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1 Increase in the thermal preference of plant communities related to climate change

2

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12

13 **ABSTRACT**

14 Latitudinal and altitudinal range shifts in response to climate change have been reported for  
15 numerous animal species, especially those with high dispersal capacities. In plants, the impact  
16 of climate change on species distribution or community composition has been documented  
17 mainly over long periods (decades) and in specific habitats, often forests. Here, we studied the  
18 change in thermal preferences of temperate flora in different habitats in France over a short  
19 period (2009-2017), using data from a standardized participatory monitoring scheme. We  
20 report a fast increase in the thermal preference of plant communities, both at national and  
21 regional scale, which we relate to climate change. This change in thermal preference mainly  
22 resulted from increased abundance of annual, warm-adapted species. Our results suggest that  
23 plant communities could have been be modified rapidly under climate change. Whether such  
24 changes are sufficient to cope with the current climate warming remains to be ascertained.

25

26 **KEYWORDS**

27 Plants, monitoring, thermal preference, climate change, life span, citizen science.

28

## 29 INTRODUCTION

30 Climate change is considered a significant global threat to biodiversity [1–3], with impacts on  
31 biodiversity from individuals to ecosystems. In ecological communities, climate change  
32 drives compositional changes, in particular via latitudinal and altitudinal shifts, especially in  
33 species with high dispersal capacities, including birds, insects or marine invertebrates [3–5].  
34 In less mobile species, such as plants, elevation has shifted upward during the 20<sup>th</sup> century in  
35 highland French temperate forests [6], although not as fast as temperatures. In contrast,  
36 lowland forests plant communities have not shifted northward, highlighting a higher inertia of  
37 the latter [7]. Whether and how plant communities are able to track climate changes in all  
38 habitat types is still unclear.

39 Most studies demonstrating an effect of climate change on plant communities used  
40 heterogeneous data collected over decades and focused on a particular habitat, owing to the  
41 scarcity of available data. To improve our understanding of how climate change and other  
42 drivers could influence biodiversity, real-time monitoring data on the basis of highly  
43 standardized schemes are required across large spatio-temporal scales [8]. Citizen science,  
44 defined as the involvement of volunteers in research [9], represents a powerful tool that can  
45 contribute to investigating the impacts of climate change on biodiversity [4,10]. Such  
46 monitoring makes it possible to report subtle changes in biological studies of climate change,  
47 including analyses of phenology, from populations to communities.

48 In this study, we examine nine years of change in plant community composition in a variety of  
49 habitats across France, using data collected through a participatory monitoring scheme, to  
50 assess whether such data can be used to detect short-term effects of climate warming. We  
51 address the following questions: (1) has the average thermal preference of plants changed  
52 over the past nine years? (2) Can this change be related to climatic variables? (3) What are the  
53 species most responsible for this change?

## 54 **MATERIALS AND METHODS**

### 55 **Monitoring data**

56 We used data from Vigie-flore, a French citizen science program monitoring wild flora and  
57 having involved a total of 321 skilled amateur botanists. The data were collected yearly  
58 between 2009 and 2017 in 586 1kmx1km squares sampled from a systematic grid (one square  
59 every 10 km), which ensures representative sampling of habitats types. Each square contains  
60 eight systematically distributed 10m<sup>2</sup> plots (Figure S1), each divided into ten 1m<sup>2</sup>-quadrats. In  
61 each plot, the presence of all vascular plants was recorded in each quadrat, as well as habitat  
62 type following the CORINE biotope nomenclature [11], a European hierarchical classification  
63 of vegetation types. For each plot, the number of quadrats in which a species was observed  
64 provides a proxy for species abundance. On average there were 2.9 years of observation per  
65 plot, and 5.3 plots sampled per 1 km<sup>2</sup> square (hence a total of 3,118 plots).

66

### 67 **Species characteristics**

68 We collected information for two species-specific attributes most likely to be related to  
69 climate change: (1) the Ellenberg temperature indicator value (hereafter ETIV), characterizing  
70 the optimum temperature class for growth and survival of a species (nine classes), and (2) life  
71 span (Electronic Supplementary Material I and Table S1). ETIV and life span were available  
72 for 1,709 and 1,780 of the 2,428 species sampled, respectively, representing 83.6% and 89.3%  
73 of total observations. We calculated the community-weighted Mean Temperature Preference  
74 (hereafter MTP), i.e. the abundance-weighted sum of ETIV of all species [12]. We also  
75 calculated the same index with presence/absence data instead of abundance, to test whether  
76 temporal trends could be detected with lower resolution data [13]. Finally, we calculated the  
77 MTP within two extreme life span classes: annuals vs. perennials. The survey sites are not  
78 distributed homogeneously in space and time, which may cause spurious temporal trends in

79 MTP due to a spatial displacement of sampled sites. To control for this, we performed the  
80 same analysis at a regional level, in Île-de-France region, the region with the highest density  
81 of sites (188 squares sampled throughout the nine years, Figure S1).

82

### 83 **Climate data**

84 We used a random forest analysis to extract the most important climatic variable explaining  
85 MTP, which was mean annual temperature (Electronic Supplementary Material II and Table  
86 S2).

87

### 88 **Statistical analyses**

89 We performed Bayesian hierarchical models to estimate the temporal trend in MTP (1) at a  
90 national scale and within Île-de-France, (2) using either abundance data or presence/absence  
91 data and (3) of annuals vs. perennials species (Electronic Supplementary Material III). We  
92 then examined the relationship between the 2009-2017 change in MTP in a plot and the  
93 temporal change in mean annual temperature, using Spearman's correlation coefficients.  
94 To identify which species drove the community-level trends, we used Bayesian models to  
95 estimate the temporal trend in abundance for the 550 most common species (75 annuals and  
96 349 perennials) that were observed at least four out of nine years and in at least ten squares  
97 (Electronic Supplementary Material III). We tested whether species trends were related to life-  
98 span (annual and perennial plants), to ETIV, or to the interaction of both variables by a linear  
99 regression in which each species was weighted by the inverse of the standard error associated  
100 with the estimated temporal trend. All analyses were performed using R version 3.2.4 [14]  
101 (Electronic Supplementary Material IV).

102

## 103 **RESULTS**

104 At the community level, MTP increased through time at the national scale, both with  
105 abundance and presence/absence data (Figure 1a,c). This increase was also observed within  
106 Île-de-France (Figure 1c and S2). At the national scale, the temporal trend was significantly  
107 larger in northern vs. southern France (not shown). The increase in MTP of plant communities  
108 occurred simultaneously with an increase in mean annual temperature (Electronic  
109 Supplementary Material II, Table S3, Figure S3), such that there was a significant positive but  
110 weak correlation between MTP change and the mean annual temperature change over time  
111 (Figure 1d): plots in which the temperature has increased tended to be also plots for which  
112 MTP has increased. Moreover, we found a significant increase in MTP of annual, but not of  
113 perennial species, at national and regional scales (Figure 1b,c).

114

115 Changes at the community level were explained by differences in temporal trends among  
116 species. We found a significant positive relationship between species temporal trends and life  
117 span (Estimate=0.194,  $n=424$ ,  $df=1.402$ ,  $F=3.978$ ,  $P=0.047$ , Figure 2). The interaction  
118 between ETIV and life span was close to significance (Estimate=-0.028,  $n=424$ ,  $df=1.402$ ,  
119  $F=3.013$ ,  $P=0.083$ ), but no relation was found between temporal trends and ETIV.

120

## 121 **DISCUSSION**

122 Our work complements longer-term, single habitat studies by documenting a small but steady  
123 increase in MTP over all habitat types at national and regional scales, detectable over nine  
124 years only, most likely driven by temperature change. This increase is measurable even with  
125 presence/absence data, suggesting a true reshuffling of plant communities, as opposed to mere  
126 abundance fluctuations of common species. In contrast to Bertrand and collaborators [7], who  
127 observed no response of lowland forest plant communities to climate change on a longer  
128 period, we show with a dataset encompassing mostly low-altitude sites that lowland plant

129 communities can be modified by climate change, despite their limited dispersal capabilities.  
130 The difference may arise because our dataset contained a high proportion of open habitats, in  
131 which plant communities may experience higher turnover than in forests. MTP changes  
132 appear to be driven chiefly by changes in occurrence or abundance of annuals, with rapid life  
133 cycles, as revealed by the examination of the temporal trends of the 550 most common  
134 species (79 % of observations). The general pattern of a decline of cold-adapted species and a  
135 relative stability, or increase, of warm-adapted species is consistent with longer-term studies  
136 documenting responses to climate change via species latitudinal and altitudinal range shifts, or  
137 local changes in abundance (including local decline and extinction of cold-adapted species),  
138 particularly in European and North American temperate forests [6,7,15–17].

139 The detection of this subtle but rapid change in plant communities was made possible by  
140 citizen science monitoring and a large sampling effort in space and time. Such data can be of  
141 great value [18] but still come with several downsides deserving further attention. For  
142 example, possible biases could be related to uneven sampling effort, identification errors or  
143 uncomplete trait data. Spatial heterogeneity in the sampling effort was addressed by  
144 examining trends within a small region. Identification errors, as well as missing trait data are  
145 unlikely to be systematically biased in favor of high thermal preference, such that these  
146 problems should not influence our results. Finally, the observed trend in MTP could be caused  
147 partly by temporal changes in species phenology. Because the Vigie-flore protocol  
148 recommends a single annual spring survey, there may be a phenology-influenced bias in  
149 species detection and identifiability against undeveloped or non-flowered species. Climate  
150 change has led to phenological shifts in flowering plants [19], which could increase the  
151 detectability of warm-adapted species as the climate warms.

152

153 Whether such rapid community changes are sufficient to cope with the current climate



154 warming remain to be ascertained. Future research efforts could also be focused on analyzing  
155 trends in MTP across habitats or protection regimes and on identifying possible consequences  
156 of changes for plant-pollinator interactions.

157

## 158 **COMPETING INTERESTS**

159 The authors declare no competing interests.

160

## 161 **AUTHORS' CONTRIBUTIONS**

162 VD, NM and EP conceived the ideas and designed methodology; GM, VD and EP analysed  
163 the data; GM and EP led the writing of the manuscript. All authors contributed to the drafts  
164 and gave final approval for publication.

165

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172

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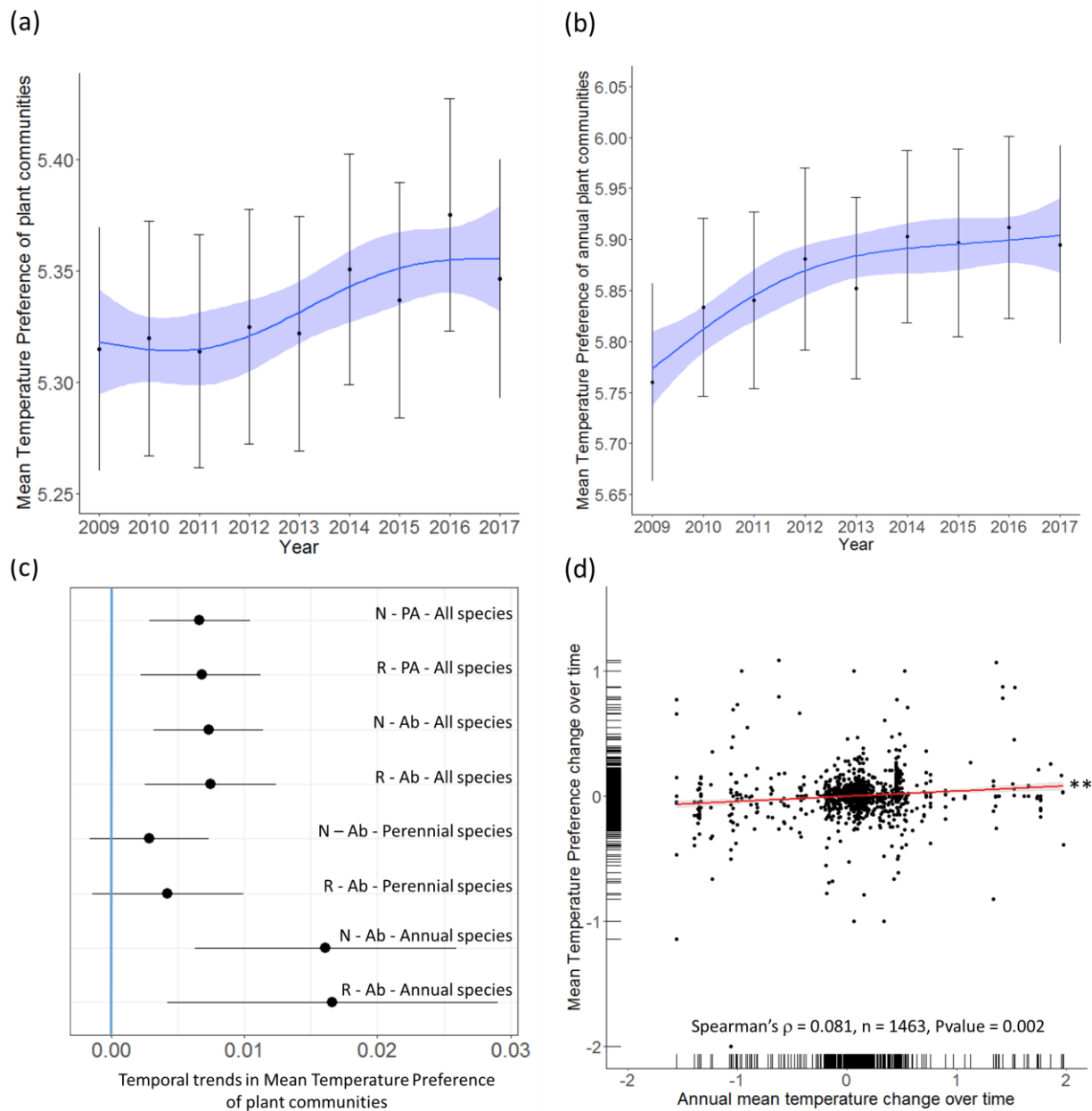
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- 225
- 226



228

229 Figure 1. National temporal trend in MTP of plant communities from 2009 to 2017 calculated

230 with abundance data, (a) for all species or (b) annual species only. The blue line is a

231 generalized additive model estimate of the temporal trend, with its associated standard error

232 (blue band). The black dots and error bars correspond to the inter-annual variations of the

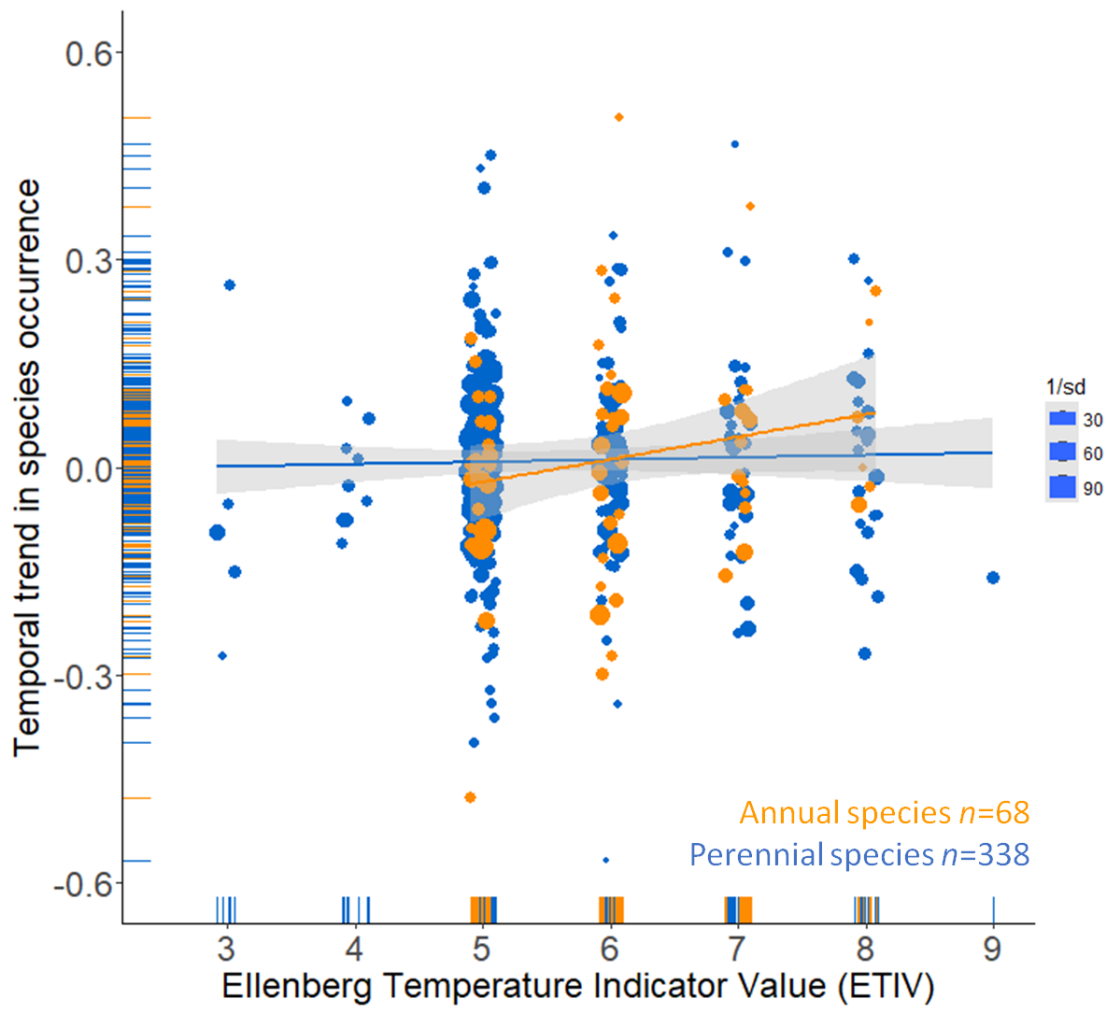
233 variable, with its associated standard error. (c) Temporal trends in MTP from 2009 to 2017

234 estimated using Bayesian models. N/R: National/Regional scale, Ab/PA:

235 Abundance/Presence-Absence data. Dots indicate the mean of the posterior distribution, and

236 bars correspond to the 95 % credible interval for the temporal trends. (d) Correlation between  
237 the plant MTP change and the annual mean temperature change over time. Each point  
238 represents one plot.

239



240

241 Figure 2. Relationship between the temporal trends of the most common species and their  
 242 ETIV for annuals and perennials. Each dot represents the temporal trend for a species, with a  
 243 size proportional to the inverse of the standard error. The lines correspond to the regressions,  
 244 with their associated standard error (grey band).

1 **ELECTRONIC SUPPLEMENTARY MATERIAL**

2

3 **I. Species attributes**

4 We collected information for two species-specific attributes: (1) the Ellenberg temperature  
 5 indicator values (hereafter ETIV), characterizing the optimum temperature class for growth  
 6 and survival of a species (nine classes), from the database Baseflor [1], and (2) life span,  
 7 described using seven broad classes obtained by combining classes from the Bioflor [2] and  
 8 LEDA [3] databases (Table S1).

9

10 Table S1. Procedure used to combine life span information from Bioflor and LEDA  
 11 traitbases.

<b>Life span (Bioflor database)</b>	<b>Life span (LEDA database)</b>	<b>Single or combined life span categories</b>	<b>Occurrence</b>
a (annual)	Annuals	annual	17
a (annual) - b (biennial)	Annuals	annual/biennial	1
b (biennial)	Annuals	annual/biennial	1
p (pluriennial-pollakanthic)	Annuals	annual/pluriennial	1
a (annual)	annuals + perennials	annual/pluriennial	1
p (pluriennial-pollakanthic)	annuals + perennials	annual/pluriennial	1
p (pluriennial-pollakanthic)	annuals + perennials + poly-annuals < 5 years (short-lived perennials)	annual/pluriennial	2
a (annual) - b (biennial) - p (pluriennial-pollakanthic)	annuals + perennials + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
a (annual) - p (pluriennial-pollakanthic)	annuals + perennials + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	2
p (pluriennial-pollakanthic)	annuals + perennials + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	5
p (pluriennial-pollakanthic)	annuals + perennials + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	annual/biennial/pluriennial	1
p (pluriennial-pollakanthic)	annuals + perennials + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials) + poly-annuals 5-50 years (medium-lived perennials)	annual/biennial/pluriennial	1
p (pluriennial-pollakanthic)	annuals + perennials + strict monocarpic bi-annuals and poly-annuals + poly-annuals 5-50 years (medium-lived perennials)	annual/biennial/pluriennial	2
a (annual)	annuals + perennials + summer annuals	annual/pluriennial	2
a (annual)	annuals + perennials + summer annuals + strict monocarpic bi-annuals and poly-	annual/biennial/pluriennial	1

	annuals		
a (annual) - b (biennial)	annuals + perennials + summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	3
a (annual) - p (pluriennial-pollakanthic)	annuals + perennials + summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
b (biennial)	annuals + perennials + summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
b (biennial) - h (pluriennial-hapaxanthic)	annuals + perennials + summer annuals + strict monocarpic bi-annuals and poly-annuals < 5 years (short-lived perennials)	annual/biennial/pluriennial	1
a (annual)	annuals + perennials + summer annuals + winter annuals	annual/pluriennial	2
a (annual)	annuals + perennials + summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	3
a (annual) - b (biennial)	annuals + perennials + summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
a (annual)	annuals + perennials + summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	annual/biennial/pluriennial	1
a (annual) - p (pluriennial-pollakanthic)	annuals + perennials + summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	annual/biennial/pluriennial	1
a (annual) - b (biennial) - h (pluriennial-hapaxanthic)	annuals + perennials + winter annuals	annual/biennial/pluriennial	1
a (annual)	annuals + perennials + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
p (pluriennial-pollakanthic)	annuals + poly-annuals > 50 years (long-lived perennials)	annual/pluriennial	1
a (annual)	annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	16
a (annual) - b (biennial)	annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	4
a (annual) - b (biennial) - p (pluriennial-pollakanthic)	annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
b (biennial)	annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	3
b (biennial) - h (pluriennial-hapaxanthic)	annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
a (annual)	annuals + summer annuals	annual	34
a (annual)	annuals + summer annuals + poly-annuals > 50 years (long-lived perennials)	annual/pluriennial	1
a (annual)	annuals + summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	10
a (annual) - b (biennial)	annuals + summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	2
a (annual)	annuals + summer annuals + strict monocarpic bi-annuals and poly-annuals + poly-annuals 5-50 years (medium-lived perennials)	annual/biennial/pluriennial	1
a (annual)	annuals + summer annuals + winter annuals	annual	5



a (annual)	annuals + summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	18
a (annual) - b (biennial)	annuals + summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
a (annual)	annuals + summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals + poly-annuals 5-50 years (medium-lived perennials)	annual/biennial/pluriennial	1
a (annual)	annuals + winter annuals	annual	2
a (annual)	annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	11
a (annual) - b (biennial)	annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	2
a (annual)	perennials	annual/pluriennial	2
a (annual) - p (pluriennial-pollakanthic)	perennials	annual/pluriennial	2
b (biennial) - p (pluriennial-pollakanthic)	perennials	biennial/pluriennial	1
h (pluriennial-hapaxanthic)	perennials	pluriennial	1
p (pluriennial-pollakanthic)	perennials	pluriennial	396
p (pluriennial-pollakanthic)	perennials + poly-annuals < 5 years (short-lived perennials)	pluriennial	28
p (pluriennial-pollakanthic)	perennials + poly-annuals < 5 years (short-lived perennials) + poly-annuals > 50 years (long-lived perennials)	pluriennial	1
p (pluriennial-pollakanthic)	perennials + poly-annuals < 5 years (short-lived perennials) + poly-annuals > 50 years (long-lived perennials) + poly-annuals 5-50 years (medium-lived perennials)	pluriennial	3
p (pluriennial-pollakanthic)	perennials + poly-annuals < 5 years (short-lived perennials) + poly-annuals 5-50 years (medium-lived perennials)	pluriennial	26
p (pluriennial-pollakanthic)	perennials + poly-annuals > 50 years (long-lived perennials)	pluriennial	11
p (pluriennial-pollakanthic)	perennials + poly-annuals > 50 years (long-lived perennials) + poly-annuals 5-50 years (medium-lived perennials)	pluriennial	2
a (annual)	perennials + poly-annuals 5-50 years (medium-lived perennials)	annual/pluriennial	1
a (annual) - p (pluriennial-pollakanthic)	perennials + poly-annuals 5-50 years (medium-lived perennials)	annual/pluriennial	2
p (pluriennial-pollakanthic)	perennials + poly-annuals 5-50 years (medium-lived perennials)	pluriennial	84
a (annual)	perennials + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
b (biennial) - h (pluriennial-hapaxanthic)	perennials + strict monocarpic bi-annuals and poly-annuals	biennial/pluriennial	3
b (biennial) - h (pluriennial-hapaxanthic) - p (pluriennial-pollakanthic)	perennials + strict monocarpic bi-annuals and poly-annuals	biennial/pluriennial	1
b (biennial) - p (pluriennial-pollakanthic)	perennials + strict monocarpic bi-annuals and poly-annuals	biennial/pluriennial	3
p (pluriennial-pollakanthic)	perennials + strict monocarpic bi-annuals and poly-annuals	biennial/pluriennial	4

b (biennial)	perennials + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	biennial/pluriennial	2
b (biennial) - p (pluriennial-pollakanthic)	perennials + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	biennial/pluriennial	1
a (annual) - b (biennial) - h (pluriennial-hapaxanthic) - p (pluriennial-pollakanthic)	perennials + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials) + poly-annuals 5-50 years (medium-lived perennials)	annual/biennial/pluriennial	1
p (pluriennial-pollakanthic)	perennials + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials) + poly-annuals 5-50 years (medium-lived perennials)	biennial/pluriennial	1
b (biennial) - p (pluriennial-pollakanthic)	perennials + strict monocarpic bi-annuals and poly-annuals + poly-annuals 5-50 years (medium-lived perennials)	biennial/pluriennial	2
p (pluriennial-pollakanthic)	perennials + strict monocarpic bi-annuals and poly-annuals + poly-annuals 5-50 years (medium-lived perennials)	biennial/pluriennial	3
a (annual) - p (pluriennial-pollakanthic)	perennials + summer annuals	annual/pluriennial	3
b (biennial) - h (pluriennial-hapaxanthic) - p (pluriennial-pollakanthic)	perennials + summer annuals	annual/biennial/pluriennial	1
h (pluriennial-hapaxanthic) - p (pluriennial-pollakanthic)	perennials + summer annuals	annual/pluriennial	3
a (annual) - b (biennial) - p (pluriennial-pollakanthic)	perennials + summer annuals + poly-annuals < 5 years (short-lived perennials)	annual/biennial/pluriennial	1
a (annual) - p (pluriennial-pollakanthic)	perennials + summer annuals + poly-annuals < 5 years (short-lived perennials) + poly-annuals 5-50 years (medium-lived perennials)	annual/pluriennial	1
p (pluriennial-pollakanthic)	perennials + summer annuals + poly-annuals 5-50 years (medium-lived perennials)	annual/pluriennial	2
a (annual) - b (biennial)	perennials + summer annuals + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	annual/biennial/pluriennial	1
p (pluriennial-pollakanthic)	perennials + summer annuals + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	annual/biennial/pluriennial	1
h (pluriennial-hapaxanthic) - p (pluriennial-pollakanthic)	perennials + summer annuals + strict monocarpic bi-annuals and poly-annuals + poly-annuals 5-50 years (medium-lived perennials)	annual/biennial/pluriennial	1
a (annual)	perennials + summer annuals + winter annuals	annual/pluriennial	1
b (biennial) - p (pluriennial-pollakanthic)	perennials + summer annuals + winter annuals	annual/biennial/pluriennial	1
b (biennial) - h (pluriennial-hapaxanthic)	perennials + summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
p (pluriennial-pollakanthic)	perennials + winter annuals	annual/pluriennial	1
p (pluriennial-	perennials + winter annuals + poly-annuals	annual/pluriennial	1

pollakanthic)	> 50 years (long-lived perennials)		
a (annual) - b (biennial)	perennials + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
b (biennial)	perennials + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
b (biennial) - h (pluriennial-hapaxanthic)	perennials + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
a (annual) - b (biennial)	poly-annuals < 5 years (short-lived perennials)	annual/biennial/pluriennial	1
b (biennial)	poly-annuals < 5 years (short-lived perennials)	biennial/pluriennial	1
b (biennial) - p (pluriennial-pollakanthic)	poly-annuals < 5 years (short-lived perennials)	biennial/pluriennial	1
p (pluriennial-pollakanthic)	poly-annuals < 5 years (short-lived perennials)	pluriennial	8
p (pluriennial-pollakanthic)	poly-annuals < 5 years (short-lived perennials) + poly-annuals 5-50 years (medium-lived perennials)	pluriennial	5
p (pluriennial-pollakanthic)	poly-annuals > 50 years (long-lived perennials)	pluriennial	3
p (pluriennial-pollakanthic)	poly-annuals > 50 years (long-lived perennials) + poly-annuals 5-50 years (medium-lived perennials)	pluriennial	2
a (annual) - p (pluriennial-pollakanthic)	poly-annuals 5-50 years (medium-lived perennials)	annual/pluriennial	1
b (biennial) - p (pluriennial-pollakanthic)	poly-annuals 5-50 years (medium-lived perennials)	biennial/pluriennial	1
p (pluriennial-pollakanthic)	poly-annuals 5-50 years (medium-lived perennials)	pluriennial	32
a (annual)	strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	2
a (annual) - b (biennial)	strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
b (biennial)	strict monocarpic bi-annuals and poly-annuals	biennial/pluriennial	14
b (biennial) - h (pluriennial-hapaxanthic)	strict monocarpic bi-annuals and poly-annuals	biennial/pluriennial	5
b (biennial) - p (pluriennial-pollakanthic)	strict monocarpic bi-annuals and poly-annuals	biennial/pluriennial	1
p (pluriennial-pollakanthic)	strict monocarpic bi-annuals and poly-annuals	biennial/pluriennial	1
a (annual) - b (biennial) - h (pluriennial-hapaxanthic)	strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	annual/biennial/pluriennial	1
b (biennial) - h (pluriennial-hapaxanthic)	strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	biennial/pluriennial	1
p (pluriennial-pollakanthic)	strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	biennial/pluriennial	1
a (annual)	summer annuals	annual	65
a (annual) - b (biennial) - p (pluriennial-pollakanthic)	summer annuals	annual/biennial/pluriennial	1
a (annual) - p (pluriennial-pollakanthic)	summer annuals	annual/pluriennial	1
p (pluriennial-pollakanthic)	summer annuals	annual/pluriennial	1
a (annual)	summer annuals + poly-annuals 5-50 years (medium-lived perennials)	annual/pluriennial	1

a (annual) - p (pluriennial-pollakanthic)	summer annuals + poly-annuals 5-50 years (medium-lived perennials)	annual/pluriennial	1
a (annual)	summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	9
a (annual) - b (biennial)	summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
a (annual) - b (biennial) - h (pluriennial-hapaxanthic)	summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
b (biennial)	summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
b (biennial) - p (pluriennial-pollakanthic)	summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	2
a (annual) - p (pluriennial-pollakanthic)	summer annuals + strict monocarpic bi-annuals and poly-annuals + poly-annuals 5-50 years (medium-lived perennials)	annual/biennial/pluriennial	1
a (annual)	summer annuals + winter annuals	annual	19
a (annual) - b (biennial)	summer annuals + winter annuals	annual/biennial	1
a (annual) - p (pluriennial-pollakanthic)	summer annuals + winter annuals + poly-annuals < 5 years (short-lived perennials)	annual/pluriennial	1
a (annual)	summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	4
a (annual) - b (biennial)	summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
a (annual) - b (biennial)	summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	annual/biennial/pluriennial	1
a (annual)	winter annuals	annual	6
a (annual) - b (biennial)	winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial	1
a (annual) - p (pluriennial-pollakanthic)	winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
b (biennial)	winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
NA	annuals	annual	5
NA	annuals + summer annuals	annual	3
NA	perennials	pluriennial	57
NA	perennials + strict monocarpic bi-annuals and poly-annuals	biennial/pluriennial	1
NA	perennials + summer annuals + strict monocarpic bi-annuals and poly-annuals + poly-annuals 5-50 years (medium-lived perennials)	annual/biennial/pluriennial	1
NA	poly-annuals 5-50 years (medium-lived perennials)	pluriennial	3
NA	strict monocarpic bi-annuals and poly-annuals	biennial/pluriennial	1
NA	strict monocarpic bi-annuals and poly-annuals + poly-annuals < 5 years (short-lived perennials)	biennial/pluriennial	1
NA	summer annuals	annual	26
NA	summer annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	6
NA	summer annuals + winter annuals	annual	1
NA	summer annuals + winter annuals + strict monocarpic bi-annuals and poly-annuals	annual/biennial/pluriennial	1
NA	winter annuals	annual	1
a (annual)	NA	annual	72
a (annual) - b (biennial)	NA	annual/biennial	7

a (annual) - b (biennial) - h (pluriennial-hapaxanthic)	NA	annual/biennial/pluriennial	1
a (annual) - p (pluriennial-pollakanthic)	NA	annual/pluriennial	4
b (biennial)	NA	biennial	10
b (biennial) - h (pluriennial-hapaxanthic)	NA	biennial/pluriennial	2
b (biennial) - p (pluriennial-pollakanthic)	NA	biennial/pluriennial	3
h (pluriennial-hapaxanthic) - p (pluriennial-pollakanthic)	NA	pluriennial	1
p (pluriennial-pollakanthic)	NA	pluriennial	284
p (pluriennial-pollakanthic) - p (pluriennial-pollakanthic)	NA	pluriennial	1
NA	NA	NA	917

12

13

## 14 II. Climate data and Random Forest analysis

15

16 For each plot, we collected daily mean temperature, daily minimum temperature, daily  
17 maximum temperature and daily precipitation sum between 2009 and 2017 from the  
18 ENSEMBLES dataset [4], using data from the nearest E-OBS station in France on a 0.25  
19 degree grid. Climate data were extracted using the R package climateExtract [5], and devtools  
20 [6]. We then calculated 10 climatic variables per plot, two using annual data (mean annual  
21 temperature and annual temperature anomaly) and eight using information from January to  
22 May (growing period of many plants): mean temperature, temperature anomaly, mean  
23 maximum temperature, number of heatwave days ( $T^{\circ}\text{C} > 27^{\circ}\text{C}$ ), freezing days ( $T^{\circ}\text{C} < 0^{\circ}\text{C}$ ),  
24 rainy days, drought days, and pluviometry. The temperature anomaly is the sum of the  
25 differences between the observed daily temperature and the mean temperature over a period  
26 on a site.

27

28 We then performed a Random Forest regression analysis to identify the climatic variable(s)  
29 explaining the greatest variability in MTP of plant communities. The Random Forest analysis

30 is a nonparametric technique derived from classification and regression trees. This method,  
31 which has been applied in various ecological studies [7,8], shows high accuracy and the  
32 ability to model complex interactions between variables. To perform the model, we defined  
33 two essential parameters: *mtry*, i.e. the number of variables to try at each split, and *ntree*, i.e.  
34 the number of trees to run. To maximize the accuracy of the Random Forest analysis, i.e.  
35 minimize the measure of the prediction error (Out Of Bag (OOB) error), *mtry* and *ntree* can  
36 be varied. We determined the parameter *mtry* thanks to the internal RF function TuneRF [R  
37 package randomForest, 9]; this function computes the optimal number of variables starting  
38 from the default (total number of variables/3 for regression) and tests half and twice this  
39 threshold for the value with the minimum OOB error rate. It is already known that a *mtry* of 1  
40 can produce good accuracy [9,10], but it is recommended to include at least two variables to  
41 avoid using also the weaker regressors as splitters [11]. Here, even if the best accuracy was  
42 obtained for a *mtry* of 1, we performed the Random Forest regression analysis with a *mtry* of  
43 2 following Grömping [11]. The *ntree* parameter was set to 1000 to obtain stable results.

44 Variable importance of the 10 climatic variables (i.e. the mean annual temperature, the annual  
45 temperature anomaly, and eight variables estimated from January to May: mean temperature,  
46 temperature anomaly, mean maximum temperature, number of heatwave days, freezing days,  
47 rainy days, drought days, and pluviometry) was estimated as the total decrease in node  
48 impurities, measured by residual sum of squares from splitting on the variable, averaged over  
49 all trees.

50 Finally, as a result of the Random Forest regression analysis, we selected the annual mean  
51 temperature, the most relevant climatic variable by ranking the variables according to their  
52 importance measure (Table S2).

53 We performed a linear regression of the annual mean temperature against years to describe the  
54 temporal trend of climate change on the sampled plots of the study. We included geographical

55 coordinates in the model to account for residual spatial autocorrelation. We recovered one  
56 slope per square, since climate data were only available at that scale; all plots within a scale  
57 were thus attributed the same temporal trend in climate data, describing the temporal trend of  
58 annual mean temperature.

59

60 Table S2. Importance measures of the 10 climatic variables resulting from a Random Forest  
61 regression analysis and explaining the share of variability of the MTP of plant communities.

<b>Climatic variables</b>	<b>Importance</b>
Annual mean temperature	725
Number of freezing day from January to May	365
Mean temperature from January to May	342
Mean maximum temperature from January to May	243
Number of drought day from January to May	204
Pluviometry from January to May	160
Annual temperature anomaly	135
Temperature anomaly from January to May	133
Number of rainy day from January to May	99
Number of heatwave day from January to May	55

62

63

### 64 **III. Estimation of temporal trends in mean temperature preference and species** 65 **occurrence**

66 We performed Bayesian hierarchical models to estimate the temporal trend in MTP of plant  
67 communities (1) at a national scale and within Île-de-France, (2) using either abundance data  
68 or presence/absence data and (3) of annuals vs. perennials species. The underlying model  
69 describes the MTP value as a function of year for all plant communities. We assumed that  
70 MTP of plant communities was normally distributed, with a mean that depended linearly on  
71 year, geographical coordinates and survey square, and constant variance. The linear model  
72 was the following:

73  $MTP_{ijk} = m + a*year_i + b*lat_{ijk} + c*long_{ijk} + d*lat_{ijk}^2 + e*long_{ijk}^2 + Square_j + \sigma_{ijk}^2$   
74 where  $MTP_{ijk}$  is the mean temperature preference of the plant community in plot  $k$  of square  $j$   
75 and year  $i$ ,  $m$  is the intercept,  $lat$  and  $long$  are the latitude and longitude of the plot,  $Square$  is  
76 the random effect of square with variance  $\sigma_s^2$  and  $\sigma_{ijk}^2$  is the residual variance.

77 We also performed Bayesian hierarchical models to generate estimates of the temporal trend  
78 in common species abundance, as estimated at the 10m<sup>2</sup> plot level by the number of 1m<sup>2</sup>  
79 quadrats in which these species were observed. We selected the 550 most common species  
80 that were observed at least four out of nine years and in at least ten squares. We modeled  
81 species abundance assuming a binomial distribution with  $n = 10$  trials and a logit-transformed  
82 probability  $p$  depending linearly on year, survey plot, square and geographical coordinates as  
83 follows:

$$84 \text{logit}(p_{ijk}) = m + a*year_i + b*lat_{ijk} + c*long_{ijk} + d*lat_{ijk}^2 + e*long_{ijk}^2 + Square_j + Plot_k$$

85 where  $p_{ijk}$  is the probability to observe the species in each 1m<sup>2</sup> square of plot  $k$  of square  $j$  and  
86 year  $i$ ,  $m$  is the intercept,  $lat$  and  $long$  are the latitude and longitude of the plot,  $Square$  is the  
87 random effect of square with variance  $\sigma_s^2$ ,  $Plot$  is the random effect of plot with variance  $\sigma_p^2$ .

88 For all Bayesian hierarchical models, we chose only non-informative priors, sampled from  
89 Gaussian distributions with a mean of 0 and a variance of  $10^{10}$  for most parameters, and  
90 gamma distributions with shape parameter  $k = 0.001$  and rate  $\beta = 0.001$  for precision (inverse  
91 of variance) parameters. Parameters were estimated using WinBUGS [12]. Four chains were  
92 run using priors to draw 100,000 samples, discarding the first 50,000 iterations. Samples were  
93 thinned by 1 in 10 to reduce autocorrelation and obtain mean trends from the remaining  
94 posterior distributions. Convergence was checked using the Rhat statistics (all Rhat < 1.2) and  
95 WinBUGS traceplots (superposition of the 4 chains). Posterior mean community and species  
96 trends were interpreted as different from zero when 95 % of the highest posterior density  
97 interval did not include zero.



99 **IV. R packages used**

100

101 All analyses were performed using R version 3.2.4 [13] and R packages *Taxonstand* version  
 102 2.1 [14], R packages *TR8* [15], R packages *climateExtract* version 0.2.0 [5], R packages  
 103 *randomForest* [9], R packages *caret* version 6.0-78 [16], R packages *plotmo* version 3.3.4  
 104 [17], R packages *R2jags* version 0.5-7 [18], R packages *mcmcplots* version 0.4.2 [19], R  
 105 packages *car* [20], R packages *lme4* [21], R packages *nlme* version 3.1-131 [22], R packages  
 106 *dplyr* version 0.7.3 [23], R packages *reshape2* [24], R packages *devtools* version 1.13.4 [6], R  
 107 packages *effects* version 2.1.0 [25], R packages *ggplot2* version 2.1.0 [26], R packages  
 108 *ggthemes* version 3.4.0 [27], R packages *gridExtra* version 2.3 [28]. Plant functional traits  
 109 were collected using the R package *TR8* [15].

110

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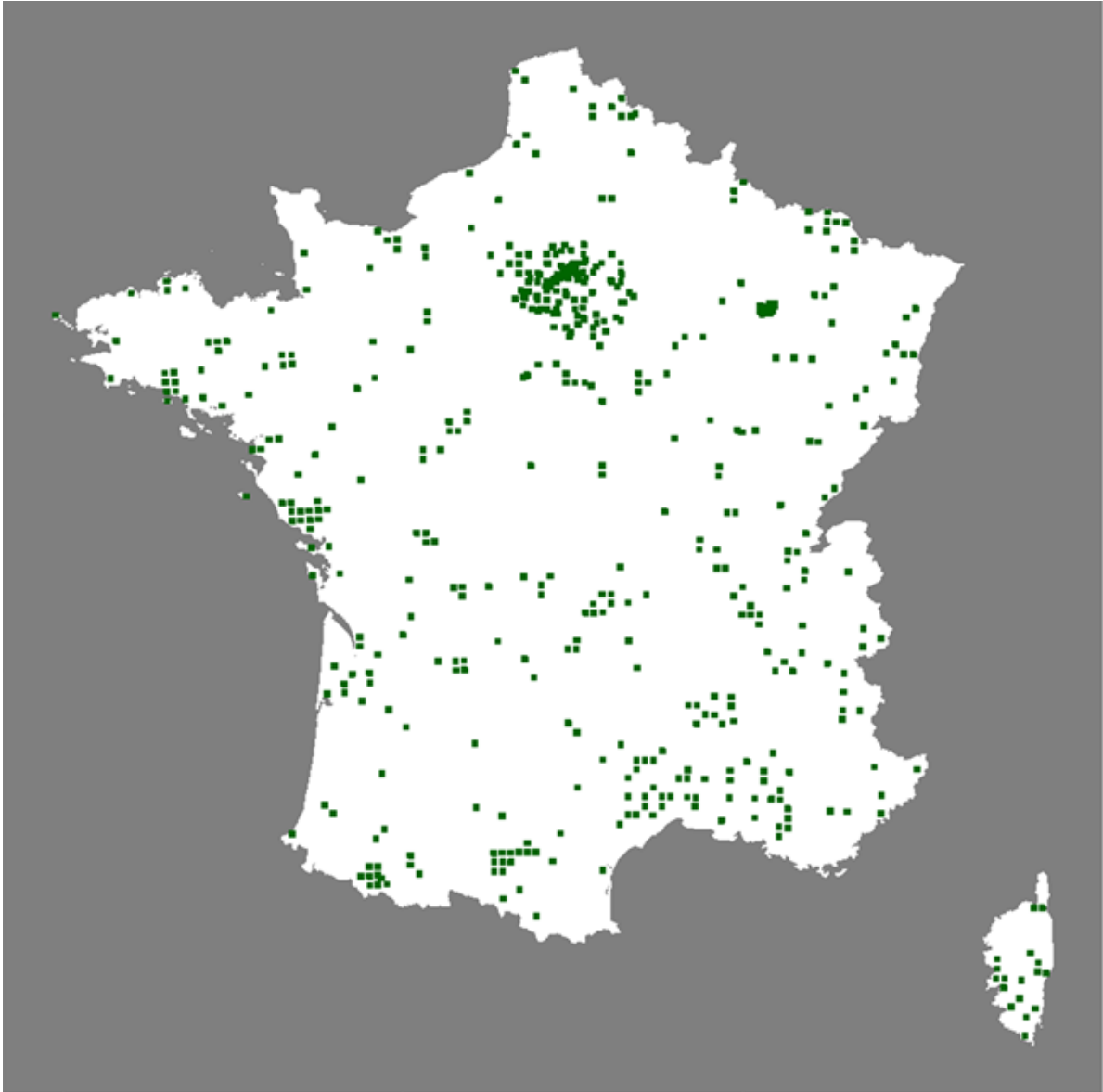
163

164 Table S3. Type II Anova results for the linear mixed models testing  
165 for a temporal change in the mean annual temperature over time.

<b>Fixed effects</b>	<b><i>n</i></b>	<b>Estimate</b>	<b>Standard error</b>	<b>Chisq</b>	<b><i>P</i> value</b>
Year	7854	0.1094	0.0032	1203.82	<0.001
Longitude	7854	3.9921	0.7605	27.56	<0.001
Latitude	7854	-7.5612	1.9008	15.82	<0.001
Longitude*Longitude	7854	-0.0318	0.0096	10.89	<0.01
Latitude*Latitude	7854	0.0819	0.0204	16.15	<0.001
Longitude*Latitude	7854	-0.0872	0.0158	30.30	<0.001

166

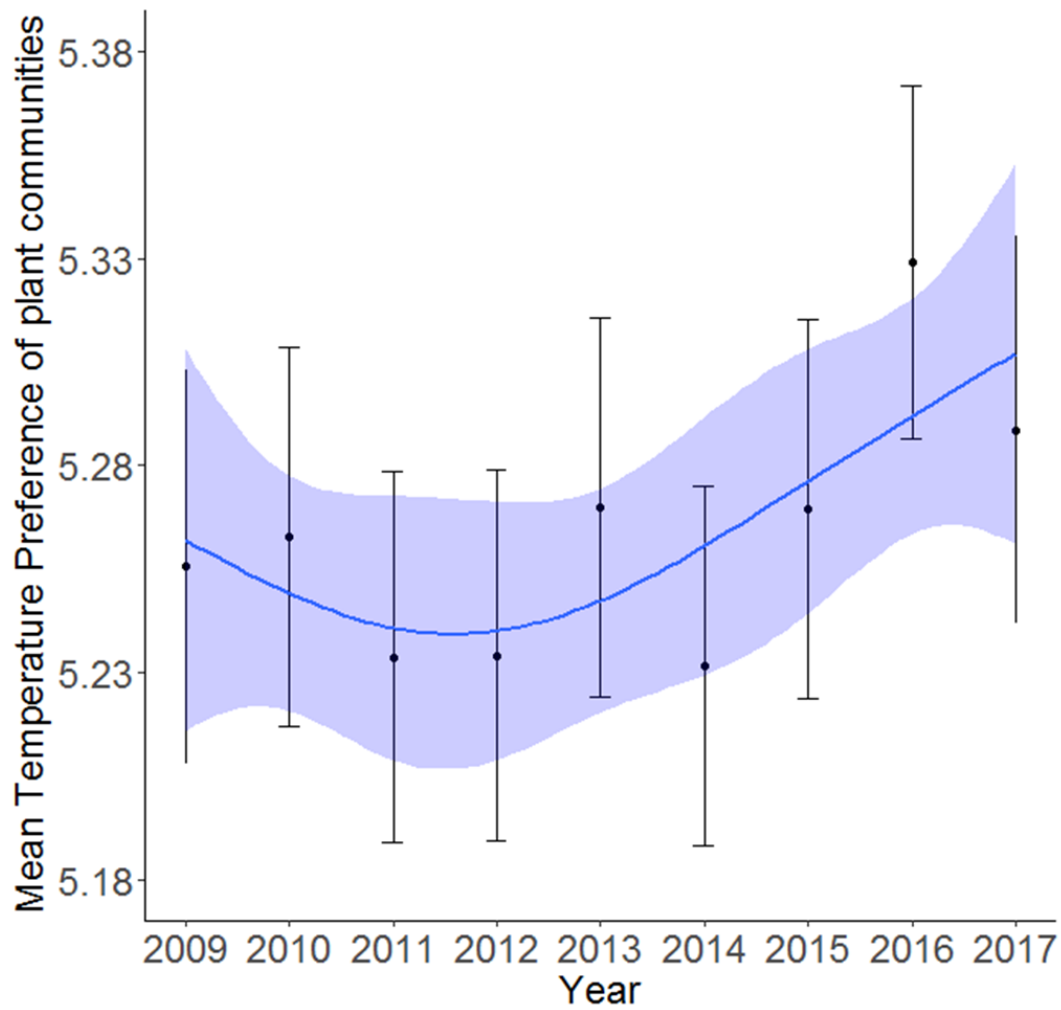
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169 Figure S1. Spatial distribution of the Vigie-flore survey squares.

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171

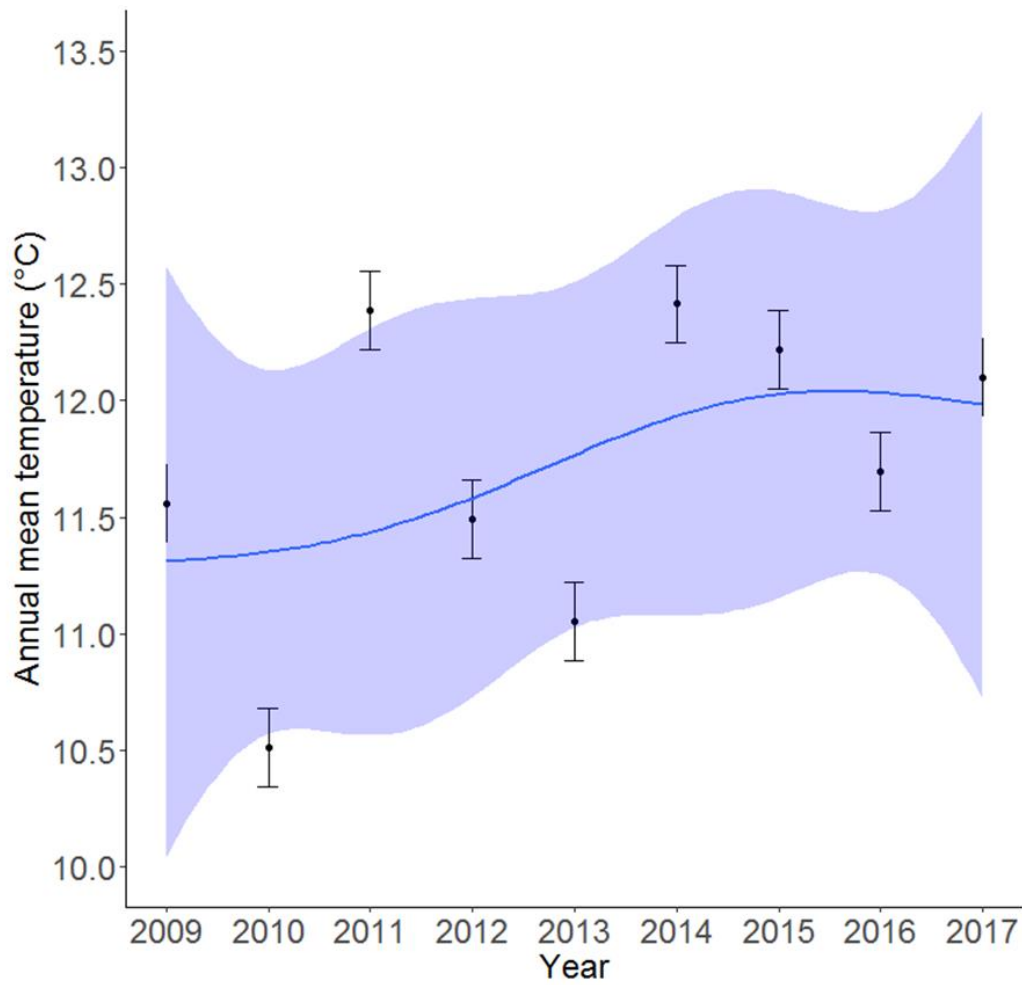
172 Figure S2. Regional temporal trend in MTP of plant communities from 2009 to 2017

173 calculated with abundance data in Île-de-France. The blue line is a generalized additive model

174 estimate of the temporal trend, with its associated standard error (blue band). The black dots

175 and error bars correspond to the inter-annual variations of the variable, with its associated

176 standard error.



177

178 Figure S3. Temporal trend of annual mean temperature estimated from 2009 to 2017 on  
179 sampled sites in France. The blue line is a generalized additive model estimate of the temporal  
180 trend, with its associated standard error (blue band). The black dots and error bars correspond  
181 to the inter-annual variations of the variable, with its associated standard error.

182

183 List S1. The 321 Vigie-flore volunteers involved in the wild flora monitoring:

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185 Anglaret Cédric, Arnould Loic, Arondel Bruno, Association Asterella, Association Les Amis  
186 Du Jardin Botanique Littoral Paul Jovet, Association Les Marais Du Verdier, Association Tela  
187 Botanica, Aupoix Alain, AUTRET Françoise, Avenas Élise, Avril Damien, Balard Yvette,  
188 Balloux Gabriel, Baradat Mathilde, Barbet-Massin Morgane, Barreda Flavie, Bastin André,  
189 Batsere Françoise, Baudet Nicolas, Baurens-Franc Christophe, Bebin Clément, Bégin Sophie,  
190 Benezet Ruddy, Béraud Jean-Marc, Berger Romain, Biancardini Famille, Bircker Loic,  
191 Bodiguel Brigitte, Boisbineuf Christelle, Boissier Marc, Bonnafoux Florence, Bonnafoux  
192 Vincent, Bonneau Pierre, Bonneil Philippe, Bos Nathalie, Bosquet Christian, Bouard Hervé,  
193 Boudies Catherine, Bouffard Frédéric, Bouligand Sandrine, Boutegege Serge, Bouveris  
194 Nicole, Bouvier Chantal, Brajon Émilie, Brasseur Jean-Emmanuel, Breuil Anne, Briand  
195 Françoise, Brin Antoine, Buckvald Nathalie, Bultel Yvan, Burchianti Mireille, Busch  
196 Geneviève, Callewaert Pierre, Calme Catherine, Calmet Claire, Camenen-Houdayer Danièle  
197 Canel Celie, Canevet Marie-Françoise, Caron Matthieu, Casenave Isabelle, Catieau Alexis,  
198 Causeur Nicole, Cellier Pierre, Chabanois Gérard, Chamaux Jérôme, Chammard Émilie,  
199 Chappert-Bessiere Joceline, Chapuis Gabriel, Chardinal Sophie, Chatelain Marion, Cherrier  
200 Camille, Chevalier Adélie, Chevalier Richard, Chiffolleau Bertrand, Cholet Jérémie, Clochard  
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204 Aymeric, De La Brosse Caroline, Delafoy Arielle, Delisle Pascal, Delphin Chantal,  
205 Deschatres Aurelien, Desvois Régine, Devers Florence, Dezerald Hervé, Domenech Boris,  
206 Douard Anne, Douarre Marie, Druez Flora, Dubosc Sarah, Duffaut Philippe, Dumas  
207 Françoise, Dumez Nicolas, Durand Alexandre, Duron Quiterie, Duytschaever Francis, Engel



208 Geneviève, Eriksson Marion, Esnault Sarah, Etcheverry Georgette, Farcat Charlotte, Fatz  
209 Pierre-Marie, Féral Camille, Fernandes Val, Filleur Lucas, Fournel Isabelle, Fourvel Jean-  
210 Marc, Fried Guillaume, Galerme Jean Baptiste, Galerme Jean Pierre, Garnier Boudier Joanne,  
211 Gatto Claire, Gaudry Jérôme, Gauthier Jacques, Gelin Muriel, Gelmetti Anne Marie, Geneix  
212 Gilles, Georganidis Michèle, Germaine Clémence, Ghesquiere Jean-Christophe, Ghestem  
213 Murielle, Goguet Liselotte, Gombault Clémentine, Gorremans Jean-Luc, Gotteland Pierre,  
214 Gourdel Laurence, Gourlin Benjamin, Grange Milena, Grignon Céline, Guais Daniel,  
215 Guichard Bernard, Guiller Clémence, Guittet Jean, Haeffner Hugues, Haenggi Philippe,  
216 Hance Emmanuel, Happe David, Heuze Sylvère, Hillion Jeanne, Hubert Eric, Hugot Nicolas,  
217 Huve Rosalia, Indorf Marc-Frederic, Jacot Pierre-Alain, Jagoda Daniel, Jardin Botanique  
218 Besançon, Jargeat Patricia, Javaux Benjamin, Jaymond Delphine, Joset Henri, Jourdan  
219 Christine, Joyaux Sandrine, Jullin Franck, Kania Daniel, Laffargue Lucie, Lafon Céline,  
220 Lagier Anne-Marie, Lallemand Johann, Lambert Cécile, Lamouroux Paule, Lanciaux  
221 Maxime, Lantuejoul Eric, Larbouillat Annick, Lavialle Jeanne, Le Fur Patrick, Le Garrec  
222 Sandra, Leblanc Marie, Leclerc Catherine, Leduc Vinciane, Lefebvre Manon, Lekieffre Alix,  
223 Lemoine Yves, Lemouzy Claire, Leneveu Justine, Lenne Patricia, Lepage Elen, Lequeuvre  
224 Charly, Lerat Christine, Lerat Elodie, Lesné Sébastien, Leveslin Gérard, Leviol Isabelle,  
225 Levy-Leonesio Patricia, Locqueville Jonathan, Lodziak Michel, Lonchamp Jean-Pierre,  
226 Longeot Yves, Luciani Bernadette, Luigi Catherine, Mace Bruno, Machon Nathalie, Magrou  
227 Nathalie, Maguet Nicole, Marchal Pierre-Luc, Marsteau Christine, Martin Gabrielle, Martin  
228 Hilaire, Martin Nicolas, Martinelli Marion, Masonnave François, Massouh Jacques, Master  
229 Promo, Mathieu Daniel, Mathieu Joël, Maurel Noëlie, Meyer Claire-Lise, Michel Prisca,  
230 Mistarz Margaux, Mollereau Aurore, Monferrand Christophe, Monthus Alain, Montpiéd  
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233 Pierre, Neveu Dany, Nicolas Dole, Nonglaton Gilles, Noraz Éloïse, Onf Bergerie, Ostermann  
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244 Dominique, Tauran Julien, Texier-Pauton Élodie, Thébault Ludovic, Thiebaut David, Thys  
245 Évelyne, Tinchant Anne, Tinguay Hugues, Torre Fabrice, Tositti Arnaud, Toty Anne, Truong  
246 Minh-Xuan, Turcati Laure, Tzvetan Gwladys Mai, Valette Nicolas, Van Panhuys-Sigler  
247 Michèle, Vérite Vincent, Viallon Camille, Vidal Rodolphe, Videlot Vincent, Vilard Vanessa,  
248 Villeneuve Aurélie, Virton-Lavorel Anthony, Wahl Marie-Salomé, Waligorski Stanislas,  
249 Wernert Dominique, Wolff Anne, Ybres Nicolas.