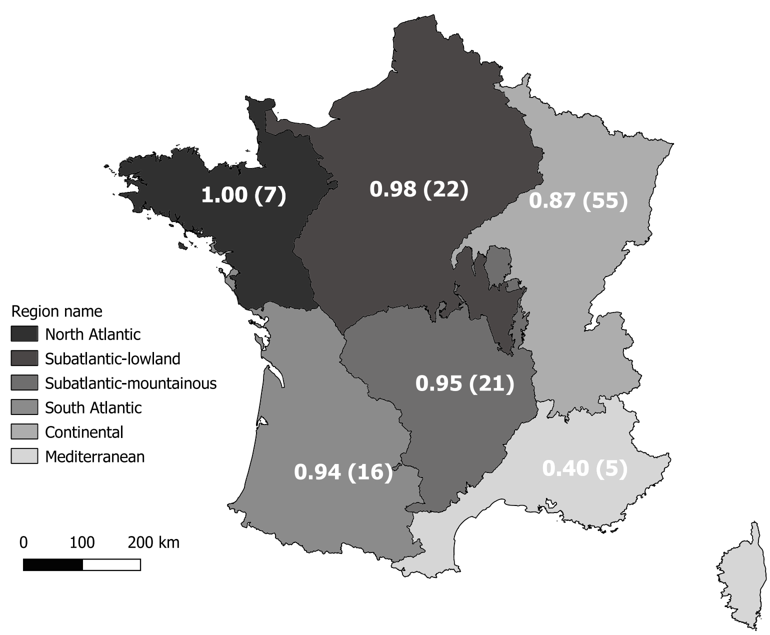

Fig. 2 Overall frequency of vegetation control according to the survey of forest managers performed in six regions in France. For each region, the average frequency of intervention for vegetation control (0, rarely or never; 0.5, sometimes; 1, frequently or very frequently) and the number of respondents (in brackets) are indicated. The shades of gray indicate the average frequency of vegetation control in each study region

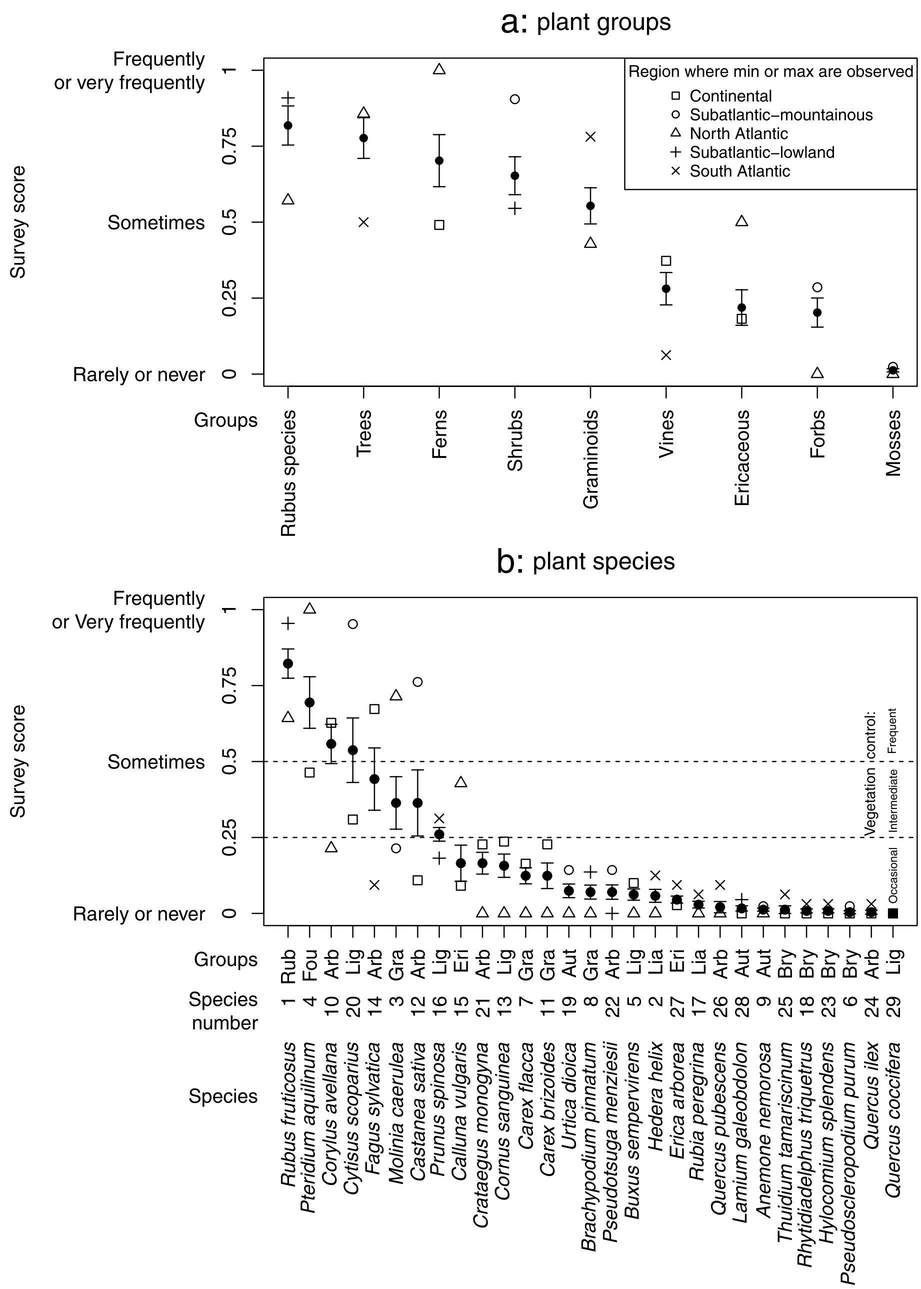

Fig. 3 Intervention scores for **a** the nine plant groups and **b** the 29 plant species across the five study regions (mean, standard error, maximum, and minimum value) computed from the forest manager survey. The point type used for the minimum and the maximum values for each group or species indicates the region where the value is observed. Groups and species were ranked by decreasing average frequency of intervention. In **b**, dashed horizontal lines correspond to the thresholds, $y = 0.25$ and $y = 0.5$, used in the three sets of conditions that define species requiring frequent, intermediate, and occasional vegetation control according to forest managers. "Groups" correspond to the plant group to which each species belongs and "species numbers" to the number assigned to each species and given in Appendix Table 4

In total, respondents added 33 species not included in the preliminary list (Table 2 *in* Dumas et al. 2022). Among the 33 species, three trees and one shrub were cited by more than 5% of the respondents: *Betula* sp., *Carpinus betulus* L., *Populus tremula* L., and *Ulex europaeus* L. No species was added by more than 20% of the respondents.

3.2 NFI indicators of the frequency of vegetation control operations

All plant groups were present in more than 60% of the forest area on average over the five study regions (i.e., excluding the Mediterranean region), with the exception of the ericaceous group that was present in only 25.9% of the forest area

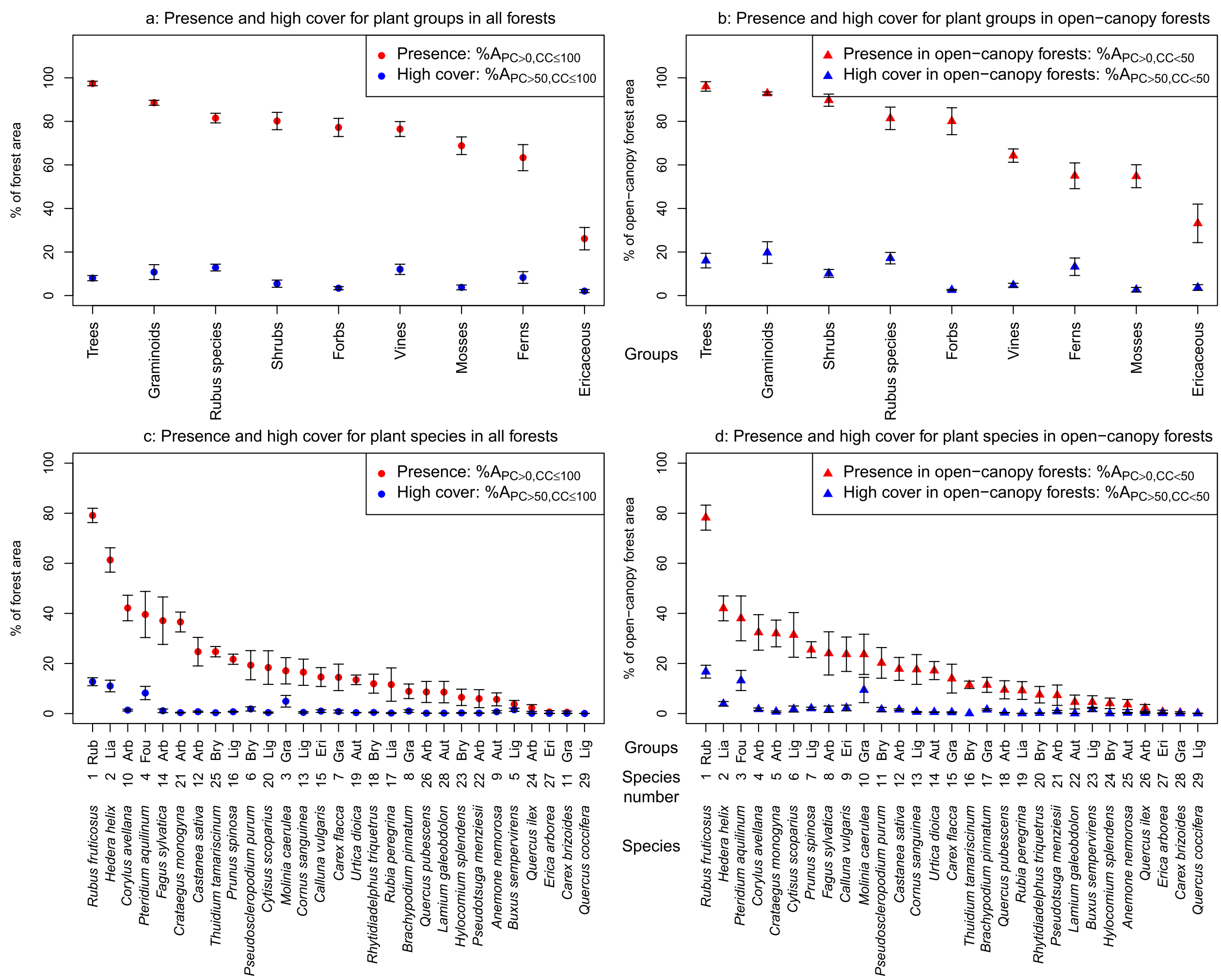

Fig. 4 NFI indicators (mean ± standard error) across the five regions: indicator of plant presence and of plant high cover in all forests, $\%A_{PC>0,\,CC\leq 100}$ and $\%A_{PC>50,\,CC\leq 100}$ (**a** and **c**), and indicator of plant presence and of plant high cover in open-canopy forests, $\%A_{PC>0,\,CC<50}$ and $\%A_{PC>50,\,CC<50}$ (**b** and **d**), for (**a** and **b**) plant groups and (**c** and **d**) plant species, respectively. In each graph, species and groups are ranked by decreasing order of (**a** and **c**) $\%A_{PC>0,\,CC\leq 100}$ values or (**b** and **d**) $\%A_{PC>0,\,CC<50}$ values. Please note that the scale of the y-axis changes between the plots

($\%A_{PC>0,\ CC\leq 100}$, Fig. 4a). When considering only forests with open canopy ($\%A_{PC>0,\ CC<50}$, Fig. 4b), group presence values increased for shrubs and graminoids, decreased for mosses and vines, and remained similar for all other groups, compared to the values obtained in all forests.

The indicator of high group cover in all forests ($\%A_{PC>50,\ CC\leq 100}$, Fig. 4a) presented a different pattern than that of group presence ($\%A_{PC>0,\ CC\leq 100}$), and there was a moderate link between these two indicators (r_s = 0.55, p<0.001). The mean percentage of forest area where groups were present with a high cover was much smaller than for presence, and ranged between 2.0% (ericaceous species) and 12.7% (*Rubus* species).

Nine species were present in more than 20% of the forest area ($\%A_{PC>0,\ CC\leq 100}$, Fig. 4c): *Rubus fruticosus* and *Hedera helix* L. were considerably more frequent than other species, with values of 78.3% and 60.7%, respectively. For the indicator of high plant cover in forests with open canopies ($\%A_{PC>50,\ CC<50}$, Fig. 4d), the order of the most frequent species changed considerably compared to the indicator of high plant cover in all forests ($\%A_{PC>50,\ CC\leq 100}$, Fig. 4c), with an increase of tree and graminoid scores and a decrease of the vine score.

The relationship between species presence and species high cover was influenced by canopy opening, with a stronger correlation for open-canopy forests (r_s = 0.83, p < 0.001) than for all forests (r_s = 0.72, p < 0.001). All correlations among indicators for plant species and groups are given in Dumas et al. (Dumas et al. 2022, Tables 3 and 4).

3.3 Selection of the best NFI indicator

Regardless of canopy conditions, indicators of species presence ($\%A_{PC>0,\ CC\leq 100}$ and $\%A_{PC>0,\ CC<50}$) were poorly linked to the frequency of vegetation control operations reported in the survey of forest managers ($r_s \leq 0.5$ for plant groups and $r_s < 0.7$ for plant species; Dumas et al. (Dumas et al. 2022, Fig. 1). The indicator of high cover in all forests ($\%A_{PC>50,\ CC\leq 100}$) was also moderately linked to survey scores for plant groups and for plant species ($r_s = 0.49$ and 0.55, resp.). Finally, when only considering open-canopy forests, the indicator of high cover ($\%A_{PC>50,\ CC<50}$) yielded the best fit, both for plant groups and plant species ($r_s = 0.79$ and 0.68, respectively; Fig. 5).

For this indicator, the regression curve was well fitted to the group data ($r_s = 0.79$): larger values of $\%A_{PC>50,\ CC<50}$ were associated with higher frequencies of vegetation control operations, up to a certain level where a plateau was reached (around a survey score of 0.9). The frequency of vegetation control operations required by some groups seemed to be systematically underestimated (ferns, *Rubus*) or overestimated (graminoids, vines) by the indicator $\%A_{PC>50,\ CC<50}$.

The fit between survey score and the proportion of open-canopy forests with high species cover ($\%A_{PC>50,\ CC<50}$) was not as good for plant species as it was for plant groups ($r_s = 0.68$; Fig. 5). The point corresponding to *Molinia caerulea* (code 3) in the South Atlantic region was removed from the regression fit since it was well below all other points for this level of $\%A_{PC>50,\ CC<50}$.

3.4 Identification of the main species requiring vegetation control operations and estimation of forest area affected by each species

A list of the main species requiring vegetation control during the tree regeneration stage in French non-Mediterranean forests, obtained based on the indicator $\%A_{PC>50,\ CC<50}$, using the procedure described in 2.5.4. and thresholds defined in 2.5.1, was established (Table 3).

The final list contained 15 species, with 11 species requiring frequent vegetation control (threshold of $\%A_{PC>50,\ CC<50} = 0.17$ in ROC curve analysis) and four species requiring intermediate vegetation control (threshold of $\%A_{PC>50,\ CC<50} = 0.12$ in ROC curve analysis). All other species were excluded from the list. Except for four species (*Hedera helix*, *Pseudoscleropodium purum* (Hedw.) M. Fleisch., *Brachypodium pinnatum* (L.) P. Beauv., *Buxus sempervirens* L.), all species had been identified by forest managers as needing vegetation control or had been added as supplementary species in the survey.

Rubus fruticosus, *Pteridium aquilinum*, and *Molinia caerulea* were the species most frequently found with a high cover in forests with open canopies, with $\%A_{PC>50,\ CC<50}$ values of 15.5%, 13.9%, and 13.6%, respectively. These three species showed $\%A_{PC>50,\ CC<50}$ values well above the other species. The 15 species of the final list belonged to eight out of the nine plant groups, and no species from the forb group was included in the final list.

Between 2006 and 2018, forests with open canopies (*CC* < 50%) represented on average 20% of the total forest

Table 3 Main species requiring vegetation control during the tree regeneration stage according to the indicator $\%A_{PC>50,\ CC<50}$ and area with species cover > 50% in open-canopy forests expressed in relative ($\%A_{PC>50,\ CC<50}$, %) and absolute (area: 10^3 ha) values, estimated at the national scale (excluding the Mediterranean region) between 2006 and 2018. Species are ranked by decreasing $\%A_{PC>50,\ CC<50}$ values. For each species, the species group to which it belongs is indicated. Species in bold or plain type correspond to the species requiring frequent or intermediate vegetation control, respectively

Plant species	Plant group	$\%A_{PC>50,\ CC<50}$ (expressed in % of the open-canopy forest area)	Forest area (10^3 ha)
Pteridium aquilinum	Ferns	15.5	391
Molinia caerulea	Graminoids	13.9	350
***Rubus fruticosus* aggr.**	Rubus	13.6	344
Hedera helix	Vines	3.88	98
Calluna vulgaris	Ericaceous	3.54	89
Pseudoscleropodium purum	Mosses	2.46	62
Brachypodium pinnatum	Graminoids	1.95	49
Buxus sempervirens	Shrubs	1.86	47
Prunus spinosa	Shrubs	1.84	46
Corylus avellana	Trees	1.82	46
Cytisus scoparius	Trees	1.74	44
Ulex europaeus	Shrubs	1.66	42
Fagus sylvatica	Trees	1.60	40
Castanea sativa	Trees	1.48	37
Carpinus betulus	Trees	1.27	32

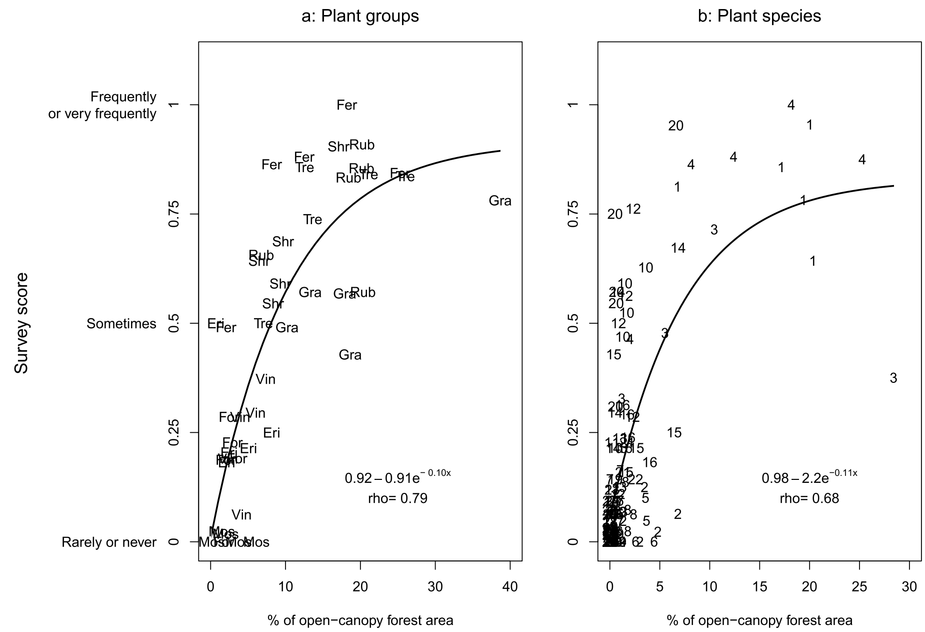

Fig. 5 Forest manager survey score as a function of $\%A_{PC>50,\,CC<50}$ (percentage of the forest area in open-canopy conditions where **a** the plant group or **b** the plant species shows high cover, as defined in Table 2 in each of the five regions. Black curves correspond to the prediction of the asymptotic model according to Eq. 1. In each plot, each group or each species has five repetitions (one per region). **a** Names correspond to plant group names, and **b** numbers correspond to species number, as defined in Appendix Table 4. Please note that the y-axis scale changes between the two plots.

area in non-Mediterranean France. Among open-canopy forests, stands where *Pteridium aquilinum*, *Molinia caerulea*, and *Rubus fruticosus* showed a high cover (*PC* > 50%) represented, on average, 391,000 ha, 350,000 ha, and 344,000 ha, respectively. However, since the total area of open-canopy forests in France highly varies with large-scale disturbances such as storms or pests, the exact surface area affected by each understory plant species may considerably change from year to year.

4 Discussion

4.1 NFI data may be used to identify species requiring vegetation control and to quantify the associated forest area

Our study showed that NFI data may be used to determine which species require vegetation control during the tree regeneration stage, by applying an easily computed indicator. The percentage of non-Mediterranean forest area where the plant species or plant group showed a high cover in forests with open canopy (indicator $\%A_{PC>50,\,CC<50}$) was well correlated with the frequency of vegetation control operations estimated by forest managers. The procedure to compute the indicator and to quantify the area related to each understory plant species is of particular interest since it uses open NFI data and does not require any additional field or survey data. Such NFI data are available in many other countries (Tomppo et al. 2010; Vidal et al. 2016).

To our knowledge, our work is the first study that provides a method to quantify the area concerned by the main species requiring vegetation control at a large geographical scale. The estimated forest area affected by these species appears to be extensive, with an average of more than 300,000 ha for each of the three main understory species, out of a total of 2,523,000 ha of open canopy forests, between 2006 and 2018 in non-Mediterranean France. The area provided for each species is the area where the species shows a high cover in forests with open canopy, averaged over the 17 years covered by our data set. It cannot be converted into an area that would require vegetation control on an annual basis, because it sums forest plots that have been open for a variable number of years. Such an estimation would require additional information on the duration since the last canopy opening, which would inform on the temporal dynamics of understory plant species response to canopy opening. Such information is presently not available in the French NFI data set.

4.2 Understory species requiring vegetation control during the tree regeneration stage

Fifteen species were identified as requiring frequent vegetation control. They belonged to various plant groups, in agreement with the previous literature, where plants from multiple groups were reported to hinder tree regeneration (Balandier et al. 2006; Frochot et al. 2002).

Mosses were the only group that was never controlled by forest managers according to our survey, although several studies performed in boreal regions have shown adverse effects on tree regeneration caused by moss species such as *Hylocomium splendens* (Hedw.) Schimp. (Hörnberg et al. 2011; Stuiver et al. 2014). This discrepancy might be due either to suboptimal growth conditions for mosses in temperate climates or to an underestimation of moss impacts on tree regeneration by forest managers.

Several species requiring vegetation control during the tree regeneration stage according to our study based on French forests are cited in the international literature as being problematic for tree regeneration (Fig. 2 *in* Dumas et al. 2022), showing that some of the main species requiring vegetation control in France (namely *Rubus fruticosus*, *Pteridium aquilinum*, *Molinia caerulea*, and *Calluna vulgaris*) are also considered as competitive species in terms of regeneration, at least at the European level. The correspondence between the species identified in our study and the species most cited in the international literature agrees with the review by Gaston (1996) who showed a correlation between local (i.e., species cover or species frequency within a restricted area) and global cover (i.e., species distribution range). We expect our NFI indicator to give similar results if applied to different geographical ranges, and the validity of our list of species will probably be greater than in the case of non-Mediterranean French forests.

A criterion used for the construction of two NFI indicators was the ability of a species to show a high cover (plant cover > 50%) over a large forest area. This criterion was important since it improved the correlation between forest managers' survey scores and NFI indicators, compared to indicators based only on species presence. The correlation between species cover and competitive ability has previously been demonstrated in many studies performed in pots or small-scale field plots (Gaudet and Keddy 1988; Gaudio et al. 2011; Tolhurst and Turvey 1992). As a result, species that frequently covered a large proportion of the forest ground were found to be the ones requiring the most vegetation control according to forest managers at a regional scale.

In addition, some of these species are known to maintain a high probability of presence under closed-canopy conditions, e.g., *Pteridium aquilinum* (Gaudio et al. 2011; Van Couwenberghe et al. 2011) or *Rubus fruticosus* (Harmer et al. 2012; Van Couwenberghe et al. 2011), enabling them to persist under closed canopy and to gain an initial advantage over other species when the canopy opens.

4.3 Discrepancies between NFI indicator and survey results

Some discrepancies were observed between the score of the best NFI indicator ($\%A_{PC>50,\ CC<50}$) and the survey results for *Hedera helix*, *Pseudoscleropodium purum*, *Brachypodium pinnatum*, and *Buxus sempervirens.* These four species were identified by our procedure as species requiring vegetation control during the tree regeneration stage, but forest managers did not declare them as being frequently controlled. On the other hand, *Betula pendula* Roth and *Populus tremula* were not identified by our procedure, although more than 5% of forest managers declared that they controlled them. Different reasons may explain the discrepancies observed for these species.

Hedera helix and *Pseudoscleropodium purum* had high $\%A_{PC>50,\ CC<50}$ scores (3.88% and 2.46%, respectively) and low survey scores (0.05 and 0.004, respectively). The two species probably have a reduced competitive effect on the tree seedlings, due to their vertical stature and to their limited growth in high light environments. *Hedera helix* has been described as sciaphilous (Metcalfe 2005), and very little information is available for *Pseudoscleropodium purum*. In our study, the proportion of forests where *Hedera helix* and *Pseudoscleropodium purum* show a high cover ($\%A_{PC>50,\ CC<100} = 11.0\%$ and 1.8%, respectively) was high compared to the proportion of open-canopy forests where they show a high cover ($\%A_{PC>50,\ CC<50} = 3.9\%$ and 1.6%, respectively), suggesting that they do not benefit from canopy openings and may be considered as sciaphilous. This feature may explain the low intervention rate expressed by forest managers during the tree regeneration stage. Indeed, the heliophilous character of most species known to hinder tree regeneration is well documented (Balandier et al. 2006; Royo and Carson 2006). These species take advantage of canopy openings to quickly outgrow seedlings and other understory plant species.

Forest managers rated graminoids as requiring frequent vegetation control operations in most regions (survey score of 0.55 on average across all regions, with a maximum of 0.78 in the South Atlantic). However, among all of the graminoid species, *Molinia caerulea* was the only species with a high survey score (average score of 0.36 and a score of 0.37 in the South Atlantic), and no other graminoid species was added by more than 5% of forest managers in Section 5 of the survey. This might indicate that graminoid species are not correctly identified by forest managers and, consequently, that individual species may not be recognized by forest managers and are therefore controlled without knowing to which species they belong. Although graminoid species may have strong adverse effects on tree regeneration (Coll et al. 2004; Collet et al. 1996), the survey did not identify individual graminoid species other than *Molinia caerulea. Brachypodium pinnatum* did not come out in the survey of forest managers, although it had a large indicator score (1.95%), probably meaning that it is not well determined by forest managers. The quality of species identification in our survey is limited by expert knowledge. On the contrary, NFI data rely on inventories made by trained field operators with good botanical and phytosociological knowledge (Maciejewski et al. 2020), so that $\%A_{PC>50,\ CC<50}$ is expected to be more robust to species misidentification than the survey of forest managers. The importance of *Brachypodium pinnatum* as a competitive species towards tree regeneration is thus probably underestimated by French forest managers.

Buxus sempervirens had a high $\%A_{PC>50,\ CC<50}$ score (1.86%), but forest managers did not declare that they controlled it. *Buxus sempervirens* is a thermophilous species, often growing in low-productive, south facing, dry and calcareous forests (Lenoble and Broyer 1945). In these stands, forest management is usually very extensive. Forest regeneration is thus left to natural dynamics and *Buxus sempervirens* is not controlled in these stands.

Understory tree species examined in our study had two possible statuses: crop species, i.e., species favored by forest managers to constitute the future stand, or non-crop species. Crop trees are chosen by forest managers based on local context (climate, site fertility) and expected economic, ecological, and social outcomes. Depending on the region, *Fagus sylvatica*, *Castanea sativa*, and *Carpinus betulus* are seen as crop or non-crop species. In some regions, *Fagus sylvatica* and *Carpinus betulus* are considered to be strong competitors towards young crop tree species and are controlled through regular tending operations (Collet et al. 2008; Ligot et al. 2013), depending on silvicultural objectives. The examples of *Buxus sempervirens*, *Fagus sylvatica*, and *Carpinus betulus* illustrate the effects of management objectives on the classification of the understory plant species (requiring vegetation control or not) and suggest that the results of our study are related to the present management objectives and would have differed in another management context. On the contrary, *Betula pendula* and *Populus tremula* were qualified as requiring vegetation control in Section 5 of the survey by 16 and 12 forest managers, respectively, while having low $\%A_{PC>50,\ CC<50}$ scores. The reasons for this discrepancy remain unclear.

4.4 Implications for forest management

Our study accurately identified which species require vegetation control according to forest managers. It gave a view of the current situation concerning potential regeneration and plantation problems in France by providing an initial quantification of the surface areas currently affected by species requiring vegetation control during the tree regeneration stage and by providing information about the spatial distribution of the forest stands concerned by vegetation management operations.

Our results showed that the surface areas requiring vegetation control are far from being negligible: *Pteridium aquilinum*, *Molinia caerulea*, and *Rubus fruticosus* were each present with a high cover in more than 13% of non-Mediterranean French forests with open canopies. All these forest stands are colonized with a species requiring vegetation control during the tree regeneration stage.

Vegetation control, whether by mechanical or chemical methods, has potential environmental impacts on biodiversity or long-term soil fertility (Ammer et al. 2011; Aust et al. 2004; Balandier et al. 2006). It also has a significant economic cost and may impact the social values of a forest (Ammer et al. 2011; Willoughby et al. 2004). The surface area to which these methods are applied is of primary importance when estimating the overall impacts of vegetation management and when identifying the main risks associated with the practices, at both regional and national scales. We showed that a substantial part of the managed forests, outside the Mediterranean region, requires vegetation control in order to reach silvicultural objectives set by the forest managers. In future works, results from our study could be combined with other information about multiple performances (economic, environmental, and social) of vegetation control methods to help to define forest policies, management incentives and silvicultural guidelines.

5 Conclusions

Our study showed that vegetation control during stand regeneration is crucial for most forest managers outside the Mediterranean region, and that three species (*Pteridium aquilinum*, *Molinia caerulea*, and *Rubus fruticosus*) are present with a high cover, each in more than 13% of open-canopy forests.

We provided a method to determine understory plant species that require vegetation control during the tree regeneration stage. The method is easier to use and more reliable than expert surveys and may be applied at various geographical scales and in various regions. Finally, it allows us to estimate the area of forests with open canopies affected by each understory species requiring vegetation control and therefore gives access to the potential area to which vegetation control methods could be applied. This is a novelty in forest management and an important step towards allowing forest managers to assess the economic investment required for stand regeneration, as well as the potential impacts of vegetation control operations. This assessment is critical for fueling the debate on stand regeneration methods.

Appendix

Table 4

Table 4 List of the 100 species used in step 3. Species numbered 1 to 29 corresponded to the preliminary list of species used in steps 1 and 2. Species 1–29 and species 30–100 were ordered by decreasing frequency in plots where the species is present with a high cover according to NFI data

Species name	Species number	Species name	Species number	Species name	Species number
Rubus fruticosus aggr.	1	*Deschampsia flexuosa* (L.) Trin.	34	*Quercus robur* L.	68
Hedera helix L.	2	*Lonicera periclymenum* L.	35	*Oxalis acetosella* L.	69
Molinia caerulea (L.) Moench	3	*Vaccinium myrtillus* L.	36	*Deschampsia cespitosa* (L.) P. Beauv.	70
Pteridium aquilinum (L.) Kuhn	4	*Juniperus communis* L.	37	*Galium odoratum* (L.) Scop.	71
Buxus sempervirens L.	5	*Carpinus betulus* L.	38	*Prunus padus* L.	72
Pseudoscleropodium purum (Hedw.) M. Fleisch	6	*Ruscus aculeatus* L.	39	*Cytisus oromediterraneus* Rivas Mart., T. E. Díaz, Fern. Prieto, Loidi & Penas	73
Carex flacca Schreb.	7	*Festuca ovina* L.	41	*Carex acutiformis* Ehrh.	74
Brachypodium pinnatum (L.) P. Beauv.	8	*Pseudarrhenatherum longifolium* (Thore) Rouy	42	*Carex pendula* Huds.	75
Anemone nemorosa L.	9	*Arbutus unedo* L.	43	*Vinca minor* L.	76
Corylus avellana L.	10	*Ulex europaeus* L.	44	*Rubus caesius* L.	77
Carex brizoides L.	11	*Ilex aquifolium* L.	45	*Asphodelus albus* Mill.	78
Castanea sativa Mill.	12	*Brachypodium sylvaticum* (Huds.) P. Beauv.	46	*Holcus mollis* L.	79
Cornus sanguinea L.	13	*Carex arenaria* L.	47	*Salix cinerea* L.	80
Fagus sylvatica L.	14	*Carex remota* L.	48	*Pinus pinaster* Aiton	81
Calluna vulgaris (L.) Hull	15	*Carex riparia* Curtis	49	*Mercurialis perennis* L.	82
Prunus spinosa L.	16	*Dactylis* sp.	50	*Smilax aspera* L.	83
Rubia peregrina L.	17	*Fraxinus excelsior* L.	51	*Glechoma hederacea* L.	84
Rhytidiadelphus triquetrus (Hedw.) Warnst.	18	*Phragmites australis* (Cav.) Trin. ex Steud.	52	*Sorbus torminalis* (L.) Crantz	85
Urtica dioica L.	19	*Salix atrocinerea* Brot.	53	*Acer pseudoplatanus* L.	86
Cytisus scoparius (L.) Link	20	*Ulmus minor* Mill.	54	*Plagiomnium undulatum* (Hedw.) T. J. Kop.	87
Crataegus monogyna Jacq.	21	*Abies alba* Mill.	55	*Teucrium scorodonia* L.	88
Pseudotsuga menziesii (Mirb.) Franco	22	*Bromus erectus* Huds.	56	*Picea abies* (L.) H. Karst.	89
Hylocomium splendens (Hedw.) Schimp.	23	*Eurhynchium striatum* (Hedw.) Schimp.	57	*Rubus idaeus* L.	90
Quercus ilex L.	24	*Ranunculus ficaria* L.	58	*Acer monspessulanum* L.	91
Thuidium tamariscinum (Hedw.) Schimp.	25	*Sambucus nigra* L.	59	*Eurhynchium* sp.	92
Quercus pubescens Willd.	26	*Hyacinthoides non-scripta* (L.) Chouard ex Rothm.	60	*Dioscorea communis* (L.) Caddick & Wilkin	93
Erica arborea L.	27	*Festuca altissima* All.	61	*Clematis vitalba* L.	94
Lamium galeobdolon (L.) L.	28	*Rhytidiadelphus loreus* (Hedw.) Warnst.	62	*Impatiens glandulifera* Royle	95
Quercus coccifera L.	29	*Erica scoparia* L.	63	*Calamagrostis epigejos* (L.) Roth	96
Betula pendula Roth	30	*Luzula sylvatica* (Huds.) Gaudin	64	*Rhododendron ferrugineum* L.	97
Populus tremula L.	31	*Teucrium chamaedrys* L.	65	*Alnus alnobetula* (Ehrh.) K. Koch	98
Quercus petraea (Matt.) Liebl.	32	*Ribes rubrum* L.	66	*Robinia pseudoacacia* L.	99
Ligustrum vulgare L.	33	*Pleurozium schreberi* (Willd. ex Brid.) Mitt.	67	*Carex pilosa* Scop.	100

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Code availability
The code used in the current study is available from the corresponding author on reasonable request.

Authors' contributions
ND performed the data curation and formal analysis and wrote the original draft as well as the final version. CC, JLD, and JCG conceptualized the study methodology and supervised the work and writing of the final manuscript. VB, JDB, FM, and MD provided advice about the methodology design, commented ,and corrected the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available either on the website of the French NFI (https://inventaire-forestier.ign.fr/dataIFN/) for the NFI data or on a public repository for the survey of forest managers (https://doi.org/10.57745/QH5JQH).

Declarations

Ethics approval and consent to participate
Not applicable

Consent for publication
Not applicable

Competing interests
The authors declare that they have no competing interests.

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