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# Contribution of forest management artefacts to plant diversity at a forest scale

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## Abstract

• **Introduction** Most temperate forests are managed for wood production, and some forestry practices generate typical environmental features such as roads, paths, ditches and tractor ruts, which are likely to affect forest species distribution.

• **Methods** We studied the influence of forestry artefacts on the overall forest-understory plant diversity in an ancient oak-dominated French forest with a long history of management. Two designs (grid design and paired design) were built in order to record the occurrence frequency of artefacts and to estimate the originality of the plant assemblage that they host.

• **Results** We recorded 897 plots on the grid design: 68.3% of the plots were more than 4 m away from any artefact, 23.3% were within 4 m of an artefact and 8.4% were located on an artefact. The artefact contribution to total floristic richness would lie between 8.0% and 22.6%, depending on whether the artefact surroundings were included or not in the artefact contribution. Road verges were the least frequent artefacts but provided the richest contribution to overall plant diversity (82%), whereas paths were the poorest (with only a 42% contribution). Thirteen species appeared to prefer artefacts over control plots: six forest species, five non-forest species and two generalist species.

• **Discussion** We show that forestry artefacts are key components of the floristic diversity in managed forests; therefore, forest management should take them into consideration.

**Keywords** Disturbance · Drainage ditches · Forestry artefacts · Managed forest · Paths · Roads · Tractor ruts · Vascular plants

## 1 Introduction

Most temperate forests are managed for wood production. Though forest management is often considered to be detrimental to biodiversity, species richness of vascular plants may actually be higher in managed forests than in unmanaged forests (Paillet et al. 2009). Silvicultural practices nearly always involve dividing the original forest matrix into small management units (i.e. forest stands), regardless of the regime chosen. In addition, logging operations generate artefacts such as roads, paths and tractor ruts along or within stands.

These artefacts, which may be temporary or permanent, create light and soil conditions different from those found in true forest interiors; they contribute to the creation of new microhabitats and therefore, may increase plant diversity at the forest scale (Hansen et al. 1991). However, most studies dealing with the impact of forest management on flora have neglected such artefacts in their analyses (e.g. Didier and Royer 1994; Bailly 1999; Decocq et al. 2004a) though some have investigated the originality of the flora found on roads (Parendes and Jones 2000; Watkins et al. 2003; Godefroid and Koedam 2004) or tracks and paths (Buckley et al. 2003; Decocq et al. 2004b). These studies compared the mean floristic richness of plots on artefacts and plots in the forest interior but they did not evaluate the potential role artefacts may play in introducing surplus plant species. Nevertheless, Peterken and Francis (1999) did emphasise that diversified forest habitats in intensively cultivated areas in Britain are becoming the only surviving habitat not directly affected by

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drainage, fertilisers and herbicides, and may serve as reserves of semi-natural habitat for plant species. In that sense, the conservation of non-forest species in forests may be as important as the forest species richness as long as neither exotic nor invasive species are involved. Peterken and Francis (1999) also showed that a significant proportion of the plants in British woodlands, mostly ruderal species, were related to open areas (8–50% of all plant species, the proportion increasing with forest age and surface area). However, because the authors did not make a distinction between open habitats created by logging and naturally open habitats such as glades, pools, streams and treefall gaps, it is not possible to assess from their study the relative importance of logging-created open areas to the plant diversity of British woodlands. Furthermore, some artefacts are closed rather than open areas (e.g. paths, tractor ruts).

In this study, we investigated how much of the forest plant species diversity is harboured by forestry artefacts, by considering artefact occurrence frequencies as well as the originality of the plant assemblages they host. Thus, an artefact type harbouring very original plant communities may not contribute much to the global forest diversity if this artefact is very rare in the forest. We aimed to estimate (a) the encounter rate of each forestry artefact type using a grid design and (b) the amount of surplus plant species—forest plant species or non-forest/generalist species present only on forestry artefacts. In addition, we investigated whether some artefacts tended to contribute more than others to forest diversity.

## 2 Methods

### 2.1 Study site

The study area, la Bouteille (482.5 ha), is the south-western part of the ancient royal forest of Tronçais (12,000 ha, Allier Department, centre of France). The area has been forested since the seventeenth century at least, and probably even since the early centuries of the Common Era (Dambrine et al. 2007). The forest has been dedicated to producing oak timber and has been managed as an even-aged forest since 1835. The main tree species are Sessile oak (*Quercus petraea*, 81% of the total area), Beech (*Fagus sylvatica*, 12%), Scots pine (*Pinus sylvestris*, 6%) and other deciduous species (1%), often found in mixed stands (personal observations). The soils are mainly deep, sandy, poor soils with a pH ranging from 4.3 to 5.5. Most stands in the study area are 100 to 200 years old. A clearing occupies the centre of the study area.

### 2.2 Ecological data

In spring 2001 and 2003, the presence of all vascular plants was recorded on 2-m<sup>2</sup> plots (80 cm radius) regularly spaced

according to a 50×50 m grid design in 2001 (389 plots) and to a 150×150 m grid design in 2003 (508 plots, Fig. 1a). Some of these plots were located on or close to areas where ecological conditions had been altered by forestry practices (paths and road surroundings, tractor ruts, drainage ditches and ancient charcoal burning places). We distinguished between (1) plots situated more than 4 m away from any forestry artefact (true forest controls), (2) plots situated less than 4 m from a forestry artefact (forest controls under artefact influence) and (3) plots situated on forestry artefacts. Our first aim was to estimate the contribution of forestry artefacts to plant diversity at the forest scale by contrasting plots located on or close to forestry artefacts with plots beyond the influence of any artefact (i.e. true control plots). The grid design also allowed us to estimate the encounter rate of forestry artefacts at the forest scale. A preliminary analysis on 2001 data allowed us to fix the 4-m threshold: we compared the lists of species found in pairs of plots (one on an artefact, one distant) located at different distances from each other, using the Jaccard indices of similarity (Jaccard 1901). In order to increase statistical power, we aggregated pairs of plots distant from each other by 0 to 4 m, pairs of plots distant by 4 to 10 m and pairs of plots distant by 10 to 20 m. An ANOVA test showed that the flora was more similar between the artefact and its paired forest plot when the distance was less than 4 m. However, if the 0-to-4-m pairs were removed, we did not find any significant difference in similarity indexes between pairs of plots distant by 4–10 m and pairs distant by 10–20 m (two-way ANOVA test: artefact type,  $F_{9,46}=4.46$ ,  $p$  value<0.001; distance between the artefact plot and its associated forest plot,  $F_{1,46}=2.39$ ,  $p$  value=0.13). We therefore considered that plots located more than 4 m away from the nearest artefact were beyond its influence.

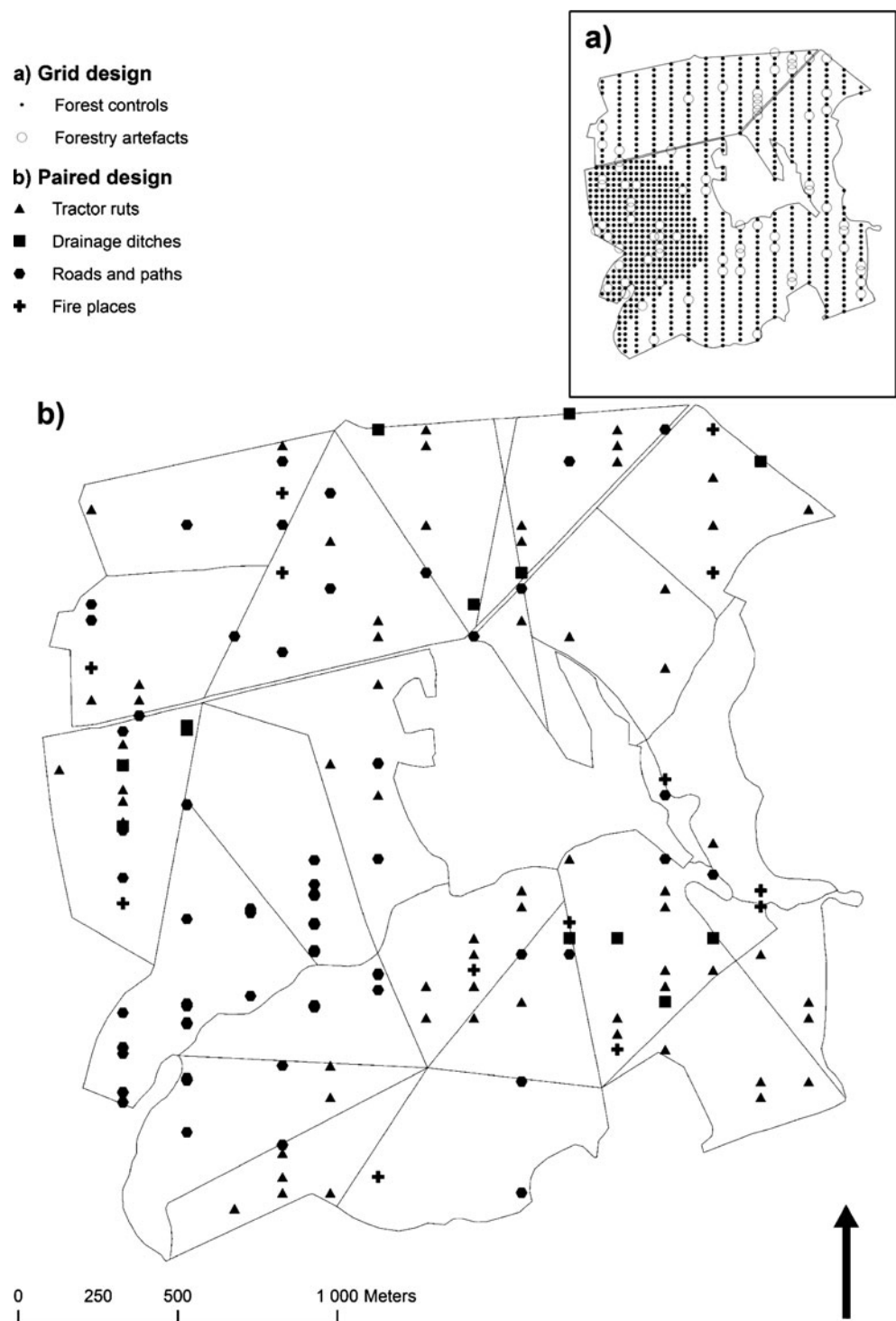
Our second aim was to investigate the contribution of the most common forestry artefacts to forest plant diversity. However, the regular grids used in 2001 and 2003 encompassed too few plots located on forestry artefacts making it impossible to conduct reliable analyses. In order to increase the sample size, a second data set was built: each time the botanists walking from one plot to the next in the regular grid crossed one of the artefacts defined above, they established a new 2-m<sup>2</sup> plot on the artefact plus a second control plot in the forest stand beyond the influence of the artefact (see Fig. 1b). Pairing plots allowed us to avoid confounding factors as much as possible (especially soil conditions).

### 2.3 Data analysis

We defined three classes of habitat preference (see Appendix) for each plant species (forest, non-forest and

**Fig. 1** Location of plots. **a** Grid design (2-m<sup>2</sup> plots are separated by 50 m along *parallel transect lines* every 50 m in 2001 and every 150 m in 2003). **b** Paired design (each time the *parallel lines* of the grid design crossed an artefact, botanists established a 2-m<sup>2</sup> plot on the artefact plus a second control plot in the forest stand beyond the influence of the artefact)

- a) Grid design**
- Forest controls
  - Forestry artefacts
- b) Paired design**
- ▲ Tractor ruts
  - Drainage ditches
  - Roads and paths
  - ✚ Fire places



generalist) by crossing information on species ecological requirements provided by (Rameau et al. 1989; Ellenberg et al. 1992; Jauzein 1995; Honnay et al. 1998; Dupouey et al. 2002). Although most forest species were shade-tolerant, some light-demanding species almost exclusively encountered in forests were also included in the forest category

(such as *Molinia caerulea*, *Carex pallescens*, *Primula elatior*, *Melampyrum pratense*).

The grid design, which provided us with a fair estimate of the artefact's occurrence frequency at the forest scale, allowed us to calculate the contribution of the artefacts to the overall floristic diversity as the ratio of number of

species present only on artefacts to the total number of species at the forest scale. This calculation combined both the floristic richness of the forest artefacts and the true occurrence frequency of the artefacts at the forest scale. We used rarefaction curves (Gotelli and Colwell 2001) provided by EstimateS (Colwell 2004) in order to associate a standard deviation to the observed species richness. Indeed, by randomly generating samples of plots with replacement from the pool of recorded plots, rarefaction curves estimate the cumulated number of species  $SR_n$  recorded on average with  $n$  plots ( $n < N$ ,  $N$  being the total number of plots actually recorded). Finally, for  $n = N$ ,  $SR_n = SR_N$  (the number of species actually recorded on the  $N$  plots). Resampling plots with replacement allows EstimateS to associate a standard deviation to  $SR_N$ . We computed three sample-based rarefaction curves considering four different pools of plots: (1) all plots (“all plots” pool), (2) plots at least 4 m away from any forestry artefact—sufficiently far to be considered more or less beyond its influence (“forest plots” pool), (3) plots located on artefacts (“artefact plots” pool) and (4) the remaining plots which were within 4 m of a forestry artefact—likely to be intermediate between “artefact plots” and “forest plots” (“artefact surrounding” pool). In order to evaluate to what extent forest and artefact plots respectively contributed to overall plant diversity, we used the following formula  $\%CONTRIB_j = (SR_{all,plots} - SR_i) / SR_{all,plots}$ , where  $SR_{all,plots}$  was the number of species cumulated over all grid plots and  $SR_i$  the number of species cumulated over all plots that did not belong to pool  $j$  (if the “all plots” pool is the universal set,  $i$  is the complement of  $j$  in the “all plots” pool, with  $j$  being “forest plots” pool, “artefact plots” pool, “artefact surrounding” pool, “forest plus artefact surrounding” pool and “artefact plus artefact surrounding” pool).

We then calculated 5 %CONTRIB values for the five following pools of plots: (1) artefacts, (2) artefact surroundings, (3) forest controls, (4) artefacts *plus* surroundings and (5) forest controls *plus* surroundings. The values were calculated either for all plant species or only for forest species. We estimated the standard deviation of the %CONTRIB values using the standard deviations (SD) for all the SR indices provided by EstimateS. To do so, we randomly generated 5,000 values of the SRs assuming they followed a normal distribution  $N(SR, SD)$ . We then calculated 5,000 values for the %CONTRIB indices, from which we simply calculated the mean value and its standard deviation.

As no single artefact type was sufficiently frequent within the grid design to be studied separately, we used the paired design to assess whether some artefacts contributed to the overall diversity more than others. For the artefacts with at least ten occurrences in the paired design, we computed three sample-based rarefaction curves: the first with only artefact plots, the second with only control plots, and the third with all plots. This “all plots” curve differed

slightly from the one calculated for the grid design because each artefact plot was coupled to its paired control plot before running EstimateS calculations (thus plots were accumulated two by two; ignoring the paired nature of the data would have led to biased standard deviation estimates). The %CONTRIB indices were calculated using the same formulae as for the grid design, the only difference being that there was no “artefact surrounding” pool in the paired design (for the paired design as a universal set, the “forest plots” pool and the “artefact plots” pool are absolute complements). In order to allow comparisons between the %CONTRIB of each artefact type, all the values were calculated for a sample of 12 pairs of plots from the total recorded sample. To do that, for each artefact type, we randomly sampled 12 of the available pairs of plots and calculated the cumulated number of species. Then we repeated this procedure 50 times as to estimate the mean number of species harboured by 12 pairs of plots and its standard deviation. Finally, to investigate the potential preference for or avoidance of each microhabitat type for the most commonly occurring species, we performed McNemar tests on species occurrence records. To assess whether the differences observed between the artefacts and their paired controls were caused by differences in light availability, we calculated the mean Ellenberg light indicator value for each artefact and control plot. Ellenberg et al. (1992) assigned scores along an arbitrary nine-point scale to many European plants according to their apparent light availability requirements ( $L$ ). Mean  $L$  indicator values were simply calculated as the arithmetic mean of Ellenberg species indicator values over all the species listed at a given plot (independently from their cover percentage in the plot).

### 3 Results

#### 3.1 Occurrence frequency of forest artefacts

From the 897 circular plots in the grid design, only 613 (68.3%) were more than 4 m away from any artefact, 209 (23.3%) were within 4 m of an artefact and 75 (8.4%) were located directly on artefacts. The grid design allowed us to sample eight artefact types: road, road verges, paths, path embankments, tractor ruts, drainage ditches, charcoal burning places and edges. We made a distinction between paths and forest roads: paths were less than 4 m wide, with no surface material added and their right-of-way was less than 1 m on each side. Forest roads were gravelled and their right-of-way was more than 2 m on each side. Canopy openings created by forest roads were almost twice as wide as canopy openings created by paths. Among the 75 plots on artefacts, 29 (38.7%) were on tractor ruts, 15 (20.0%) on



paths, four (5.3%) on ditches, four (5.3%) on road verges and two (2.7%) on path embankments. Tractor ruts were therefore by far the most frequently encountered artefact type at the forest level.

The paired design, which allowed us to accurately study what the original vegetation was like in each artefact type, included 163 pairs of plots corresponding to eight artefact types. Among these eight artefact types, only five were sufficiently sampled to give accurate results: road verges (15 pairs of plots), paths (34 pairs of plots), path embankments (19 pairs of plots), tractor ruts (63 pairs of plots) and drainage ditches (12 pairs of plots).

### 3.2 Overall contribution of artefacts to forest plant diversity

The respective contribution of the “artefact”, “forest” and “artefact surrounding” pools of plots to the overall diversity of the forest (considering either all plant species or only forest species) is provided in Table 1. Figure 2 shows the accumulation curves that were used to calculate these contributions. The 75 plots located directly on artefacts harboured 8.0% of the total species richness (forest and non-forest species) and 6.2% of the forest species richness at the forest scale. In other words, 8.0% of the 109 species found in the forest occurred only on these plots and not on the 608 true forest plots or on the 214 plots situated on artefact surroundings. Similarly, 6.2% of the 58 forest species found in the forest occurred only on artefact plots at the forest scale. Even though road verges were quite rare at the forest scale (only four of the 897 plots on the grid design), they still contributed greatly to total species richness, since they harboured five original species, which were never found on any of the 608 true forest plots in the grid design (see Table 2). Compared to road verges, tractor ruts were sampled 29 times in the grid design, but they held only one species which was never found on the 608 forest plots. When considering the 75 plots located on artefacts *plus* the 214 plots located on artefact surroundings, these 289 plots harboured 22.6% of the total species richness and 18.1% of the forest species richness (species that were never encountered in the 608 forest plots).

### 3.3 Individual contribution of artefacts to forest plant diversity

The paired design allowed us to compare artefact types with regard to the originality of the vegetation they harbour. In Table 2, one can see that road verges were by far the most original artefact type, with a %CONTRIB of 81.6% (all species). In other words, if 12 pairs of plots were randomly sampled among the 15 pairs of plots on road verges recorded in the design, these 12 artefact plots would harbour on average 63 species among which 53 would never be found on the 12 paired control plots. Twelve pairs of plots (artefact + control plots) would harbour on average 65 species. We thus estimated that road verges contributed for  $53/65=81.6\%$  to the diversity of the 12 pairs of plots on road verges. As a comparison, the %CONTRIB for the four other artefact types lied between 42% and 52% (all species). We observed more variability in the %CONTRIB for forest species: from 70.5% for road verges to 32.9% for paths. Among artefact types, road verges harboured thus the most original plant community as regards both the whole species pool and the forest species pool, while paths harboured the least. However, it is interesting to note that the flora on path *embankments* (as opposed to the paths themselves) was quite original as regards forest species (%CONTRIB of 58.8%) whereas they are in line with the other artefact types as regards the whole species pool (%CONTRIB of 51.8%).

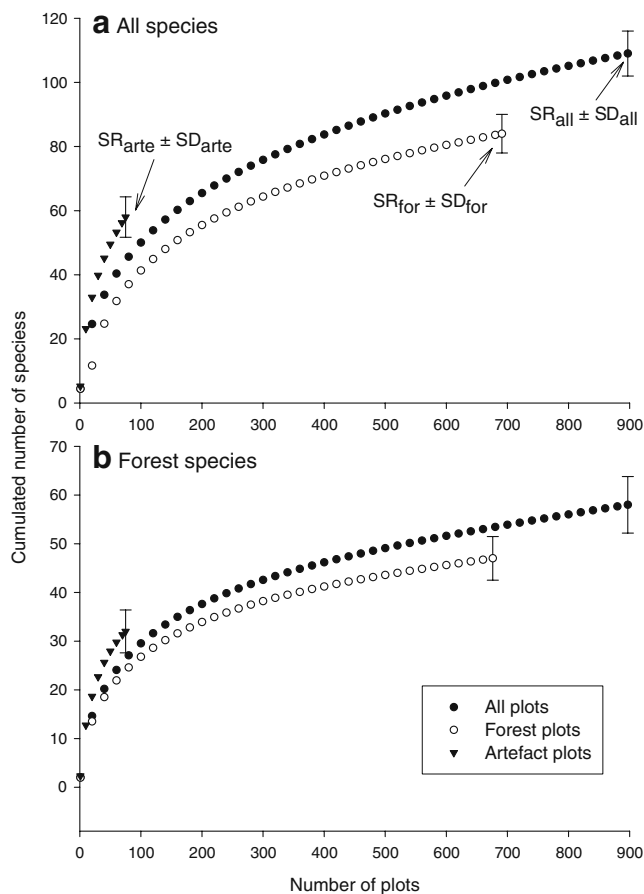
### 3.4 Species responses to forestry artefacts

One hundred and fifty-seven species were recorded, among which 155 were native of the study area. We considered *Pinus sylvestris* and *Robina pseudoacacia* as native species as they were both introduced in the study area several centuries ago and are now regarded as denizens. None of the species were endangered, but two were mentioned as worthy of monitoring at the regional scale (Antonetti et al. 2006). Despite the relatively low power of most of our statistical tests due to small sample sizes (except for tractor ruts), a number of species showed a significant preference for or avoidance of some artefact types (Table 3). Thirteen species were

**Table 1** Cumulated number of species on artefact plots, surrounding plots and forest control plots (mean  $\pm$  standard), for all species and forest species only

Pool of plots	No. of plots	Cumulated no. of species		%CONTRIB	
		All species	Forest species	All species	Forest species
Artefact	75	58 $\pm$ 6.3	32 $\pm$ 4.1	8.0 $\pm$ 8.4	6.2 $\pm$ 14.7
Artefact surrounding	214	69 $\pm$ 5.6	38 $\pm$ 3.8	11.5 $\pm$ 7.6	9.6 $\pm$ 13.0
Forest	608	84 $\pm$ 6.0	47.0 $\pm$ 4.5	21.7 $\pm$ 7.2	20.1 $\pm$ 10.6
Artefacts <i>plus</i> surrounding	289	85 $\pm$ 5.4	46.0 $\pm$ 3.9	22.6 $\pm$ 7.5	18.1 $\pm$ 11.5
Forest <i>plus</i> surrounding	822	100 $\pm$ 6.2	54.0 $\pm$ 6.2	46.7 $\pm$ 6.8	44.5 $\pm$ 9.1
All	897	109 $\pm$ 7.0	58.0 $\pm$ 5.8		

See text for details on %CONTRIB calculation



**Fig. 2** Accumulation curves from the regular grid design considering either **a** all plant species or **b** only forest species. The “All plots” category includes all forest (*for*) plots, artefact (*arte*) plots and plots close to artefacts.  $SR_{all}$ ,  $SR_{for}$  and  $SR_{arte}$  values were used to calculate the contribution of artefacts to the forest plant diversity %CONTRIB (Table 1)

significantly more frequent on artefacts than on forest controls: six were forest species and the remaining were either non-forest species (five species) or generalist species (two species). Of the three species which were more frequent on forest controls, two were forest species. Nearly all the species which showed a preference for or avoidance of an artefact type also showed the same pattern when considering all artefact types jointly. Only *Carpinus betulus* had no apparent habitat preference when all artefact types were considered together; however, it was significantly more frequent on path embankments than on forest controls. ANOVA tests showed that the mean Ellenberg light index of the plots varied significantly with the plot position (on/off of artefact) for road verges ( $F_{1,28}=24.0$ ,  $p$  value $<0.001$ ), tractor ruts ( $F_{1,122}=14.2$ ,  $p$  value $<0.001$ ), and drainage ditches ( $F_{1,22}=5.2$ ,  $p$  value $=0.03$ ), but not for paths or path embankments. For road verges, tractor ruts and drainage ditches, the mean Ellenberg light index was higher on artefact plots than on their associated forest plots.

## 4 Discussion

### 4.1 Overall contribution of artefacts to forest plant diversity

The contribution of artefacts to the total plant diversity of the forest would be between 8.0% and 22.6% for all plant species and 6.2% to 18.1% for forest plants, depending on whether the plots within 4 m of an artefact are considered to be still under the influence of the artefacts or not. This 4-m threshold was fixed according to a preliminary analysis made in 2001 that revealed that plots 4–10 m distant from an artefact were no more similar to artefact plots than plots 10–20 m distant from an artefact. This result is in line with other studies that have demonstrated that the effect of roads does not extend more than 5 m into the forest for vascular plants (Watkins et al. 2003; Avon et al. 2010), even though forest roads have sometimes been suspected of affecting communities more than 100 m into the forest interior (Reed et al. 1996; McGarigal et al. 2001). At first glance, our results are close to those found by Skov and Lawesson (2000) who reported that 25% of the total floristic richness in a managed forest was supported by intra-forest open spaces generated by forest management. Indeed, we observed that five of the 13 species most frequently found on artefacts were non-forest, light-demanding species. Yet, our study area was almost exclusively composed of closed stands more than 100 years old and did not include either regeneration or young stands. However, it is well-known that young forest stages hold more herbaceous species than older forest stages (Deconchat and Balent 2001; Roberts and Zhu 2002; Loya and Jules 2008): had such young stages been included in our study area, the apparent preference of some light-demanding species for artefact habitats may well have disappeared. We also observed increased mean Ellenberg light indices on road verges, drainage ditches and tractor ruts. This result may seem surprising for tractor ruts since they are not usually considered to be true canopy openings. However, we observed that *Hedera helix* (liana) and *Ilex aquifolium* (shrub) were less frequent on tractor rut plots than on their associated forest plots. It is therefore likely that tractors destroy the shrubs and break the lowest tree boughs on their way through the forest, thus allowing more light to reach the ground.

This leads us to note that the disturbances generated by forestry practices not only include canopy openings and improvement of light conditions: forest management may also create shaded microhabitats such as drainage ditches. Indeed, we found that six shade-tolerant forest species formed part of the pool of species more frequent on artefacts than on forest control plots (*Carex remota*, *Carex sylvatica*, *C. betulus*, *Circaea lutetiana*, *Geranium robertianum*, *Viola reichenbachiana*). Soil disturbance and

**Table 2** Cumulated number of species and %CONTRIB on artefact and forest control plots ( $\pm$ SD), computed on a 12-plot basis for each artefact type, considering all plant species and only forest species

Artefact type	Grid design		Paired design					
	No. of plots	No. original species	No. of plots	Pool of plots	Cumulated no. of species		%CONTRIB	
					All species	Forest species	All species	Forest species
Road verges	4	5	15	Forest	12.0 $\pm$ 3.2	8.0 $\pm$ 2.4	2.9 $\pm$ 0.1	7.4 $\pm$ 0.1
				Artefact	63.0 $\pm$ 4.5	25.1 $\pm$ 1.9	81.6 $\pm$ 0.1	70.5 $\pm$ 0.1
				Both	65.2 $\pm$ 4.5	27.1 $\pm$ 1.7		
Paths	15	3	34	Forest	16.4 $\pm$ 3.2	9.5 $\pm$ 2.3	10.8 $\pm$ 0.1	15.4 $\pm$ 0.2
				Artefact	25.5 $\pm$ 3.0	12.1 $\pm$ 2.5	42.4 $\pm$ 0.1	32.9 $\pm$ 0.2
				Both	28.8 $\pm$ 3.1	14.7 $\pm$ 2.6		
Path embankments	2	0	19	Forest	14.2 $\pm$ 2.7	7.2 $\pm$ 2.0	8.3 $\pm$ 0.1	6.0 $\pm$ 0.2
				Artefact	26.8 $\pm$ 3.1	16.5 $\pm$ 2.7	51.4 $\pm$ 0.1	58.8 $\pm$ 0.1
				Both	29.5 $\pm$ 3.3	18.0 $\pm$ 2.6		
Drainage ditches	4	2	12	Forest	18.0 $\pm$ 3.4	10.0 $\pm$ 2.2	9.4 $\pm$ 0.1	16.3 $\pm$ 0.2
				Artefact	34.0 $\pm$ 4.0	14.0 $\pm$ 2.3	51.9 $\pm$ 0.1	39.8 $\pm$ 0.2
				Both	38.0 $\pm$ 4.1	17.0 $\pm$ 2.3		
Tractor ruts	29	1	63	Forest	15.1 $\pm$ 2.9	8.2 $\pm$ 2.0	8.1 $\pm$ 0.2	13.0 $\pm$ 0.2
				Artefact	24.3 $\pm$ 2.9	11.3 $\pm$ 1.9	42.9 $\pm$ 0.1	36.3 $\pm$ 0.2
				Both	26.9 $\pm$ 3.1	13.3 $\pm$ 2.2		

See text for details on %CONTRIB calculation

repeated vegetation removal most probably play a role in differentiating the environmental conditions between forestry artefacts and forest control sites (Fleming et al. 1994; Zenner and Berger 2008).

Lastly, though tractor ruts, paths and roads are often considered to be primary vectors for the dispersal of non-forest and exotic species (Buckley et al. 2003; Zenner and Berger 2008), in our case, all the 157 species recorded on either the grid or the paired design were native to the study area (Antonetti et al. 2006). We agree with Peterken and Francis (1999) that the refuge value of woodlands for some open space species whose survival may be endangered by the degradation of non-forest open habitats in the surrounding landscape is worth considering. Although, it may reasonably be argued that more than half the species supported by forestry artefacts are generalist or non-forest species and as such have little conservation value in forests, it is important to note that all of the species recorded were indigenous to the study area.

#### 4.2 Each artefact type contributes specifically to forest plant diversity

Each artefact type contributes more to the forest diversity if it is frequent at the forest scale and/or if it harbours original

species. The grid and paired designs were thought out to give information respectively on artefact frequency at the forest scale and on the originality of the plant assemblages found on the artefacts, so both designs were necessary to study the contribution of artefacts to forest plant diversity. For instance, road verges were by far the richest forestry artefact type: 12 plots held 63 species whereas all other forestry artefacts only reached 24 to 34 species for the same number of plots. This is consistent with Buckley et al. (2003), Watkins et al. (2003) and Wolf et al. (2008) who found that overall species richness and species diversity were significantly higher on road sides than in the forest interior. However, the grid design showed that road verges were also one of the less frequently encountered artefact types in the forest (0.4% of the total area—four plots) compared to other artefacts, especially tractor ruts (3.2% of the total area—29 plots). Nevertheless, according to the grid design, we recorded 19 species on the four plots situated on road verges, among which four species were never observed on the 613 true forest plots in the grid design. As a comparison, of the 25 species recorded on the 29 tractor rut plots in the grid design, only one was never observed on true forest plots.

Drainage ditches were also quite rare at the forest level (0.4% of the forest area) whereas they appeared to harbour



**Table 3** Species preference/avoidance for the artefacts based on species occurrence frequency and associated McNemar tests (only species with a significant difference in occurrence frequency between artefact and forest control plots are presented)

Artefact type	Species	Habitat preferendum	Frequency		McNemar test	
			Forest	Artefact	Stat	<i>p</i> value
All artefacts ( <i>n</i> =156)	<i>Agrostis capillaris</i>	NON FOR	1%	4%	22.0	<0.001
	<i>Ajuga reptans</i>	NON FOR	1%	4%	4.2	0.04
	<i>Carex remota</i>	FOR	0%	9%	9.1	0.002
	<i>Carex sylvatica</i>	FOR	1%	3%	12.1	<0.001
	<i>Circaea lutetiana</i>	FOR	0%	4%	5.1	0.02
	<i>Geranium robertianum</i>	FOR	2%	8%	6.8	0.009
	<i>Hedera helix</i>	FOR	56%	42%	8.5	0.004
	<i>Holcus mollis</i>	NON FOR	8%	25%	19.3	<0.001
	<i>Ilex aquifolium</i>	FOR	31%	13%	17.4	<0.001
	<i>Juncus effusus</i>	GEN	2%	10%	8.5	0.004
	<i>Lonicera periclymenum</i>	GEN	40%	29%	4.5	0.03
	<i>Potentilla erecta</i>	NON FOR	0%	1%	6.1	0.01
	<i>Taraxacum officinale</i>	GEN	0%	4%	5.1	0.02
	<i>Veronica chamaedrys</i>	NON FOR	0%	4%	4.2	0.04
	<i>Viola reichenbachiana</i>	FOR	3%	9%	5.1	0.02
Road verges ( <i>n</i> =15)	<i>Agrostis capillaris</i>	NON FOR	0%	73%	9.1	0.003
	<i>Holcus mollis</i>	NON FOR	0%	53%	6.1	0.01
	<i>Ilex aquifolium</i>	FOR	53%	0%	6.1	0.01
	<i>Potentilla erecta</i>	NON FOR	0%	40%	4.2	0.04
	<i>Viola reichenbachiana</i>	FOR	0%	53%	6.1	0.01
Paths ( <i>n</i> =34)	<i>Agrostis capillaris</i>	NON FOR	3%	26%	6.1	0.01
	<i>Carex sylvatica</i>	FOR	0%	18%	4.2	0.04
	<i>Hedera helix</i>	FOR	56%	29%	4.3	0.04
	<i>Holcus mollis</i>	NON FOR	0%	18%	4.2	0.04
	<i>Ilex aquifolium</i>	FOR	38%	9%	8.1	0.004
	<i>Lonicera periclymenum</i>	GEN	41%	21%	4.0	0.05
Path embankments ( <i>n</i> =19)	<i>Carpinus betulus</i>	FOR	0%	18%	4.2	0.04
Tractor ruts ( <i>n</i> =63)	<i>Hedera helix</i>	FOR	57%	37%	6.9	0.009
	<i>Holcus mollis</i>	NON FOR	10%	22%	4.1	0.04
	<i>Ilex aquifolium</i>	FOR	44%	19%	10.2	0.001
	<i>Juncus effusus</i>	GEN	2%	14%	4.9	0.03

Preferred habitat (see Table 4)

FOR forest species, NON FOR non-forest species, GEN generalist species

an interesting part of the total plant diversity: among all the plant species recorded on the 12×2 plots (paired design) located either on drainage ditches or on control plots, one half was present only on drainage ditches. Nevertheless, our limited sample size did not allow us to reliably identify the list of species growing preferentially along ditches. Corney et al. (2006) found that forest drainage ditches tended to harbour some non-forest species. When studying the vegetation diversity in coniferous plantation forests, Smith et al. (2007) found

that drainage ditches hold a richer plant community compared to road banks and setbacks. However, these two studies did not control for soil type. The presence of drainage ditches probably depended at least partially on soil conditions thus making it impossible to disentangle the effect of soil and land use types in their study. Our paired design allowed us to avoid this problem since soil conditions were mostly the same between plots located on drainage ditches and their paired forest control plots. Tractor ruts were by far the most abundant forestry

artefacts in our study area (29 plots were located on tractor ruts among the 75 artefact plots in the grid design). In France, forest machinery is of quite recent use; tractor loading was introduced only a few decades ago and we can therefore expect that tractor ruts will certainly continue to increase in number in the future. While nearly half of all plant species recorded either on tractor ruts or on the associated forest control plots were present on tractor ruts only, on the contrary, some other forest species appear to have been negatively impacted by tractor traffic (*H. helix* and *I. aquifolium*), possibly attributable to soil compaction. A similarly balanced impact of tractor ruts has also been reported in North America (Zenner and Berger 2008). Soil modifications due to the repeated passes of skidders and other forest machinery may be long-lasting (Godefroid et al. 2007) and may cause a progressive shift in plant communities within tree stands in the future.

## 5 Conclusion

Even if roads and paths have well-known negative impacts on some taxonomic groups such as birds (Reijnen et al. 1995), amphibians (Eigenbrod et al. 2008), reptiles (Shepard et al. 2008) and insects (Koivula and Vermeulen 2005), we emphasise the need to study the floristic composition of forestry artefacts, which would allow forest managers to take them into consideration when planning forestry operations, in agreement with Mitchell and Kirby (1989), Skov (1997) and Peterken and Francis (1999). Concurrently, ecologists should not neglect such forestry artefacts when assessing the diversity at a forest scale. By recognising the ecological value of roads and paths, management practices aiming at maximising their refuge value may be developed and promoted. Attention should probably be paid to road surfacing material, traffic intensity and frequency and intensity of road verge maintenance (Godefroid and Koedam 2004). Similarly, as the largest effect of skidder trails on plant composition occurs with the first few passes (Zenner and Berger 2008), concentrating skidder traffic to a designated trail system would result in a lesser impact on plant diversity.

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## Appendix

**Table 4** List of plant species and their habitat preference (forest—FOR, non-forest—NON FOR or generalist—GEN) from Rameau et al. (1989), Ellenberg et al. (1992), Jauzein (1995), Honnay et al. (1998) and Dupouey et al. (2002)

Species	Preferred habitat	Type
<i>Acer campestre</i>	FOR	TREE
<i>Adoxa moschatellina</i>	FOR	HERB
<i>Agrostis canina</i>	NON FOR	HERB
<i>Agrostis capillaris</i>	NON FOR	HERB
<i>Ajuga reptans</i>	NON FOR	HERB
<i>Allium ursinum</i>	FOR	HERB
<i>Anemone nemorosa</i>	FOR	HERB
<i>Anthoxanthum odoratum</i>	NON FOR	HERB
<i>Aquilegia vulgaris</i>	GEN	HERB
<i>Arum maculatum</i>	FOR	HERB
<i>Asteraceae sp.</i>	GEN	HERB
<i>Athyrium filix-femina</i>	FOR	FERN
<i>Blechnum spicant</i>	FOR	FERN
<i>Brachypodium pinnatum</i>	GEN	HERB
<i>Brachypodium sylvaticum</i>	FOR	HERB
<i>Callitriche sp</i>	GEN	HERB
<i>Calluna vulgaris</i>	NON FOR	SHRUB
<i>Cardamine flexuosa</i>	FOR	HERB
<i>Carex caryophylllea</i>	NON FOR	HERB
<i>Carex flacca</i>	NON FOR	HERB
<i>Carex laevigata</i>	FOR	HERB
<i>Carex ovalis</i>	GEN	HERB
<i>Carex pallescens</i>	GEN	HERB
<i>Carex pendula</i>	FOR	HERB
<i>Carex pilulifera</i>	GEN	HERB
<i>Carex remota</i>	FOR	HERB
<i>Carex sylvatica</i>	FOR	HERB
<i>Carex viridula</i>	GEN	HERB
<i>Carpinus betulus</i>	FOR	TREE
<i>Castanea sativa</i>	GEN	TREE
<i>Chrysosplenium oppositifolium</i>	FOR	HERB
<i>Circaea lutetiana</i>	FOR	HERB
<i>Cirsium palustre</i>	NON FOR	HERB
<i>Convallaria majalis</i>	FOR	HERB
<i>Crataegus monogyna</i>	GEN	SHRUB
<i>Cytisus scoparius</i>	GEN	SHRUB
<i>Dactylis glomerata</i>	NON FOR	HERB
<i>Danthonia decumbens</i>	GEN	HERB
<i>Deschampsia cespitosa</i>	NON FOR	HERB
<i>Deschampsia flexuosa</i>	GEN	HERB
<i>Digitalis purpurea</i>	GEN	HERB
<i>Dryopteris affinis</i>	FOR	FERN
<i>Dryopteris carthusiana</i>	FOR	FERN

**Table 4** (continued)

Species	Preferred habitat	Type
<i>Dryopteris filix-mas</i>	FOR	FERN
<i>Epilobium montanum</i>	FOR	HERB
<i>Erica cinerea</i>	NON FOR	SHRUB
<i>Euphorbia amygdaloides</i>	FOR	HERB
<i>Euphorbia dulcis</i>	FOR	HERB
<i>Evonymus europaeus</i>	FOR	SHRUB
<i>Fagus sylvatica</i>	FOR	TREE
<i>Festuca heterophylla</i>	FOR	HERB
<i>Fragaria vesca</i>	GEN	HERB
<i>Frangula dodonei</i>	GEN	SHRUB
<i>Fraxinus excelsior</i>	GEN	TREE
<i>Galeopsis tetrahit</i>	NON FOR	HERB
<i>Galium aparine</i>	GEN	HERB
<i>Galium mollugo</i>	NON FOR	HERB
<i>Galium odoratum</i>	FOR	HERB
<i>Galium palustre</i>	NON FOR	HERB
<i>Geranium robertianum</i>	FOR	HERB
<i>Geum urbanum</i>	GEN	HERB
<i>Glyceria fluitans</i>	GEN	HERB
<i>Gnaphalium uliginosum</i>	NON FOR	HERB
<i>Hedera helix</i>	FOR	LIANA
<i>Hieracium murorum</i>	FOR	HERB
<i>Hieracium sabaudum</i>	FOR	HERB
<i>Hieracium vulgatum</i>	FOR	HERB
<i>Holcus lanatus</i>	NON FOR	HERB
<i>Holcus mollis</i>	NON FOR	HERB
<i>Hyacinthoides non-scripta</i>	FOR	HERB
<i>Hypericum androsaemum</i>	FOR	HERB
<i>Hypericum pulchrum</i>	FOR	HERB
<i>Hypericum tetrapterum</i>	GEN	HERB
<i>Hypochaeris radicata</i>	GEN	HERB
<i>Ilex aquifolium</i>	FOR	SHRUB
<i>Juncus effusus</i>	GEN	HERB
<i>Juncus tenuis</i>	NON FOR	HERB
<i>Lamium galeobdolon</i>	FOR	HERB
<i>Lapsana communis</i>	FOR	HERB
<i>Lathyrus linifolius</i>	FOR	HERB
<i>Linaria repens</i>	GEN	HERB
<i>Lonicera periclymenum</i>	GEN	LIANA
<i>Lotus pedunculatus</i>	GEN	HERB
<i>Luzula multiflora</i>	GEN	HERB
<i>Luzula pilosa</i>	FOR	HERB
<i>Luzula sylvatica</i>	FOR	HERB
<i>Lysimachia nemorum</i>	FOR	HERB
<i>Malus sylvestris</i>	FOR	TREE
<i>Melampyrum pratense</i>	FOR	HERB
<i>Melica uniflora</i>	FOR	HERB
<i>Mentha suaveolens</i>	GEN	HERB
<i>Mercurialis perennis</i>	FOR	HERB

**Table 4** (continued)

Species	Preferred habitat	Type
<i>Mespilus germanica</i>	GEN	SHRUB
<i>Moehringia trinervia</i>	FOR	HERB
<i>Molinia caerulea</i>	GEN	HERB
<i>Mycelis muralis</i>	FOR	HERB
<i>Oxalis acetosella</i>	FOR	HERB
<i>Oxalis dillenii</i>	GEN	HERB
<i>Pinus sylvestris</i> *	GEN	TREE
<i>Plantago lanceolata</i>	GEN	HERB
<i>Plantago major</i>	NON FOR	HERB
<i>Poa annua</i>	NON FOR	HERB
<i>Poa nemoralis</i>	FOR	HERB
<i>Poa pratensis</i>	NON FOR	HERB
<i>Poa trivialis</i>	NON FOR	HERB
<i>Polygonatum multiflorum</i>	FOR	HERB
<i>Polygonum aviculare</i>	NON FOR	HERB
<i>Polygonum hydropiper</i>	GEN	HERB
<i>Polypodium vulgare</i>	FOR	FERN
<i>Polystichum aculeatum</i>	FOR	FERN
<i>Polystichum setiferum</i>	FOR	FERN
<i>Populus tremula</i>	GEN	TREE
<i>Potentilla erecta</i>	NON FOR	HERB
<i>Potentilla reptans</i>	GEN	HERB
<i>Potentilla sterilis</i>	FOR	HERB
<i>Primula elatior</i>	FOR	HERB
<i>Prunella vulgaris</i>	NON FOR	HERB
<i>Prunus avium</i>	FOR	TREE
<i>Prunus padus</i>	FOR	TREE
<i>Prunus spinosa</i>	GEN	TREE
<i>Pteridium aquilinum</i>	FOR	FERN
<i>Pulmonaria affinis</i>	FOR	HERB
<i>Quercus petraea</i>	GEN	TREE
<i>Ranunculus ficaria</i>	FOR	HERB
<i>Ranunculus repens</i>	GEN	HERB
<i>Robinia pseudoacacia</i> *	GEN	TREE
<i>Rosa arvensis</i>	FOR	SHRUB
<i>Rubus fruticosus</i>	NON FOR	SHRUB
<i>Rumex acetosa</i>	GEN	HERB
<i>Rumex sanguineus</i>	FOR	HERB
<i>Ruscus aculeatus</i>	FOR	SHRUB
<i>Salix caprea</i>	GEN	TREE
<i>Salix cinerea</i>	GEN	SHRUB
<i>Sambucus nigra</i>	GEN	SHRUB
<i>Sambucus racemosa</i>	GEN	SHRUB
<i>Sanicula europaea</i>	FOR	HERB
<i>Scrophularia nodosa</i>	FOR	HERB
<i>Scutellaria minor</i>	NON FOR.	HERB
<i>Senecio jacobaea</i>	GEN	HERB
<i>Senecio sylvaticus</i>	GEN	HERB
<i>Silene dioica</i>	FOR	HERB

**Table 4** (continued)

Species	Preferred habitat	Type
<i>Stachys sylvatica</i>	FOR	HERB
<i>Stellaria alsine</i>	GEN	HERB
<i>Stellaria holostea</i>	FOR	HERB
<i>Tamus communis</i>	GEN	LIANA
<i>Taraxacum officinale</i>	GEN	HERB
<i>Teucrium scorodonia</i>	NON FOR	HERB
<i>Trifolium pratense</i>	NON FOR	HERB
<i>Trifolium repens</i>	GEN	HERB
<i>Urtica dioica</i>	GEN	HERB
<i>Veronica chamaedrys</i>	NON FOR	HERB
<i>Veronica montana</i>	FOR	HERB
<i>Veronica officinalis</i>	GEN	HERB
<i>Veronica serpyllifolia</i>	GEN	HERB
<i>Viburnum opulus</i>	GEN	SHRUB

\* Denizens introduced several centuries ago

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