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1 **High-resolution assessment of French grassland dry matter and nitrogen yields**

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16 **Abstract**

17 Grasslands offer many environmental and economic advantages that put them at the heart of
18 future sustainable ruminant production systems. This study aimed to quantify and map the dry
19 matter yield (DMY) and nitrogen yield (NY) of French grasslands resulting from cutting and
20 grazing practices, based on the existing diversity of grassland vegetation, management, soil
21 and climate conditions, using a research version of the STICS crop model called PâturSTICS.
22 This model simulates daily dry matter (DM), nitrogen (N) and water fluxes involved in the
23 functioning of grasslands and crops in response to management and environmental conditions.
24 It was improved to represent deposition of animal waste on grassland soils during grazing and
25 to simulate DM production and N content of grasses and legumes more accurately.
26 Simulations were performed for locations across France on a high-resolution grid composed
27 of pedoclimatic units (PCU) obtained by combining the spatial resolutions of climate and soil.
28 The main grassland types and associated management types were determined for each PCU
29 and then simulated over 30 years (1984-2013). Using the simulated values, predictive
30 metamodels of annual grassland DMY and NY were developed from easily accessible
31 explanatory variables using a random forest approach. Annual model predictions were
32 aggregated and averaged at the PCU scale, then compared to regional observations. Predicted
33 DMY agreed with available observations, except in semi-mountainous and mountainous
34 regions, where PâturSTICS tended to overpredict DMY, probably because it ignores effects of

35 snow, frost and slope, and due to how it represents effects of temperature and water stress on
36 plant growth. According to results, three-quarters of French grasslands produce and export at
37 least 7.6 t DM ha⁻¹ yr⁻¹ and 172 kg N ha⁻¹ yr⁻¹, respectively. One-quarter of French grasslands
38 produce and export at least 10.7 t DM ha⁻¹ yr⁻¹ and 254 kg N ha⁻¹ yr⁻¹, respectively. The latter
39 are located mainly in north-western France, the north-western Massif Central, the French Alps
40 and the western Pyrénées, all of which have environmental conditions favourable for grass
41 growth. The metamodels developed are interesting proxies for PâturSTICS' predictions of
42 grassland DMY and NY. Our results provided valuable knowledge that promotes better use of
43 the potential forage production of French and European grasslands to improve protein self-
44 sufficiency and N fertilisation management in ruminant livestock systems.

45
46 **Keywords:** grassland, modelling, STICS, dry matter yield, nitrogen yield, France

47 48 **1. Introduction**

49 Ecosystem services of grasslands are increasingly promoted, in particular their ability to
50 reduce water pollution by nitrates (Cameron et al., 2013; Di and Cameron, 2002) and mitigate
51 climate change by storing carbon in their soils (Paustian et al., 2016; Soussana et al., 2010).
52 Grasslands are also of interest because of their fundamental provisioning service of producing
53 high-quality and protein-rich food products *via* ruminants, which can produce these products
54 from this protein resource that humans cannot digest directly. Grasslands are also able to
55 extract and export more nitrogen (N) from the environment than other crops (Delaby and
56 Lucbert, 1999), which makes them an interesting land use to manage N fertilisation and
57 decrease N emissions to the environment. Despite the advantages they provide, grasslands
58 may be undervalued in some French regions. Mapping French herbage dry matter (DM) and
59 N yields could therefore help assess the value of local grasslands and promote better use of
60 these areas, with positive consequences for the environment and for the self-sufficiency of
61 ruminant farms in supplying DM and protein to their animals (Brocard et al., 2016; Capitain
62 et al., 2003).

63 A process-based modelling approach is required to simulate grassland DM yield (DMY) and
64 N yield (NY) at a national scale. Several process-based models for temperate grasslands have
65 been developed since the 1990s in countries in north-western Europe. These models are used
66 mainly to address grassland productivity and greenhouse gas emissions, using either a multi-
67 model ensemble (Ehrhardt et al., 2017; Sándor et al., 2017) or a single-model approach (e.g.
68 Graux et al., 2013). Few of them are able to simulate accurately both herbage growth and N

69 and water fluxes in response to soil, climate and management drivers, including grazing.
70 Previous modelling studies have predicted current grassland productivity at European or
71 French scales, although they simplified representation of grassland processes and
72 management and/or provided model predictions at a low spatial resolution (Chang et al.,
73 2015; Huyghe et al., 2014; Ruget et al., 2006), sometimes without representing soil processes.
74 The process-based crop model STICS (Brisson et al., 2003) was chosen for this study as it
75 was found a valuable tool for studying effects of changes in agro-ecosystems on DMY over a
76 wide range of agropedoclimatic conditions in France (Coucheney et al., 2015). STICS also
77 represents soil and plant processes robustly for a range of crops including temporary and
78 permanent grasslands (Ruget et al., 2006), although it does not consider animal urine and
79 faeces deposition (i.e. “returns”) or fate.

80 The objective of this study was to provide a spatially explicit view of grassland DMY and NY
81 in France, using a mechanistic modelling approach and considering as much as possible the
82 existing variety of pedoclimatic, vegetation and management situations, and to derive
83 metamodels from annual STICS predictions that could be transferable to stakeholders.
84 Metamodels are able to simplify process-based models and predict the same outputs
85 accurately using fewer input data, provided they make predictions within the boundaries of
86 their validity domain (Luo et al., 2013). The first step was to improve STICS’ ability to
87 simulate DM and N fluxes in grasslands, in particular by representing animal returns during
88 grazing, and by comparing its predictions to a database of observed grassland yields.

90 **2. Materials and methods**

91 **2.1. Description of the PâturSTICS soil-crop model**

92 STICS is a deterministic process-based and generic soil-crop model. STICS simulates
93 consequences of changes in pedoclimatic conditions and management on crops and grassland
94 production (amount and quality) and the environment (water and air quality) (Brisson et al.
95 2003, 2009). It simulates, in a daily time step, the main soil-plant processes associated with
96 plant phenology, shoot and root growth, yield formation, microclimate, water and N balances
97 and, if desired, agricultural practices. Crop development is based calculating a daily thermal
98 index from daily mean crop temperature and basal, optimum and maximum temperature
99 thresholds for crop development. This thermal index can be decreased by sub-optimal
100 photoperiods, unattained vernalisation requirements or effects of water and nitrogen stresses.
101 The sum of the daily thermal index (expressed in degree days) is used to define crop

102 phenological stage. Potential crop production is simulated by converting the radiation
103 intercepted by photosynthetic parts of the plant into biomass using Beer's law for grasslands
104 (Varley Grancher et al., 1989) and the concept of radiation use efficiency (Monteith, 1972;
105 1977). This potential is modulated by effects of crop temperature, water and N stresses,
106 atmospheric carbon dioxide (CO₂) concentration, and potential remobilisation of crop
107 reserves. Crop N content depends on shoot biomass accumulation, root system development,
108 soil N availability and, for legumes only, biological N₂ fixation (BNF). Crop N demand is
109 derived from the maximum N dilution curve (Justes et al., 1997; Lemaire and Gastal, 1997),
110 and crop N uptake is calculated daily as the minimum of crop N demand or soil N availability.
111 N inputs to the soil-plant system include N fertilisation, BNF and precipitation. N outputs
112 include N exports associated with plant defoliations and N emissions to air and water. STICS
113 also simulates internal N fluxes (e.g. litter fall, soil organic matter mineralisation and
114 immobilisation). STICS represents the most common agricultural practices (e.g. ploughing,
115 sowing, fertilisation, harvest) and some grassland-specific practices (cutting). For the present
116 study, a research version of STICS (derived from the trunk version 8.3.1, release 1276), called
117 PâturSTICS, was developed to represent animal returns to the soil in grazed grasslands,
118 following the concepts of Faverdin and Vérité (1998). Appendix A provides PâturSTICS'
119 new equations.

121 2.2. Data collection and processing

122 2.2.1. Weather and soil conditions: definition of the spatial resolution of simulations

123 The weather information required to run STICS was provided by the mesoscale atmospheric
124 analysis system (SAFRAN) (Durand et al. 1993). Soil information from the 1:1,000,000-scale
125 soil geographic database of France (Jamagne et al., 1995) was used to parameterise STICS'
126 soil parameters. In this database, soil information is available in soil mapping units (SMU),
127 which are areas which consist of 1-6 soil types whose percentage within the SMU is known.
128 STICS soil parameters were provided by the INRA InfoSol lab. Soil organic N content in the
129 topsoil (0-30 cm) was estimated according to Mulder et al. (2015) for both temporary and
130 permanent grasslands. Soil types with an organic texture such as histosols were excluded from
131 the simulation plan (i.e. 1% of soils, 0.3% of simulations), as they lay outside STICS' validity
132 domain. Similarly, according to STICS' limits, soil organic N content in the topsoil was
133 limited to 0.4% (i.e. soil organic matter content < 7.6%; Graux et al., 2017).

134 Corsica and overseas French regions were excluded from simulations as they were not
135 included in the databases used. Combining weather and soil information at the SMU level led

136 to definition of 30,966 pedoclimatic units (PCU), each of which was no larger than 6400 ha
137 (Figure 1). Only PCU with utilised agricultural area (UAA) greater than 100 ha and with
138 grassland area greater than 10% of UAA were considered in the simulation plan. This led to
139 the definition of 15,032 PCU (i.e. half of the total number of PCU), thus excluding four
140 highly urbanised departments (Hauts-de-Seine (department code 92), Paris (75), Seine-Saint-
141 Denis (93) and Val-de-Marne (94)). Overall, 21 of 27 former (pre-2016) French
142 administrative regions and 90 of 101 French departments were simulated, with coverage
143 varying by region and department (Table 2).

144 Simulations were performed for a 30-year period (1984-2013) across France on this high-
145 resolution grid. Since slope was not available, its influence on surface water run-off was
146 ignored. Atmospheric CO₂ concentration was kept constant at its default value of 350 ppm, as
147 changing it to its mean value from 1984-2013 (i.e. 413 ppm) would have had little influence
148 on model DMY and NY predictions (due to the equations used in STICS).

149

150 2.2.2. Grassland types and duration

151 A typology of four grassland types was defined according to their level of N input self-
152 sufficiency (Table 1). Types 1 and 4 referred to permanent grasslands (never sown and at least
153 5 years old), managed extensively (e.g. most mountain grasslands) or intensively,
154 respectively. Type 2 referred to temporary grasslands sown with pure legumes (e.g. lucerne
155 (*Medicago sativa*)). Type 3 referred to temporary grasslands sown with pure grass or grass-
156 legume mixtures. As the current version of STICS cannot simulate grass-legume mixtures,
157 each species was simulated independently, and their results were aggregated later, assuming a
158 constant legume percentage of 30%. One single parameterisation each was used to represent
159 grasses and legumes in permanent or temporary grasslands, including grass-legume mixtures.
160 The grass species was parametrised similar to species such as tall fescue (*Festuca*
161 *arundinacea*) and orchard grass (*Dactylis glomerata*), while the legume species was
162 parametrised as lucerne (as clover parameterisation was not available in the STICS version
163 used).

164 The percentage of each grassland type within each PCU and the duration of temporary
165 grasslands were estimated by combining information about the use of agricultural fields from
166 the Graphical Register of Fields, derived from farmers' Common Agricultural Policy
167 declarations (available since 2004), and information from the last agricultural census (2010).
168 According to this information, the mean duration of temporary grasslands was ca. 3 years
169 (standard deviation = 1 year). Permanent grassland duration was arbitrarily set to 5 years.

170 **2.2.3. Planned management**

171 Grassland management for each grassland type in a given PCU was defined according to the
172 French ISOP system (Ruget et al., 2006), which provides this information at the scale of small
173 agricultural regions (i.e. areas with homogeneous grassland management and production
174 level; Hentgen, 1982). The diversity of grassland management in the ISOP system was
175 summarised into 30 management types (M, Figure B.1 in Appendix B) derived from a survey
176 about French grassland-specific agricultural practices (SCEES, 2000) and the expertise of
177 INRA scientists working on grasslands. Management descriptions included grassland use
178 (cutting for hay or silage, grazing, number and timing of grassland uses per year) and N
179 fertilisation practices (timing and amount of N applications). N fertiliser can be applied at the
180 end of winter and again after plant defoliation(s). To represent regional and inter-annual
181 diversity in management, the timing of operations is expressed in degree days and compared
182 to the sum of the daily thermal index for crop development (as defined in section 2.1).
183 Agricultural practices range from extensive (one cut per year) to intensive practices (up to 10
184 grazing periods per year).

185 The severity of grazing and cutting management is modelled using parameter values of
186 residual plant biomass and leaf area index after plant defoliations. To trigger planned cutting
187 and grazing events, the model checks that the degree days defined by the user have been
188 reached and that the corresponding standing biomass is greater than or equal to a minimum
189 harvestable biomass also defined by the user (Table B.2 in Appendix B). These decision rules
190 determine whether the planned cutting, grazing and associated fertilisation events are
191 performed or not. When practices in the ISOP system were considered less frequent than
192 current practices, their frequency was increased, thus improving representation of
193 consequences on the quality of ingested herbage and animal N returns to the soil.

194 Observed annual fertilisation was 0-200 kg N ha⁻¹ yr⁻¹ of ammonium nitrate; however, the
195 simulated amounts of mineral N applied represented both mineral and organic N fertilisation
196 practices. Extensive permanent grasslands (Table 1, type 1) were assumed to be only grazed
197 and not fertilised (M15, Figure B.1 in Appendix B). Pure legume swards (Table 1, type 2)
198 were associated with only five management types (M8, M12, M19, M21 and M24, Figure B.1
199 in Appendix B).

200

201 **2.3. Design and running of simulations**

202 The simulation design was built in collaboration with the EFESE study (Thérond et al., 2017).
203 To decrease the number of simulations, only the main soil types and grassland types within

204 each PCU were considered: the smallest number of soil types (from one to three) that covered
205 at least 90% of each SMU were kept in the simulation plan. Similarly, only one type of
206 grassland was selected if it covered more than 50% of a PCU. When necessary, two grassland
207 types were chosen if each covered at least 10% of a PCU. Simulations performed within each
208 PCU were therefore a combination of one climate over 30 years, 1-3 soil types and 1-2
209 grassland types, each with 1-18 management types (Figure 1). Combining all information
210 about weather and soil conditions, grassland types and associated management types led to a
211 maximum of 1,262,575 simulations, each combining one PCU, one grassland type, one
212 management type and one sequence of several years, corresponding to the grassland duration.
213 When grouping the successive grassland sequences that would occur during the 1984-2013
214 period, the number of simulations fell to 173,260. This huge number of simulations was
215 launched on the GenoToul Bioinformatics hardware infrastructure, using the STICS crop
216 model embedded in the INRA modelling platform (Bergez et al., 2013). To decrease the
217 volume of outputs and calculation time, model predictions were generated at an annual scale.

2.4. Analysis of model predictions

219 R software (v. 3.4.4) (R Core Team, 2019) was used to process and analyse data (main R
220 packages: *caret*, *data.table*, *dplyr*, *plyr*, *ranger* and *tidyr*), and generate figures (main R
221 packages: *ggplot2*, *maptools* and *rgdal*).

2.4.1. Analysis of aggregated results per pedoclimatic unit

224 Model predictions from the establishment period of grasslands (i.e. first year of the grassland
225 sequence) were excluded from analysis, as the low predicted DMY these years did not
226 represent established grasslands. Mapping mean predictions at the national scale first required
227 aggregating predictions to one mean value per PCU. Predictions were aggregated by
228 calculating weighted averages of DMY and NY, using the percentage of each input factor
229 addressed in this study: soil type, management type, grassland type and climate year. When a
230 PCU contained a grass-legume mixture (Table 1, type 3), a weighted average of model
231 predictions for grasses and legumes was first calculated. We then calculated, in this order, a
232 weighted average of soil types, management types, grassland types and finally, climate years.
233 Aggregated results per PCU were then mapped to provide an average picture of model
234 predictions at national, regional and departmental scales. Much information about simulated
235 grassland DM and N fluxes was available from model predictions. In this article, we focus on
236 predicted DMY and NY potentials.

2.4.2. Evaluation of accuracy of results

To assess the accuracy of PâturSTICS' developments, its predictions of grazing features were compared to literature data and expertise. These features include the proportion of DMY that is grazed vs. cut, the number of grazing days, expressed in livestock unit (LSU) grazing days per ha of grassland per year (Peyraud and Delaby, 2008), and animal N returns. An LSU grazing day (hereafter referred to as "grazing day") equals one day's grazing by a standard dairy cow. Grazing days were calculated by dividing the total herbage removed by animals by daily animal intake, which was set to 17 kg DM LSU⁻¹ grazing day⁻¹. We also analysed other annual management variables (N fertilisation, number of grass defoliations) that were influenced by the model's decision rules.

To assess the accuracy of model DMY predictions, mean predictions were calculated per department and region and compared to 12,739 field-growth estimates per 10-day period from a French network covering four administrative regions (Auvergne, Bretagne, Franche-Comté and Pays de la Loire, Graux et al., 2017). In each region of this network, herbage growth is measured every 10 days in at least 20 grazed paddocks of commercial farms by technicians from several livestock advisory services. Herbage biomass is estimated from herbage height measured with a rising-plate meter and from herbage density, equal to either a constant annual value (250 kg DM ha⁻¹ cm⁻¹) or seasonal values (source: Defrance et al., 2004). Herbage N content is not usually measured in this network. The quality of such observations thus depends on assumptions about herbage density. However, this network represents the diversity of grassland situations within a given region better than other observations available from local and sometimes short-term experimental sites. In each region, several thousand validated data points from 6-11 years during the 1997-2014 period (680, 3397, 5161 and 3501 data points in Auvergne, Bretagne, Franche-Comté and Pays de la Loire, respectively) were averaged per 10-day period to build regional herbage growth profiles. Several regional herbage growth profiles were defined according to discriminating factors: elevation in Auvergne, weather conditions in Bretagne, soil depth in Franche-Comté and latitude in Pays de la Loire. From these profiles, it was possible to calculate mean observed regional DMY.

2.4.3. Development of metamodels

Metamodels of annual grassland DMY and NY were developed from annual non-aggregated PâturSTICS predictions. The latter were supplemented by summary information about the textural class of the topsoil and the water holding capacity of the main soil type in each PCU.

272 To develop metamodels, we used a random forest (RF) approach that was found to be more
273 accurate in predicting the annual yields predicted by process-based models than the usual use
274 of multiple linear regressions (e.g. Jeong et al., 2016). RF is a binary-tree-based machine-
275 learning method that can be used for both classification and non-linear regression (Breiman,
276 2001). To train RF regression models, a forest of decision trees is grown. Each tree is built
277 using a random subset of *mtry* explanatory variables and a sample of source data that is
278 obtained by a random two-thirds sampling with replacement of source data. The remaining
279 one-third, called *out-of-bag* data, is set aside by the RF algorithm to internally validate
280 prediction quality of the tree. For each tree, the data are recursively split into the two most
281 homogeneous subsamples based on a threshold value of one explanatory variable identified to
282 best split the data. The split points are commonly called *nodes*. The source data are
283 bootstrapped to randomly generate a large number of random trees that are averaged and then
284 used to predict the continuous variable. The importance of explanatory variables in the
285 prediction is assessed by how often they were selected for the splits and how much they
286 increase the prediction error of the average tree after permutation of their values.

287 Ten continuous variables were selected to be both *a priori* explanatory of grassland DMY and
288 NY and easily accessible to stakeholders, while avoiding correlations between variables. They
289 related to climate, soil, vegetation and grassland management (Table 3). “Age” refers to
290 grassland age during the simulation of a grassland sequence and varied from one year to the
291 maximum grassland duration). These variables were used for training RF models to predict
292 DMY and NY, using the R *ranger* package (Wright and Ziegler, 2017), which is particularly
293 suited for high-dimensional data. We used default algorithm values for the number of trees
294 (*num.trees* = 500), set the number of explanatory variables to one-third of all available
295 explanatory variables (*mtry* = 3), and restricted the minimum size of nodes to its default value
296 for regression models (*min.node.size* = 5). The variable importance available from the *ranger*
297 R package and calculated by permutation was used to rank the explanatory variables.

298 To ensure fair comparison of RF metamodels to PâturSTICS predictions, we used a random
299 two-thirds of the dataset to train RF models and the remaining one-third to evaluate
300 performances of RF metamodels. How well the metamodel predicted PâturSTICS predictions
301 was assessed by combining a graphical and statistical approach, using common indicators for
302 validation of biophysical models (Bellocchi et al., 2010 ; Wallach et al., 2018). The indicators
303 were i) root mean square error (RMSE, Eq. 1), which is a quantitative measure of distance
304 between observed and simulated values; ii) its relative value (RRMSE, Eq. 2), which
305 expresses error as a percentage of the mean measured value; iii) Nash-Sutcliffe model

306 efficiency (EF), interpreted as the proportion of variance explained by the model; and iv)
307 graphs of observed vs. predicted DMY and NY.

308

$$309 \text{ RMSE} = \sqrt{\left(\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n}\right)} \quad (1)$$

310

$$311 \text{ RRMSE} = \frac{\text{RMSE}}{\bar{y}} \times 100 \quad (2)$$

312

$$313 \text{ EF} = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y}_i)^2} \quad (3)$$

314

315 where y_i is the measured value, \hat{y}_i is the corresponding predicted value, n the number of
316 measurements and \bar{y} is the mean of measured values. Metamodel performance was interpreted
317 from the following RRMSE thresholds: $\text{RRMSE} \leq 10\%$: excellent, $10\% < \text{RRMSE} \leq 20\%$:
318 good, $20\% < \text{RRMSE} \leq 30\%$: fair, $\text{RRMSE} > 30\%$: poor.

319

320 3. Results

321 3.1 Simulated grassland management and N inputs

322 Mean grassland management from 1984-2013 varied by region (Figures 2 and 3). The mean
323 frequency of herbage use was 3-4 grazing and/or cutting events per year, sometimes reaching
324 9 events in rare situations (Figure 3A). Herbage use appeared to be higher in northern and far
325 western Bretagne (Bre), western Pays de la Loire (PdL) and Limousin (Lim) regions (Figure
326 2A) and in the Manche (50) and Pyrénées-Atlantiques (64) departments (Figure 2B). In the
327 Bretagne, Basse-Normandie (BaN) and Haute-Normandie (HaN) regions, western Massif
328 Central, Alps and Pyrénées, grasslands were mainly grazed (Figure 3B). These areas had the
329 largest numbers of grazing days and amounts of animal N returns to the soil (Figures 3C and
330 3D). By construction, these predictions were highly correlated as they were both calculated
331 from herbage ingestion. Grasslands were used mostly for hay and silage production in the
332 Champagne-Ardenne (ChA), Lorraine (Lor), part of Pays de la Loire, Haute-Normandie and
333 Centre (Cen) regions and the south-western and eastern Massif Central (Figure 3B). Total N
334 application from mineral fertilisers, animal returns and BNF had a mean (\pm standard
335 deviation) of $108 \pm 63 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ (Figure 3F) and reached more than $200 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ in
336 some departments, such as Finistère (29) and Manche (50). French grasslands received a mean

337 of ca. 40 ± 25 kg N ha⁻¹ yr⁻¹ as mineral N fertiliser (Figure 3E), 73 ± 41 kg N ha⁻¹ yr⁻¹ as
338 animal N returns and, for PCU with grasslands containing legumes 38 ± 25 and 329 ± 44 N
339 ha⁻¹ yr⁻¹ from BNF for grass-legume mixtures and temporary sown swards of pure legumes,
340 respectively. Fertilisation was higher in northern and north-western France, with the largest
341 values predicted in the Nord-Pas-de-Calais (NPC), Picardie (Pic), Haute-Normandie, Basse-
342 Normandie, Bretagne and southern Pays de la Loire regions. Maximum N fertilisation reached
343 115 kg N ha⁻¹ yr⁻¹. Mean N returns from animal faeces and urine were 30 and 38 kg N ha⁻¹ yr⁻¹
344 ¹, respectively, with maximum values reaching 115 and 133 kg N ha⁻¹ yr⁻¹, respectively. BNF
345 by legumes was related to the geographic location of grass-legume mixtures and pure legume
346 swards. It was highest in the production area of lucerne (i.e. Champagne-Ardenne), reaching
347 nearly 250 kg N ha⁻¹ yr⁻¹.

3.2. Mean grassland DM and N yields in France

350 Mean predicted DMY agreed relatively well with observed data in Pays de la Loire and part
351 of Bretagne (Figure 4), though it was overpredicted in Bretagne under dry summer conditions.
352 Mean predicted DMY were 9.7 ± 2.2 and 7.6 ± 2.3 t DM ha⁻¹ yr⁻¹ in Bretagne and Pays de la
353 Loire, respectively (Table 2, Figure 4), while observed DMY were 8.3 - 10.6 and 6.9 - 9.1 t DM
354 ha⁻¹ yr⁻¹, respectively. Nevertheless, the model tended to overpredict observed DMY in
355 mountainous regions. For instance, in Franche-Comté, mean predicted DMY was 10.3 ± 1.0 t
356 DM ha⁻¹ yr⁻¹, while observations were 7.2 - 9.9 t DM ha⁻¹ yr⁻¹. Observations on shallow soils
357 were particularly overpredicted (Figure 4). Likewise, in Auvergne, mean predicted DMY (9.0
358 ± 2.7 t DM ha⁻¹ yr⁻¹) was notably higher than observed DMY (6.5 - 7.2 t DM ha⁻¹ yr⁻¹).

359 More generally, the map of mean predicted DMY (Figure 5B left) was consistent with
360 existing grassland productivity gradients, associated with specific soil-climate conditions
361 identified within some regions. For instance, the model partly reproduced the expected north-
362 south DMY gradient in the Pays de la Loire and the east-west DMY gradient in Bretagne
363 (Figures 4 and 5B). The mean N content of cut and grazed herbage varied from 13.1 - 31.6 g N
364 kg DM⁻¹ according to location and management, with distribution differing among regions
365 (results not shown). Nevertheless, maps of DMY and NY looked similar, as the two variables
366 were directly correlated.

367 Comparison of mean predicted DMY and NY highlighted regional and departmental
368 differences in grass forage production (Table 2, Figure 5 B and 5C). Three-quarters of French
369 grasslands produced and exported at least 7.6 t DM ha⁻¹ yr⁻¹ and 172 kg N ha⁻¹ yr⁻¹,
370 respectively. One-quarter of French grasslands produced and exported at least 10.7 t DM ha⁻¹

371 yr⁻¹ and 254 kg N ha⁻¹ yr⁻¹, respectively (Figure 5A, Table 2). These grasslands benefit from
372 environmental conditions favourable for grass growth, with the oceanic climate in north-
373 western regions of France: Bretagne (mainly Finistère (29), western Morbihan (56) and Côtes
374 d'Armor (22) departments), Basse-Normandie (mainly Manche (50) and Calvados (14)
375 departments), Haute-Normandie, Picardie and Nord-Pas-de-Calais. These productive
376 grasslands were also located in eastern regions: Franche-Comté, Champagne-Ardennes
377 (Ardenne (08) and Marne (51) departments, where most lucerne production is concentrated)
378 and Lorraine (Vosges (88) department). They were also predicted in the north-western Massif
379 Central (Limousin and Auvergne regions), the northern Alps and western Pyrénées. In
380 contrast, production of less than 5 t DM ha⁻¹ yr⁻¹ and 115 kg N ha⁻¹ yr⁻¹ was predicted in the
381 southern Pays de la Loire region (mainly Loire-Atlantique (44), Maine-et-Loire (49) and
382 Vendée (85) departments), the eastern Massif Central (mainly Haute-Loire (43) and Puy-de-
383 Dôme (63) departments), where weather was drier and/or with soils with low water holding
384 capacity, as well as in the Provence-Alpes-Côte d'Azur (PACA) region.

385

386 3.3. PâturSTICS metamodelling

387 RF metamodels successfully predicted grassland DMY and NY in the test datasets that were
388 not used to train the model, explaining 95% and 97% of variance, respectively, with good
389 agreement between predictions of RF metamodels and PâturSTICS (Table 4; Figure 6). For
390 predicted DMY, RF metamodels had RMSE of 0.77 t DM ha⁻¹ yr⁻¹ and RRMSE of 21.8%
391 compared to PâturSTICS predictions (“fair” performance). For predicted NY, RF metamodels
392 had RMSE of 16.5 kg N ha⁻¹ yr⁻¹ and RRMSE of 18.3% compared to PâturSTICS predictions
393 (“good” performance). Slopes of the regression between PâturSTICS and RF metamodel
394 predictions were 0.92 and 0.94 for DMY and NY, respectively (Pearson correlation
395 coefficient = 0.98 for both).

396 The validity domain of these metamodels encompasses a large number of soil and climate
397 situations in which French grasslands are established, with annual values of mean
398 temperatures, global radiation and precipitation ranging, respectively, from ca. -2.5 to 17°C,
399 2850-6500 MJ m⁻² yr⁻¹ and 270-3300 mm (Table 3). This corresponds to 8 climate types (e.g.
400 oceanic, semi-continental, mountainous, Mediterranean) as defined by Joly et al. (2010) that
401 are common to other European regions. The soils include shallow and sandy soils with low
402 water holding capacity (ca. 10 mm) up to deep soils with medium texture and water holding
403 capacity up to ca. 170 mm. Soil organic matter content in the topsoil ranges from 1.3-7.6%,
404 thus excluding richer soils. The duration of grasslands was limited to 5 years, which excluded

405 older permanent grasslands. Agricultural practices are representative of the 1984-2013 period
406 in France. N fertilisation did not exceed 200 kg N ha⁻¹ yr⁻¹ and thus did not represent more
407 intensive N application rates that can be observed in other European countries. The intensity
408 and frequency of herbage defoliations range from extensive to intensive practices.

409 Variable importance measures of the RF models revealed that grassland age was the most
410 influential variable for predicting grassland DMY, followed by annual global radiation and
411 mean temperature, which had similar influence, and then by soil water holding capacity,
412 annual precipitation, annual N fertilisation and soil organic N content in topsoil (Table 4).
413 Grazing days, number of cutting events and legume percentage in the vegetation had the least
414 influence on predicting grassland DMY.

415 The ranking of variables according to their influence on predicted NY was somewhat similar
416 to that on DMY, with the three most and least influential variables being the same for DMY
417 and NY. Of the top three, however, annual global radiation was the most influential variable
418 for predicting NY, closely followed by annual mean temperature and grassland age, which
419 had similar influence, and then by soil organic N content in topsoil, annual N fertilisation,
420 water holding capacity and annual precipitation.

421

422 **4. Discussion**

423 The main objective of this study was to predict French grassland DMY and NY at a high
424 spatial resolution while considering the existing diversity of soil and climate conditions,
425 grassland types and associated management types. The study achieved this objective despite
426 making certain assumptions because of the information available and model limitations,
427 which do not alter the value of the results.

428

429 **4.1. Implementation of simulations**

430 The simulation plan was designed to consider the diversity of existing soil and climate
431 conditions, grasslands and management situations in France. It could be built due to the
432 existence of other studies (i.e. French Evaluation of Ecosystems and Ecosystem Services
433 (EFESE); Théron et al., 2017) and several detailed French databases for the definition of
434 soils (1:1,000,000-scale soil geographic database of France, Jamagne et al., 1995), climates
435 (SAFRAN system, Durand et al. 1993), management types (statistical agronomic surveys on
436 grasslands and the ISOP system, Ruget et al., 2006) and grassland types and ages (Graphical
437 Register of Fields, last agricultural census). The present study seems difficult to transfer to
438 other European countries, where equivalent databases are often not available. The need to

439 have a high spatial resolution of outputs and a reasonable time to build the simulation plan
440 and calculate results led us to reuse these databases while avoiding updating management
441 information, which would have been time-consuming.

442 Some limits concern the simplifications made to reduce the number of simulations. The
443 existing diversity of grassland vegetation and agricultural practices was limited to four
444 grassland types and 30 management types, respectively, with fixed conditions for triggering
445 planned cut and grazing events. Information about agricultural practices was available at the
446 scale of small agricultural regions and was assumed to remain the same at smaller scales, thus
447 ignoring variability in agricultural practices in a given small agricultural region. Definitions
448 of grassland types and associated management types within a PCU were fixed for the
449 simulation period, thus overlooking possible local changes in the presence and percentage of
450 grassland types and associated management types. This study benefitted, however, from
451 simulated adaptation of the planned number and timing of herbage defoliations and
452 fertilisation events within a given year according to herbage availability, conditions for
453 triggering management events and climatic conditions. In addition, these assumptions helped
454 in analysis of results as they reduced the number of explicative factors and interactions
455 involved. They also provided the ability to compare similar conditions of grassland types and
456 management types under different climate and soil conditions. Finally, the simulation plan
457 provided a coherent picture of the annual frequency and timing of grass defoliations and N
458 applications, and of the local balance between grazing and cutting.

459 Other limits were related to the validity domain of STICS (v. 8.3.1, release 1276). First,
460 simulation of grass-legume mixtures did not consider changes in the legume percentage in
461 response to N fertilisation, animal N returns and defoliation, as STICS cannot simulate
462 vegetation dynamics. This is a common limit of process-based models simulating grasslands
463 at the field scale, and explains why the legume percentage was the input factor with the least
464 influence on DMY and NY predictions by RF metamodels. Second, PâturSTICS cannot
465 represent the diversity of grassland functional types in permanent grasslands (Cruz et al.,
466 2010), and parameterising the model for only one grass and legume species (tall
467 fescue/orchard grass and lucerne, respectively) may have biased predicted DMY and NY in
468 western France (Bretagne, Pays de la Loire, Poitou-Charentes), where perennial ryegrass
469 (*Lolium perenne*) and white clover (*Trifolium repens*) are the most commonly sown species.
470 Third, predictions of DMY and NY may have been biased by the current version of STICS'
471 poor representation of grassland roots and their role in soil N availability for plant growth and
472 soil carbon immobilisation. STICS was recently improved to better represent perennial organs

473 and their relationship with non-perennial organs in a *Miscanthus* (*Miscanthus* × *giganteus*)
474 case study (Strullu et al., 2014). Such improvements are intended to be generic for perennial
475 plants, supported by the functional approach of STICS, and could be adapted to the simulation
476 of grasslands and used in future simulations.

4.2. Consistency of grazing simulation

477
478
479 The grazing module we developed (Appendix A) is a simplified but useful representation of
480 animal returns during grazing in which animals are assumed to be fed with grazed grass with
481 no concentrate supply. Grassland intake was simulated as a cutting event, with all of the
482 herbage removed being assumed to feed a fluctuating number of animals that have a uniform
483 and fixed DM intake (17 kg DM day⁻¹). Animal stocking density and the length of each
484 grazing period are thus model outputs instead of inputs, but it is possible to calculate grazing
485 days. This simplification makes it difficult to compare predictions to observations, as
486 simulated herbage growth may differ from reality, and simulated grazing days may not reflect
487 the stocking density or grazing period length observed.

488 This module is based on known relationships between animal N returns during grazing,
489 animal herbage DM intake and herbage N content (Delaby and Lucbert, 1999), all of which
490 respond to N availability (including fertilisation) (Delaby et al., 1997; Delaby, 2000).
491 Predicted faecal and urinary N returns lay in the expected range of observations from the
492 literature (i.e. 30-120 and 60-350 kg N ha⁻¹ yr⁻¹ for 400-1000 grazing days, respectively)
493 (Delaby et al., 1997, Vertès et al., 2018).

494 Like most grassland simulation models, PâturSTICS assumes uniform spatial return of faecal
495 and urinary N to the soil, as representing their spatial and temporal distribution in models
496 remains a challenge (Hutchings et al., 2007; Selbie et al., 2015; Snow et al., 2009). Applying
497 animal N returns on a single day and not considering the spatial heterogeneity of dung and
498 urine patches within the paddock could have distorted predictions of grassland production and
499 N fluxes associated with animal N returns (Leterme et al., 2003). For the range of N
500 fertilisation simulated (0-200 kg N ha⁻¹ yr⁻¹), assuming a uniform spatial return of dung and
501 urine to the soil can lead models to overpredict plant N uptake and thus grassland DMY and
502 NY, as well as to overpredict ammonia emissions and underpredict nitrous oxide emissions
503 and nitrate leaching (Hutchings et al., 2007).

504

505 4.3. Evaluation of grassland DM and N yields

506 This study is the first high-resolution assessment of current DMY and NY of French
507 grasslands based on sound representation of environmental conditions, grassland types and
508 management types and on a process-based representation of soil, plant and grazing animal
509 processes.

510 Predictions of annual DMY and NY of French grassland lay in the same order of magnitude
511 as those of previous simulation studies under European (specifically, French) conditions. In
512 particular, predicted NY was consistent with that of Herrmann et al. (2005) for similar levels
513 of N fertilisation and plant defoliation regimes. Similarly, the amount and regional
514 distribution of predicted DMY in France appeared consistent with those of Huyghe et al.,
515 (2014) and Chang et al. (2015). Predicted herbage N content (13.1-31.6 g N kg⁻¹ DM) lay in
516 the same range as crude protein (CP) contents of green grass forages according to INRA feed
517 tables (INRA, 2018) (75-290 g CP kg⁻¹ DM, i.e. ca. 12.0-46.5 g N kg⁻¹ DM). Our predictions
518 of French grassland DMY were also consistent with available regional observations, giving a
519 realistic view of the diversity of French grassland productivity, especially in areas where they
520 are intensively managed.

521 Our predictions of French grassland DMY and NY support the idea that French grasslands
522 can produce large amounts of good-quality forage in regions with favourable conditions for
523 grass growth. Such predictions could be locally compared to current annual DMY and NY to
524 encourage farmers to further exploit the production potential of their grasslands and to gain in
525 feeding and protein self-sufficiency. Our results also reinforce the view that grasslands can
526 export large amounts of N through cutting and grazing, usually ca. 170 kg N ha⁻¹ yr⁻¹, which
527 is more than other crops (Lassaletta et al., 2014). This N export, due to grasslands' permanent
528 cover and ability to grow during drainage periods, may help decrease water pollution.

529 Particular situations may have limited the model's accuracy. PâturSTICS tended to
530 overpredict DMY observed in semi-mountainous and mountainous regions, perhaps because
531 it ignores effects of snow and frost, which stop and delay grass growth for several days, even
532 when favourable environmental conditions return. It could also be due to ignoring effects of
533 slope on water run-off and availability for plant growth. PâturSTICS also overpredicted DMY
534 observed in lowlands with shallow soils and/or under dry summer conditions, probably due to
535 how it represents effects of temperature and water stress on plant growth, as it tends to
536 simulate soil water content accurately (Coucheney et al., 2015; Sándor et al. 2017). However,
537 we compared PâturSTICS' predictions to observations that did not cover the entire soil,
538 climate and management conditions that had been simulated.

539 This study benefited from existing grassland monitoring networks, which are essential for
540 evaluating grassland models. However, it highlighted the lack of observations of herbage N or
541 CP content of French grasslands, which made it impossible to compare predicted herbage N
542 content or grassland NY to regional observations. This advocates for continuation and
543 expansion of existing grassland monitoring networks.

545 **4.4 Usefulness of the random forest metamodels**

546 Process-based crop models are helpful and valuable tools for predicting crop yields, as they
547 simulate crop functioning in response to environmental conditions and agricultural practices.
548 Metamodelling is an alternative to process-based models that significantly reduces the
549 requirement for input data (e.g. Luo et al., 2013; Qi et al., 2017). Metamodels are developed
550 using a statistical approach usually based on multiple linear regressions but more recently
551 based on machine-learning algorithms such as RF as a complementary or alternative
552 approach. Like Jeong et al. (2016) found for crops, we found that RF was effective in
553 predicting annual grassland DMY and NY predicted by PâturSTICS. This kind of data-mining
554 method is especially useful for developing metamodels trained by extensive simulation
555 scenarios. As a complementary approach to sensitivity analysis, RF can also identify the
556 model inputs that explain predictions the most. The metamodels we developed from
557 PâturSTICS predictions are promising as they provide immediate information from a smaller
558 number of available input information about soil, climate and grassland management. As long
559 as predictions are made within the boundaries of metamodels' validity domain, they can be
560 used to make predictions under similar European climate and management conditions, and
561 could be embedded in decision support tools dedicated to ruminant livestock systems.

563 **5. Conclusions**

564 This study provided a detailed view of French grassland dry matter and protein yield
565 potentials, considering the diversity of climates, soils, grassland types and management types.
566 In many French regions, grasslands can provide large amounts of herbage rich in protein.
567 With the expected fluctuation and increase in input prices, taking better advantage of this
568 potential could help farmers increase feed and protein self-sufficiency. Nevertheless, this
569 study made certain assumptions due to the quality of input data and to limits of the current
570 model. Future research is required to improve grassland models' representation of soil
571 processes involved in dynamics of soil organic matter. Doing so will help address

572 environmental issues related to the ability of grasslands to mitigate air pollution by
573 greenhouse gases and water pollution by nitrates.

574

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764 Figure 1. Diagram of grassland simulations performed at the resolution of pedoclimatic units
765 (PCU) in France.

766
767 Figure 2. Boundaries of A) administrative regions (pre-2016) and B) departments (current) of
768 metropolitan France, showing elevation and the main mountain ranges. See Appendix C for
769 meanings of region abbreviations and department number codes.

770
771 Figure 3. Mean annual simulated management of French grasslands over the 1984-2013
772 period: A) Number of cutting and grazing events per year (CGE), B) Grazed percentage of
773 dry matter yield (GP), C) Grazing days (GD), D) Animal nitrogen (N) returns (AN), E) N
774 fertilisation (FN), and F) Total N (TN) inputs from fertilisation, animal returns and biological
775 fixation.

776
777 Figure 4. Comparison of mean predicted grassland dry matter yield (DMY) (boxplots) to
778 mean observations (symbols) in four French regions: Auvergne (Auv), Bretagne (Bre),
779 Franche-Comté (FrC) and Pays de la Loire (PdL). Solid lines in the boxplot are medians. Blue
780 symbols are means. Whiskers represent 1.5 times the interquartile range. Predictions were
781 aggregated at the pedoclimatic unit scale over the 1984-2013 period. Observations were
782 estimated from herbage height measurements in grazed paddocks of several commercial farms
783 for 6-11 years during the 1997-2014 period, each for specific conditions of observations.

784
785 Figure 5. A) Distribution, B) map and C) regional values of (left) mean predicted grassland
786 dry matter yield (DMY) and (right) nitrogen yield (NY) over the 1984-2013 period associated
787 with cutting and grazing activities. In (A), the solid vertical line refers to the median and the
788 dashed vertical lines to the first and third quartiles. Corresponding values are indicated to the
789 right of each vertical line. Whiskers represent 1.5 times the interquartile range. See Appendix
790 C for meanings of region abbreviations.

791
792 Figure 6. Random forest (RF) model performance for test datasets assessed by comparing RF
793 metamodel and PâturSTICS predictions of dry matter yield (DMY) and nitrogen yield (NY).
794 Dashed lines are 1:1 lines, while solid blue lines are linear regressions between RF
795 metamodelled and PâturSTICS predictions.

796 Appendix A. Simulation of animal returns in grazed grasslands

797 In the research version of STICS called PâturSTICS, animal grazing is simulated as a cutting
798 event. The amount of biomass removed by the cut ($msrecfou$, t DM ha⁻¹) is assumed to
799 represent herbage dry matter intake (DMI , t DM.ha⁻¹) by the animals during their presence on
800 the field. Animal faeces and urine are represented by an application of cattle liquid manure
801 and urea, respectively, to the soil surface on the day of herbage defoliation. Some parameters
802 describing animal faeces are assumed constant and are parametrised using data for animals
803 receiving a grass-based diet: carbon (C_{respc}), mineral N (N_{minres}) and water contents
804 ($eaures$) are set to 7.4%, 0.045% and 87% of faeces fresh matter (FM), respectively.

805 Animal faeces N (N_{faeces} , kg N ha⁻¹) is estimated as a linear function of animal DMI (t DM
806 ha⁻¹) after Cutullic et al. (2013) (Eq. A.1), with a proportionality coefficient α of 7.53 g N kg⁻¹
807 DM for a grass-only diet and assuming that 20% of the faeces is returned elsewhere than on
808 grazing areas (e.g. resting areas, milking parlour, housing, paths/roads) ($p_{faeces} = 0.2$,
809 dimensionless). Animal faeces (Q_{faeces} , t FM ha⁻¹) are calculated from N_{faeces} assuming a mean
810 N content in fresh faeces ($C_{N,faeces}$) of 2.87% (Eq. A.2).

$$811 N_{faeces} = \alpha (1 - p_{faeces}) DMI \quad (A.1)$$

$$812 Q_{faeces} = \frac{10}{((100 - eaures) \times C_{N,faeces})} N_{faeces} \quad (A.2)$$

813
814
815
816 The faeces C:N ratio ($C:N_{faeces}$) is derived from plant N concentration ($C_{N,plant}$, kg N kg DM⁻¹)
817 the day before herbage defoliation, as follows (Eq. A.3):

$$818 C:N_{faeces} = \beta - \gamma C_{N,plant} \quad (A.3)$$

819
820
821 where β is the maximum C:N ratio in faeces of animals receiving a grass-based diet (32.201)
822 and γ is the slope of the linear regression line between $C:N_{faeces}$ and $C_{N,plant}$ (505.29).”

823 Decomposition of animal faeces uses existing STICS equations for simulating mineralisation
824 of organic residues, with grazing-related parameter values (Table A.1). Urea return is
825 represented as an application of mineral fertiliser, of which up to 15% can be volatilised
826 ($voleng$), taken up by plants, nitrified, leached, denitrified and immobilised in soil organic
827 matter.

828 Following the concepts of Faverdin and Vérité (1998), N in urine (N_{urine} , kg N ha⁻¹) is
829 calculated as animal N intake minus N losses in milk and faeces. We assumed a daily N
830 balance of 20.6 g N per animal (Spanghero and Kowalski, 1997) and that a dairy cow ingests
831 a mean of 17 kg of herbage DM per day and produces 25 kg of milk per day containing 31 g
832 of protein per kg of milk. Under these assumptions, the δ coefficient is set to 16.25 g N kg
833 DM⁻¹, and N_{urine} is derived from both plant N concentration ($C_{N,plant}$, kg N kg DM⁻¹) the day
834 before cutting and from herbage DMI (t DM ha⁻¹) by animals, as follows (Eq. A.4 and A.5):

835

$$836 \quad N_{urine} = (10 C_{N,plant} - \delta) (1 - p_{faeces}) DMI \quad (A.4)$$

$$837 \quad \text{With } N_{urine} = 0 \text{ if } C_{N,plant} \leq \frac{\delta}{10} \quad (A.5)$$

838

839 Animal stocking density and length of the grazing period are thus not model inputs but rather
840 model outputs. The number of livestock unit (LSU) grazing days per ha of grassland per year
841 can be calculated by dividing the total herbage removed by animals (DMI , t DM ha⁻¹) by daily
842 animal intake (17 kg DM (LSU.grazing day)⁻¹).

843

845 Table A.1. Parameter values used to represent mineralisation of animal faeces during grazing

Parameter	Definition	Unit	Value
akres	parameter of organic residue decomposition	d ⁻¹	0.064
bkres	potential rate of decomposition of organic residues	g.g ⁻¹	-0.552
awb	parameter determining the C:N ratio of biomass during organic residue decomposition	dimensionless	28.8
bwb	parameter determining the C:N ratio of biomass during organic residue decomposition	g.g ⁻¹	-325.7
cwb	minimum C:N ratio of the microbial biomass decomposing organic residues	g.g ⁻¹	13.0
ahres	parameter of organic residue humification	g.g ⁻¹	36.5
bhres	parameter of organic residue humification	g.g ⁻¹	1354.7
kbio	potential decay rate of microbial biomass decomposing organic residues	d ⁻¹	0.00213
yres	carbon assimilation yield by microbial biomass during crop residue decomposition	g.g ⁻¹	0.62

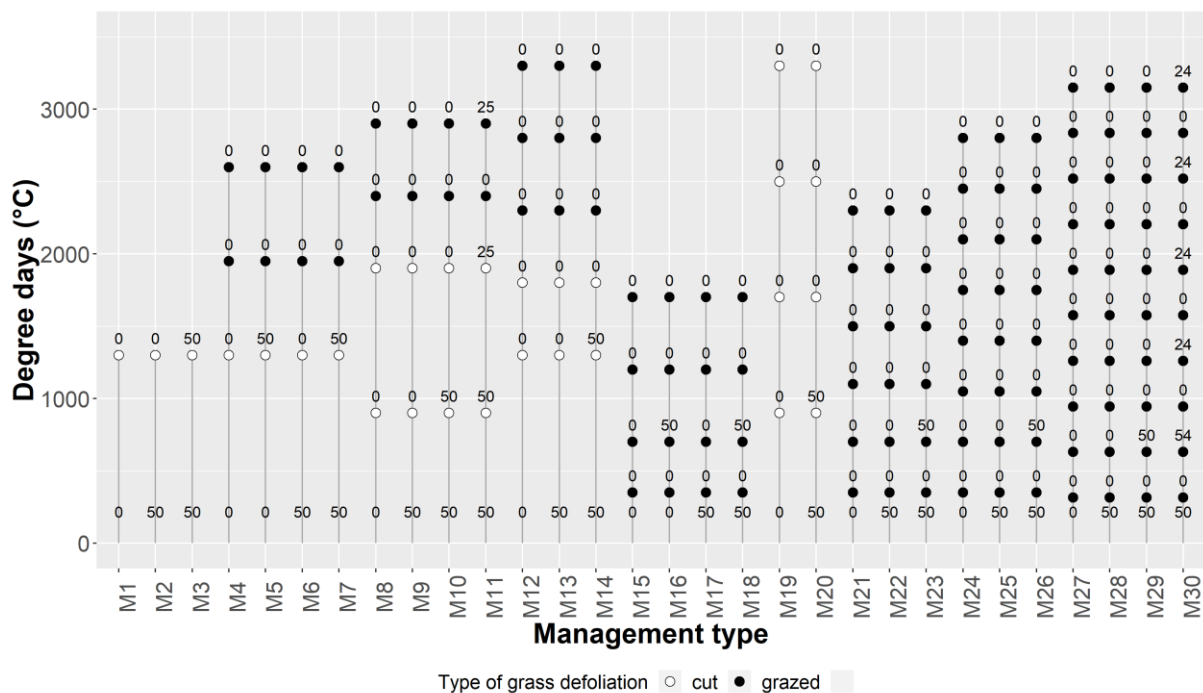
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848 Appendix B. Description of grassland management types

849 Each of the 30 management types is defined by a sequence of cutting and/or grazing events
 850 (Figure B.1). Events are planned using degree days ($^{\circ}\text{C}$), equal to the sum of the positive
 851 values of daily mean temperature minus a basal temperature. Triggering of each planned
 852 cutting and grazing event requires a minimum harvestable biomass above a target residual
 853 biomass, both defined by the model user (Table B.2). Each event can therefore be delayed and
 854 sometimes not occur depending on the availability of herbage biomass. Each event can be
 855 associated with an application of ammonium nitrate (kg N ha^{-1}). Grasslands can also receive
 856 additional winter mineral N application around 1 February. Figure B.1 shows amounts of N
 857 (kg N ha^{-1}) applied to grasslands for each management type.

858



859

860

861 Figure B.1. Definition of planned cutting or grazing events and N fertiliser applications (kg N
 862 ha^{-1}) for each management type simulated

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864 Table B.2. Conditions for triggering planned cutting and grazing events

Event	Residual biomass (t DM ha ⁻¹)	Residual leaf area index (m ² m ⁻²)	Minimum harvestable biomass (t DM ha ⁻¹)
Cutting	2.0	0.5	1.0
Grazing	1.5	1.0	0.5

865

866

867 **Appendix C. Description of French metropolitan regions and departments**

868 Table C.1. Names and abbreviations of former (pre-2016) French regions, the names of the
869 departments they contain and the departments' identification codes

870

Former region name	Former region abbreviation	Department name	Department identification code
Alsace	Als	Bas-Rhin	67
		Haut-Rhin	68
Aquitaine	Aqu	Dordogne	24
		Gironde	33
		Landes	40
		Lot-et-Garonne	47
		Pyrénées-Atlantiques	64
Auvergne	Auv	Allier	03
		Cantal	15
		Haute-Loire	43
		Puy-de-Dôme	63
Basse-Normandie	BaN	Calvados	14
		Manche	50
		Orne	61
Bourgogne	Bou	Côte-d'Or	21
		Nièvre	58
		Saône-et-Loire	71
		Yonne	89
Bretagne	Bre	Côtes d'Armor	22
		Finistère	29
		Ille-et-Vilaine	35
		Morbihan	56
Centre	Cen	Cher	18
		Eure-et-Loir	28
		Indre	36
		Indre-et-Loire	37
		Loir-et-Cher	41
		Loiret	45
Champagne-Ardennes	ChA	Ardennes	08
		Aube	10
		Haute-Marne	52
		Marne	51
Corse	Co	Corse-du-sud	2A
		Haute-Corse	2B
Franche-Comté	FrC	Doubs	25
		Haute-Saône	70
		Jura	39
		Terr. de Belfort	90
Haute-Normandie	HaN	Eure	27
		Seine-Maritime	76
Ile-de-France	IdF	Essonne	91
		Paris	75
		Seine-et-Marne	77

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		Hauts-de-Seine	92	
		Seine-Saint-Denis	93	
		Val-de-Marne	94	
		Val-D'Oise	95	
		Yvelines	78	
6	Languedoc- Roussillon	LaR	Aude	11
7			Gard	30
8			Hérault	34
9			Lozère	48
10			Pyrénées-Orientales	66
11	Limousin	Lim	Corrèze	19
12			Creuse	23
13			Haute-Vienne	87
14	Lorraine	LoR	Meurthe-et-Moselle	54
15			Meuse	55
16			Moselle	57
17			Vosges	88
18	Midi-Pyrénées	MiP	Ariège	09
19			Aveyron	12
20			Gers	32
21			Haute-Garonne	31
22			Hauts-Pyrénées	65
23			Lot	46
24			Tarn	81
25			Tarn-et-Garonne	82
26	Nord-Pas-de-Calais	NPC	Nord	59
27			Pas-de-Calais	62
28	Pays de la Loire	PdL	Loire-Atlantique	44
29			Maine-et-Loire	49
30			Mayenne	53
31			Sarthe	72
32			Vendée	85
33	Picardie	Pic	Aisne	02
34			Oise	60
35			Somme	80
36	Poitou-Charentes	PoC	Charente	16
37			Charente-Maritime	17
38			Deux-Sèvres	79
39			Vienne	86
40	Provence-Alpes-Côte d'Azur	PACA	Alpes-de-Haute-Provence	04
41			Alpes-Maritimes	06
42			Bouches-du-Rhône	13
43			Hautes-Alpes	05
44			Var	83
45			Vaucluse	84
46	Rhône-Alpes	RhA	Ain	01
47			Ardèche	07
48			Drôme	26
49			Haute-Savoie	74
50			Isère	38
51			Loire	42

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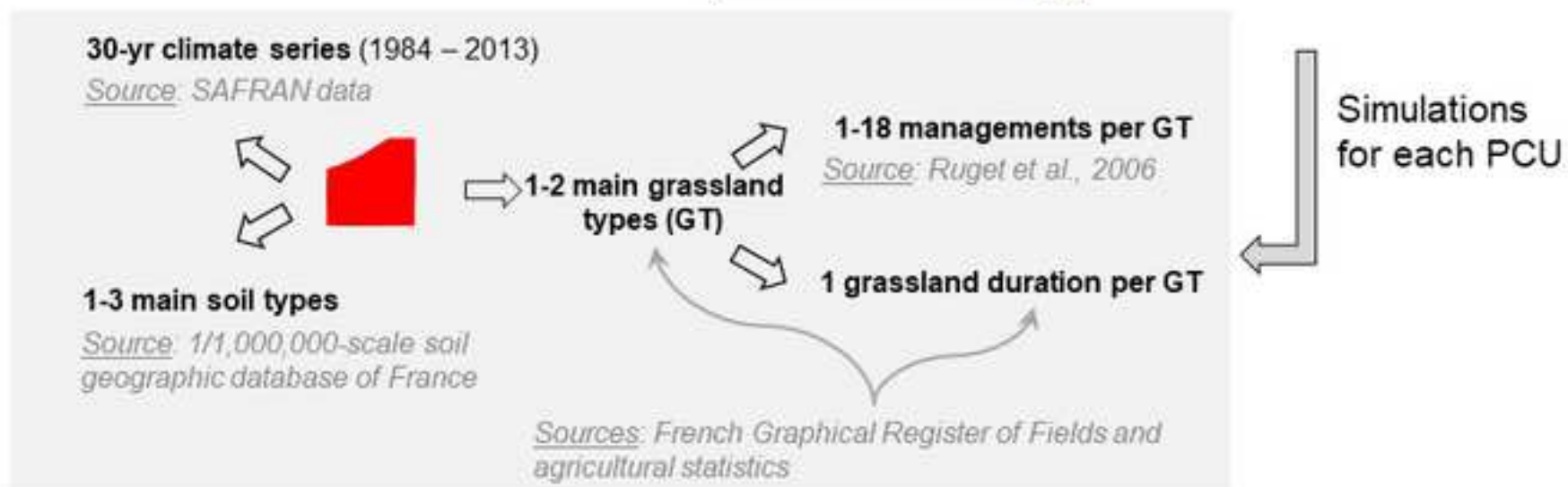
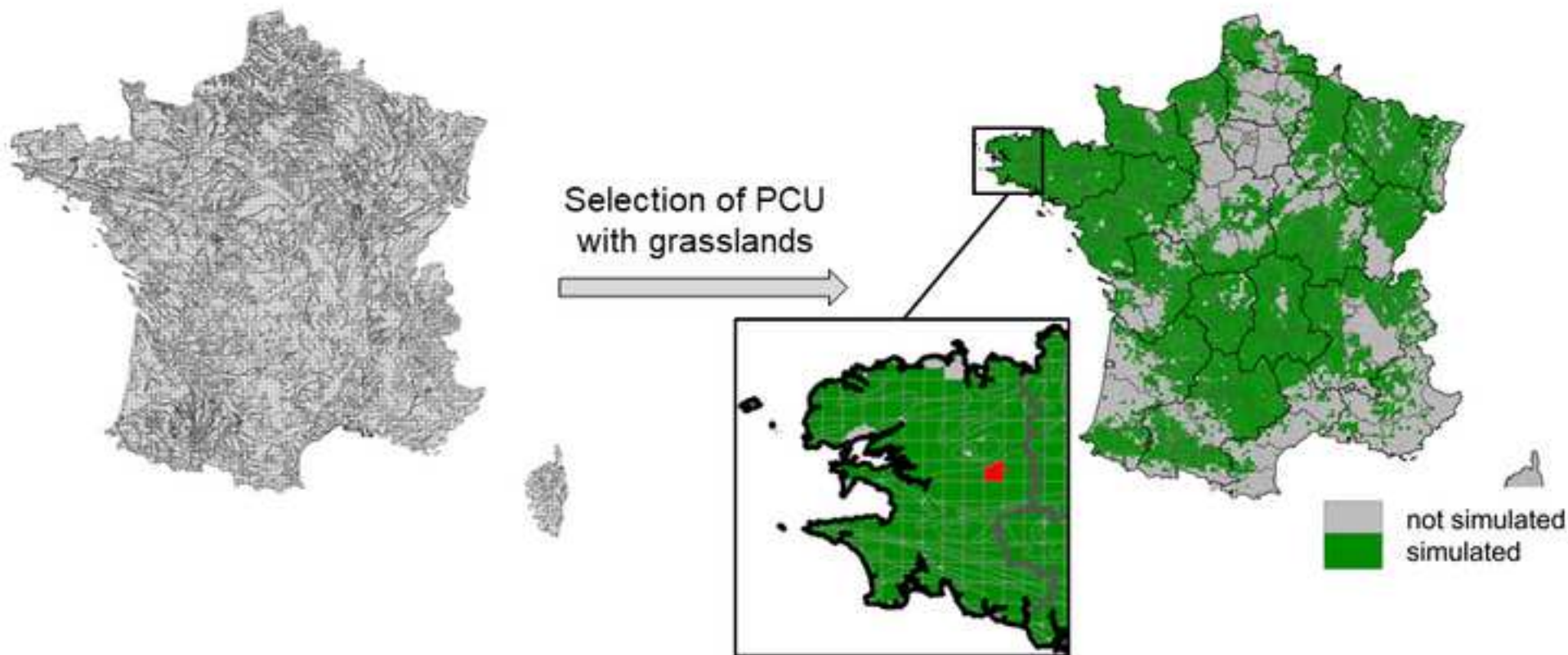
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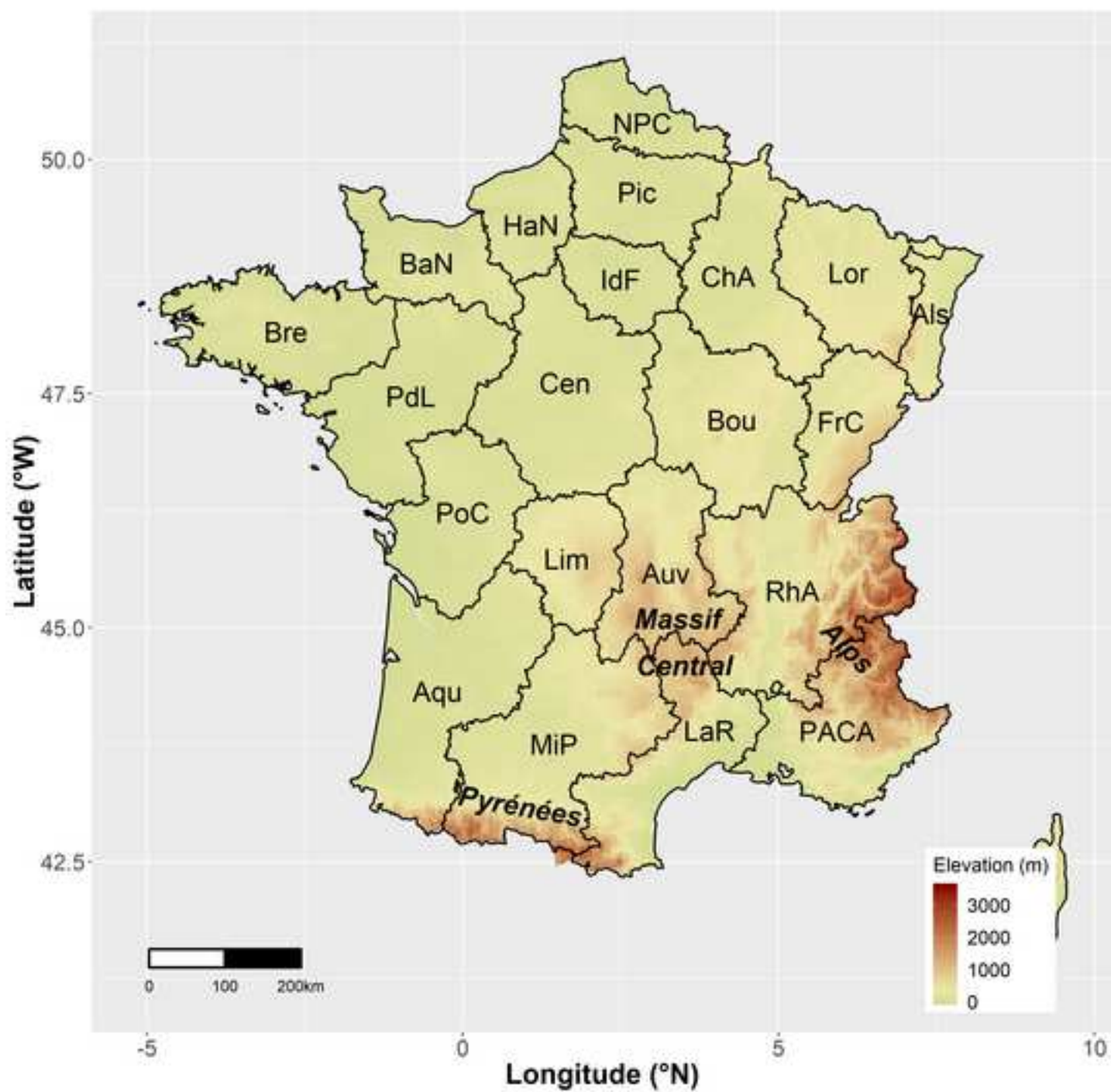
Figure1

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Resolution of simulations





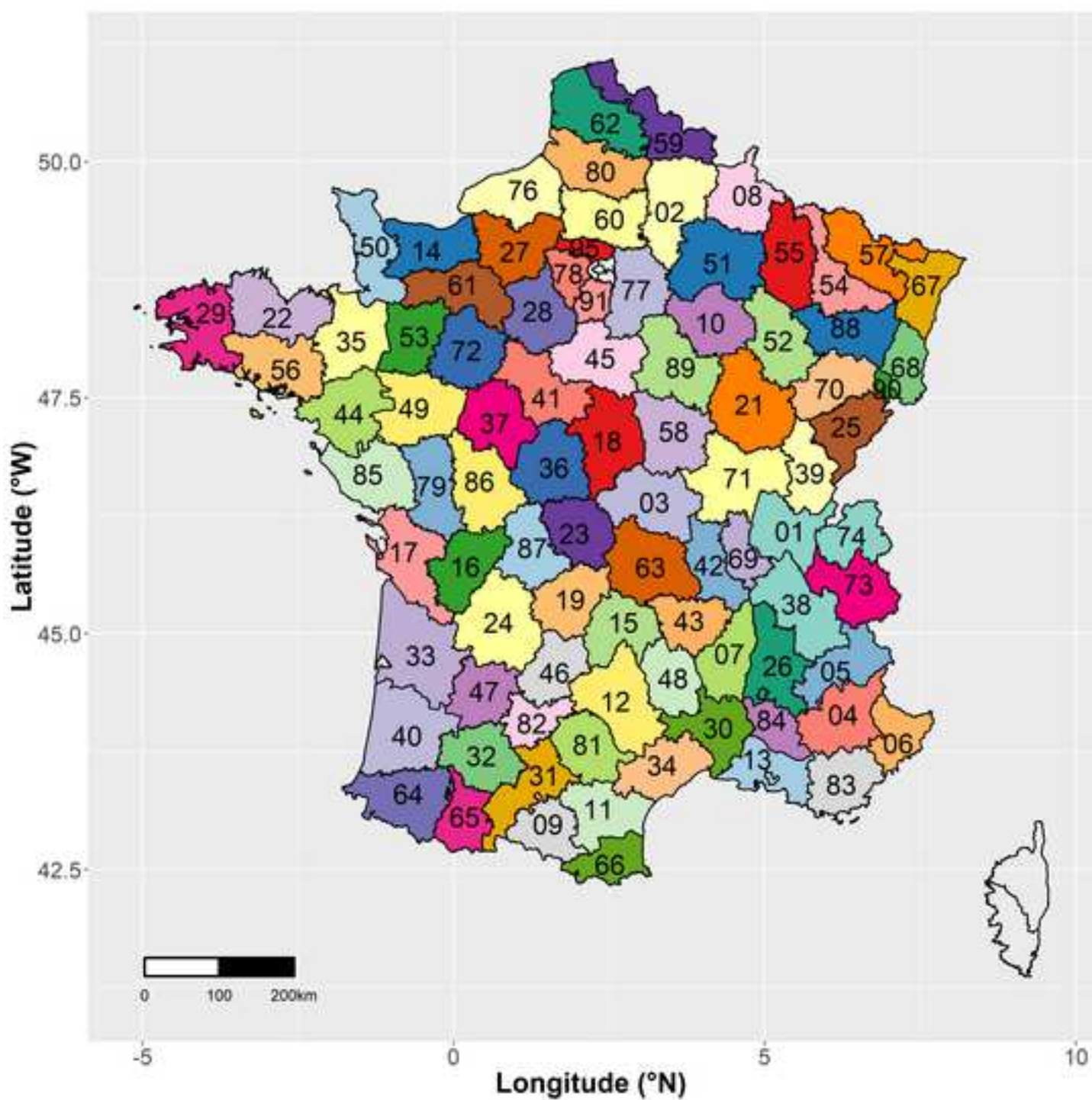
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Figure2B

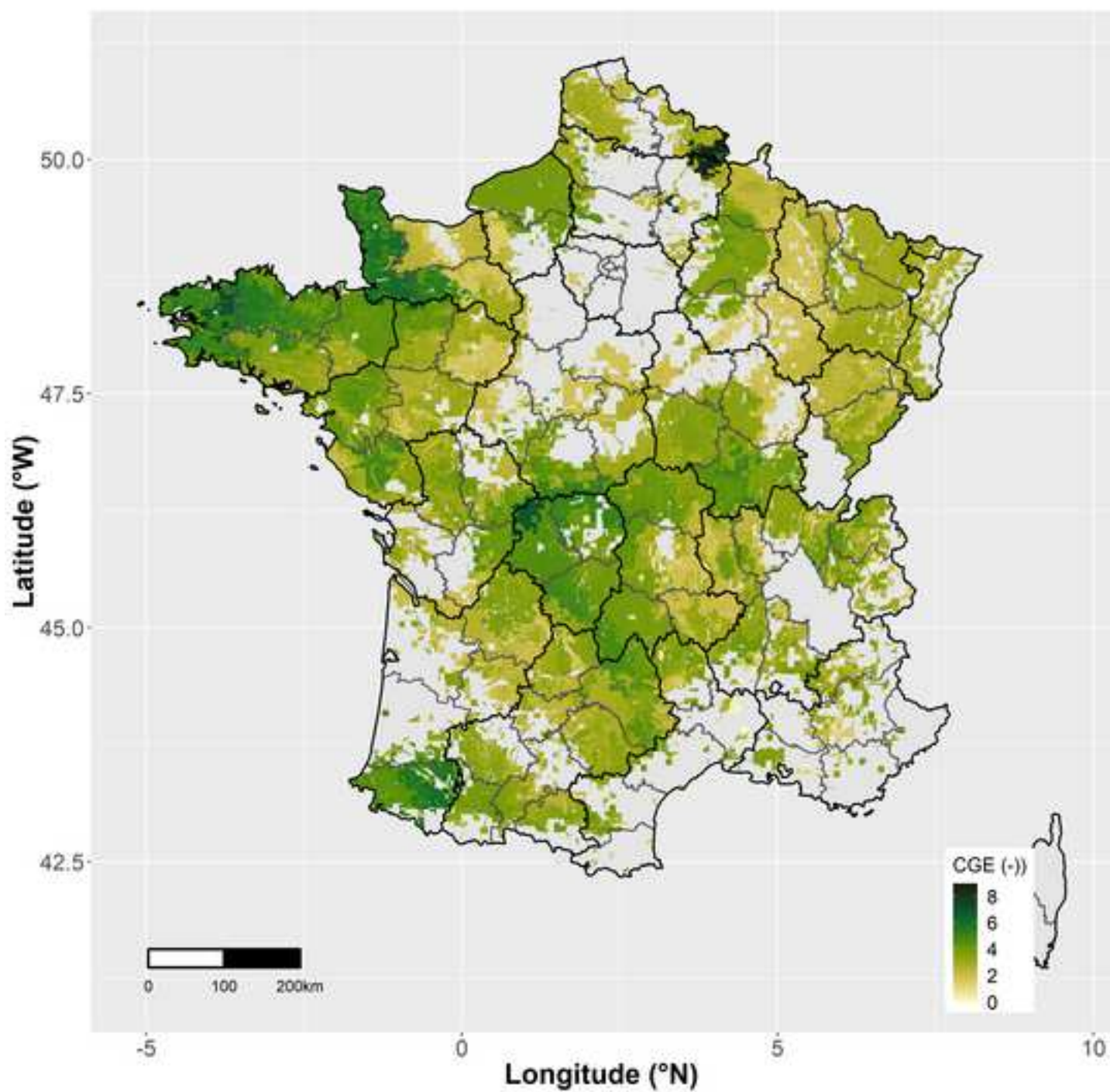
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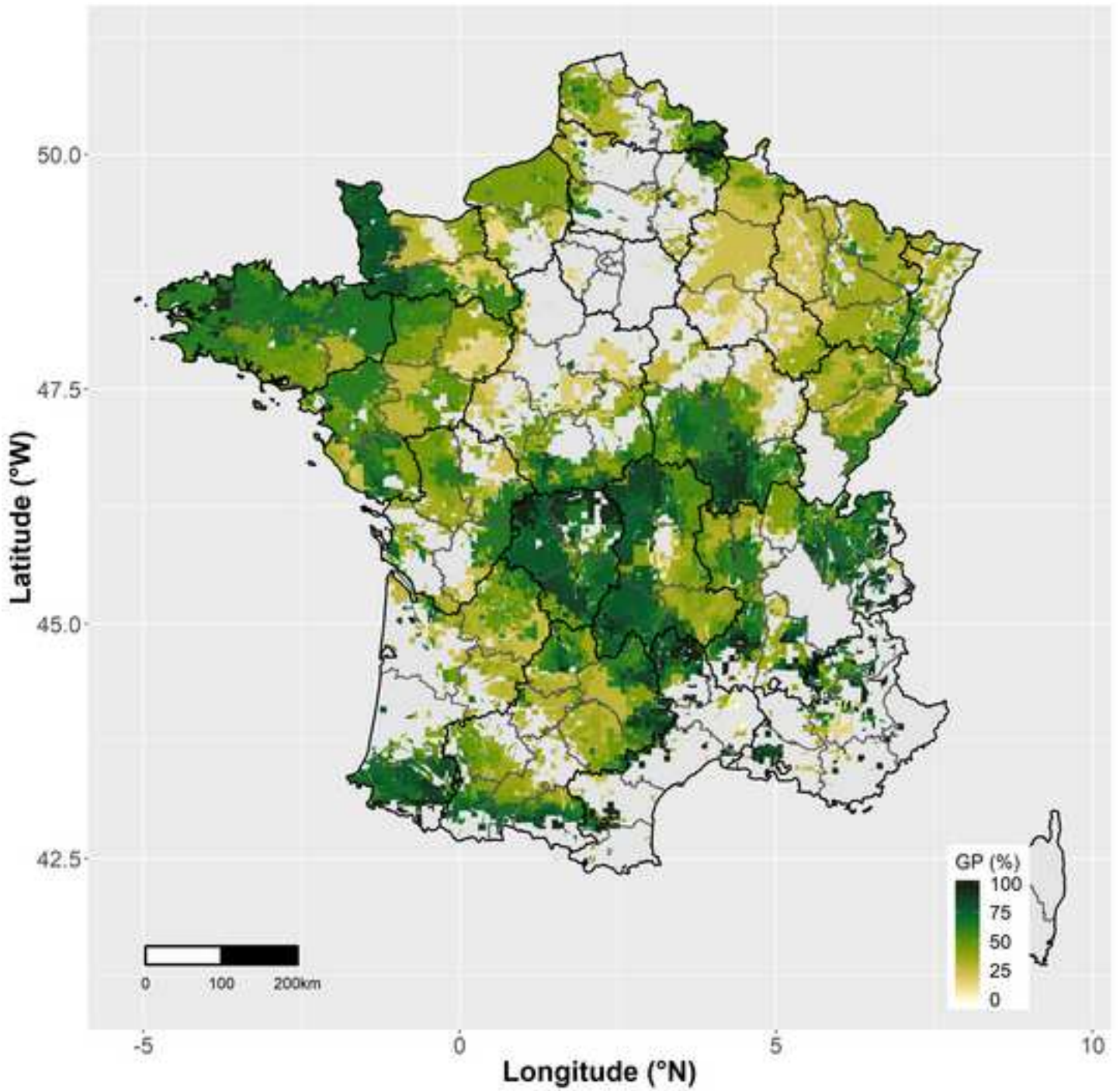
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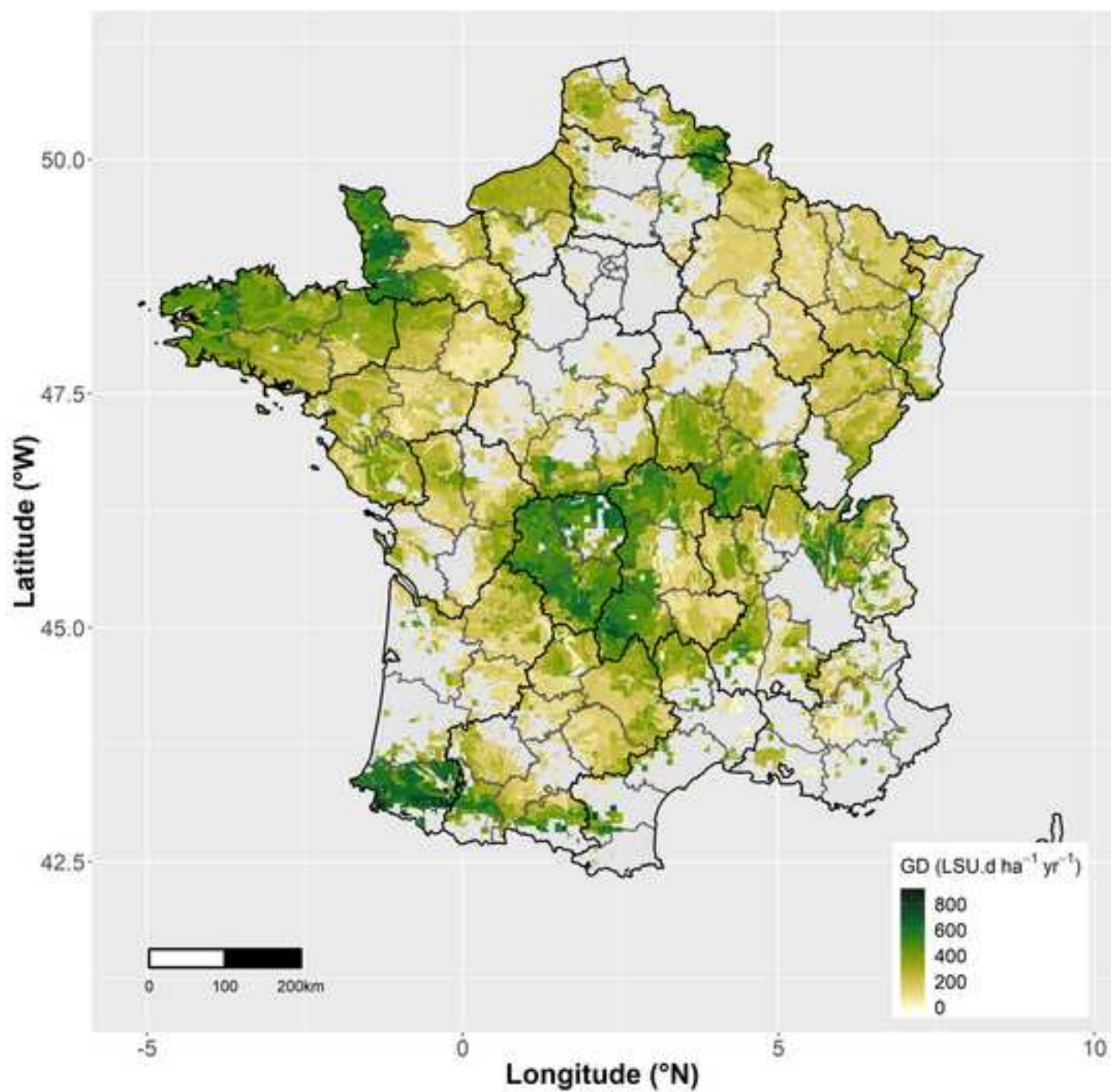
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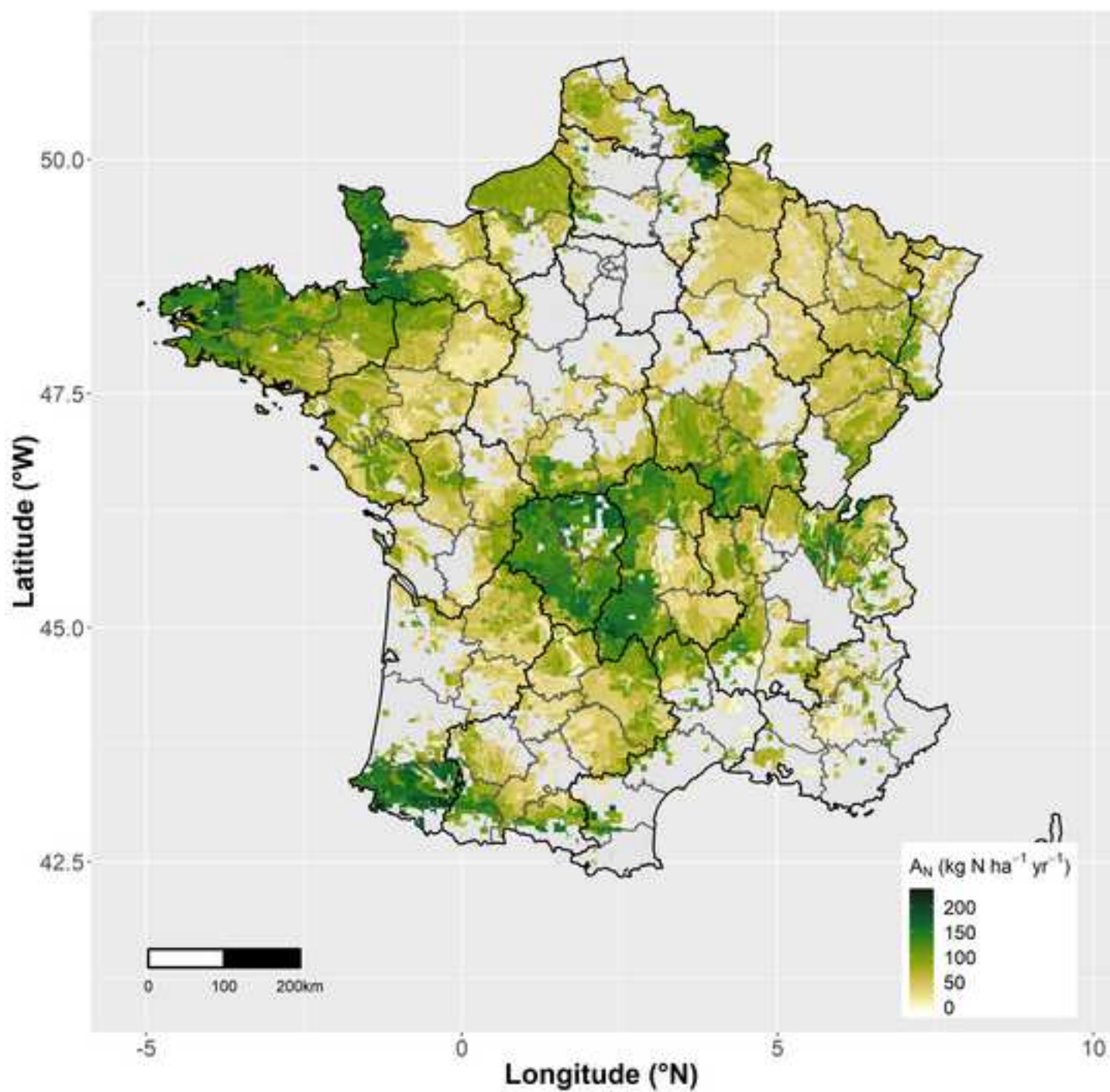
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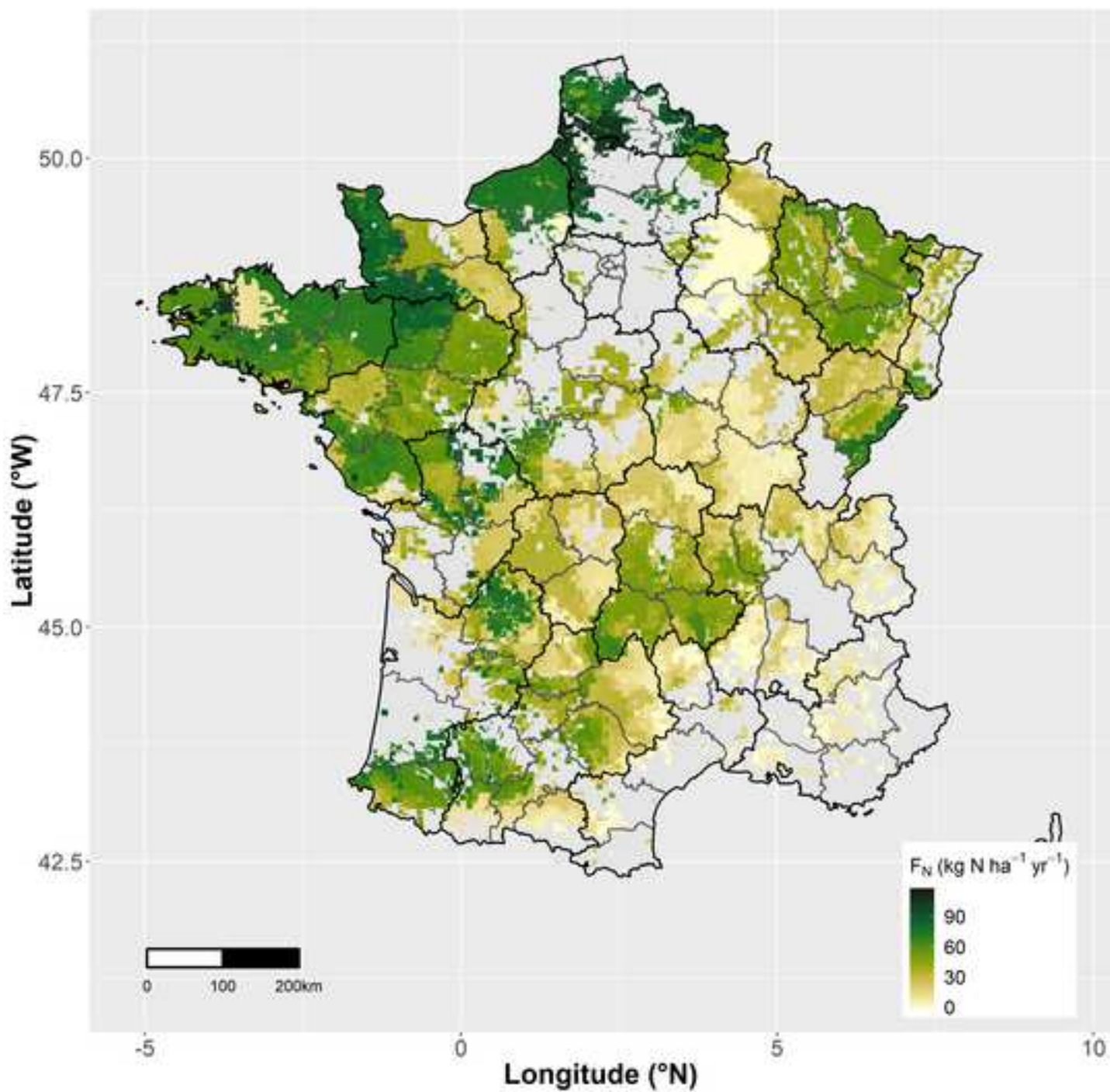
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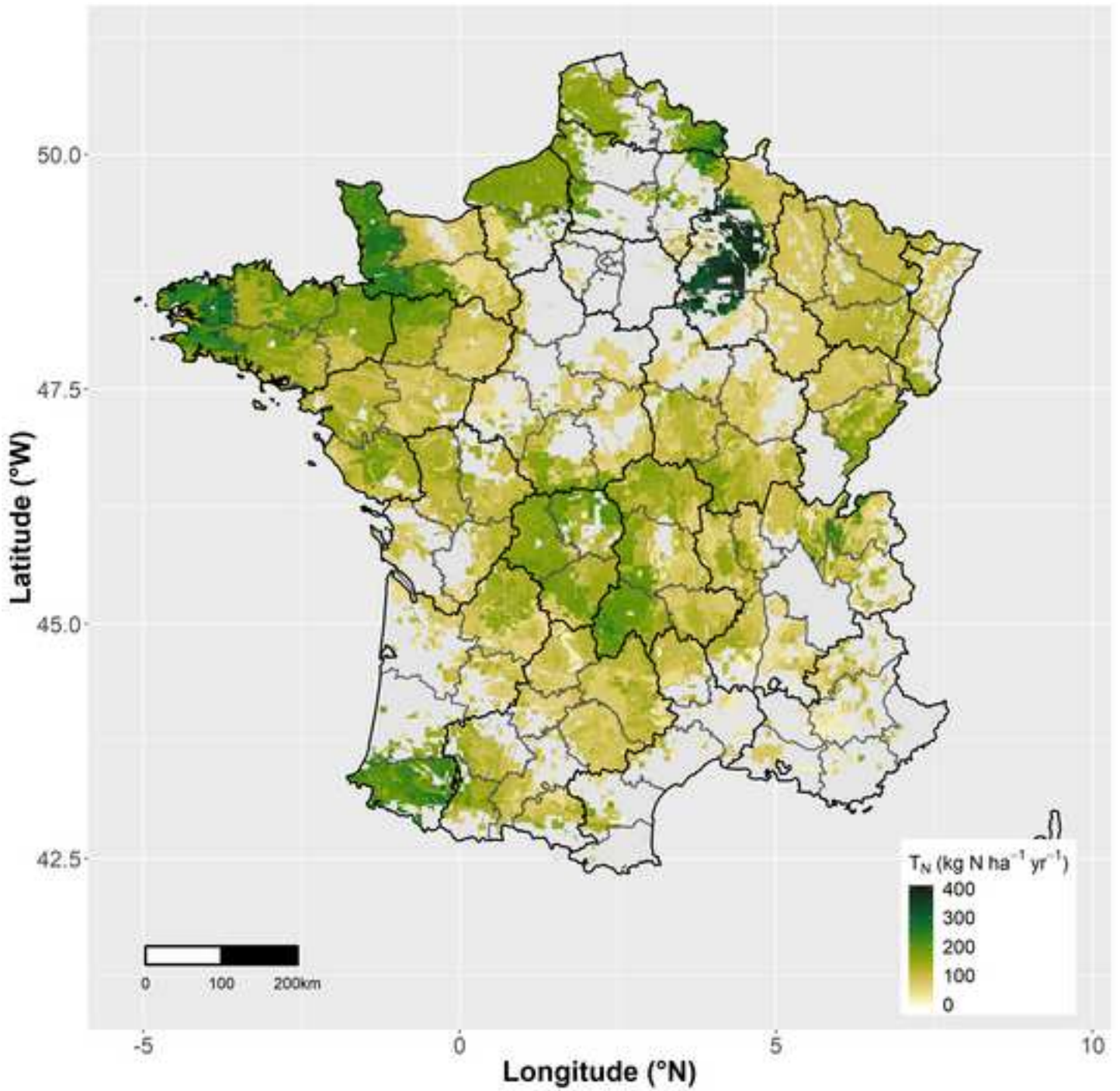
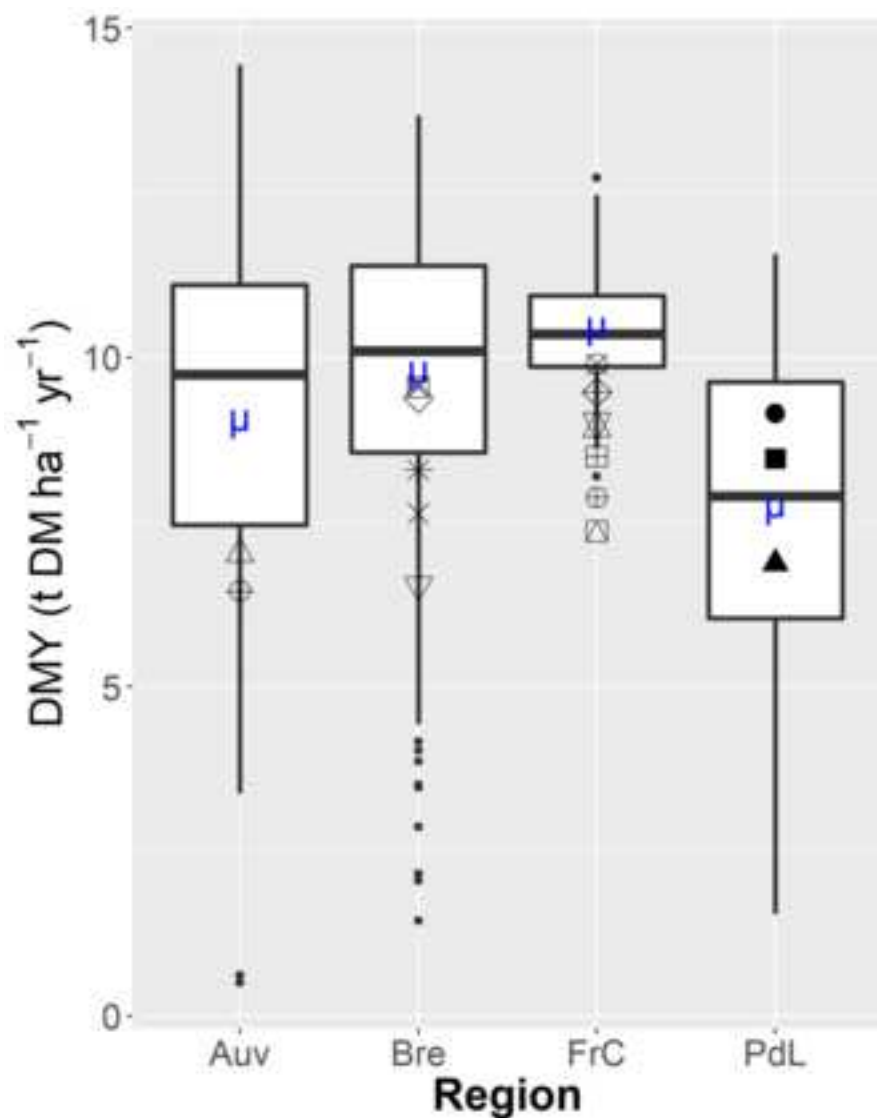


Figure4

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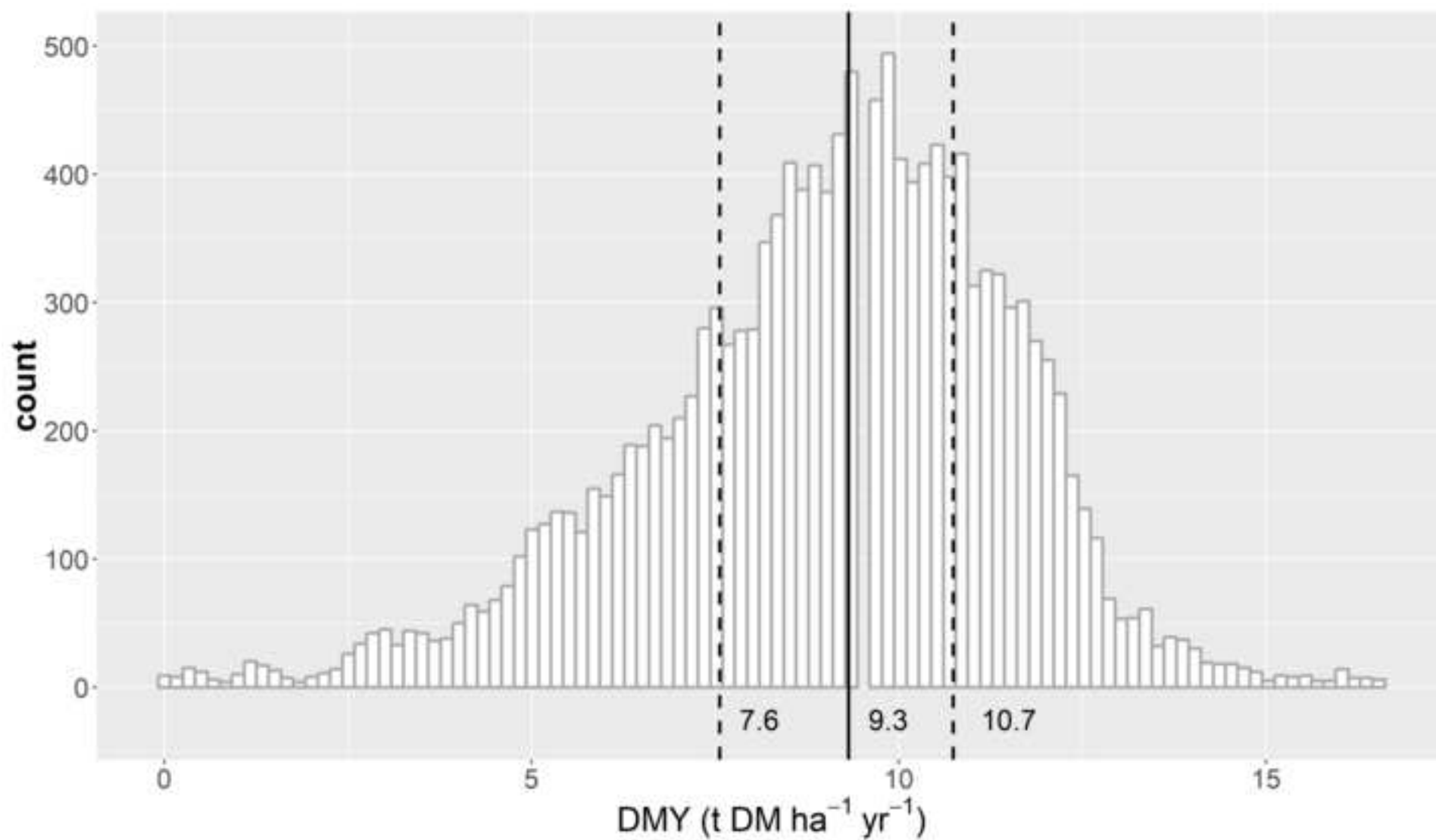
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**Conditions of observations**

- Auv-Lowland
- △ Auv-Mountainous
- + Auv-Semi-mountainous
- × Bre-Early development in spring, dry conditions in summer
- ◇ Bre-Early development in spring, intermediate conditions in summer
- ▽ Bre-Late development in spring, dry conditions in summer
- ⊠ Bre-Late development in spring, humid conditions in summer
- * Bre-Late development in spring, intermediate conditions in summer
- ⊕ FrC-Lowland on deep soils
- ⊕ FrC-Lowland on shallow soils
- ⊗ FrC-Mountain on deep soils
- ⊗ FrC-Mountain on shallow soils
- ⊗ FrC-Plateau on deep soils
- ⊗ FrC-Plateau on shallow soils
- PdL-Middle
- PdL-North
- ▲ PdL-South

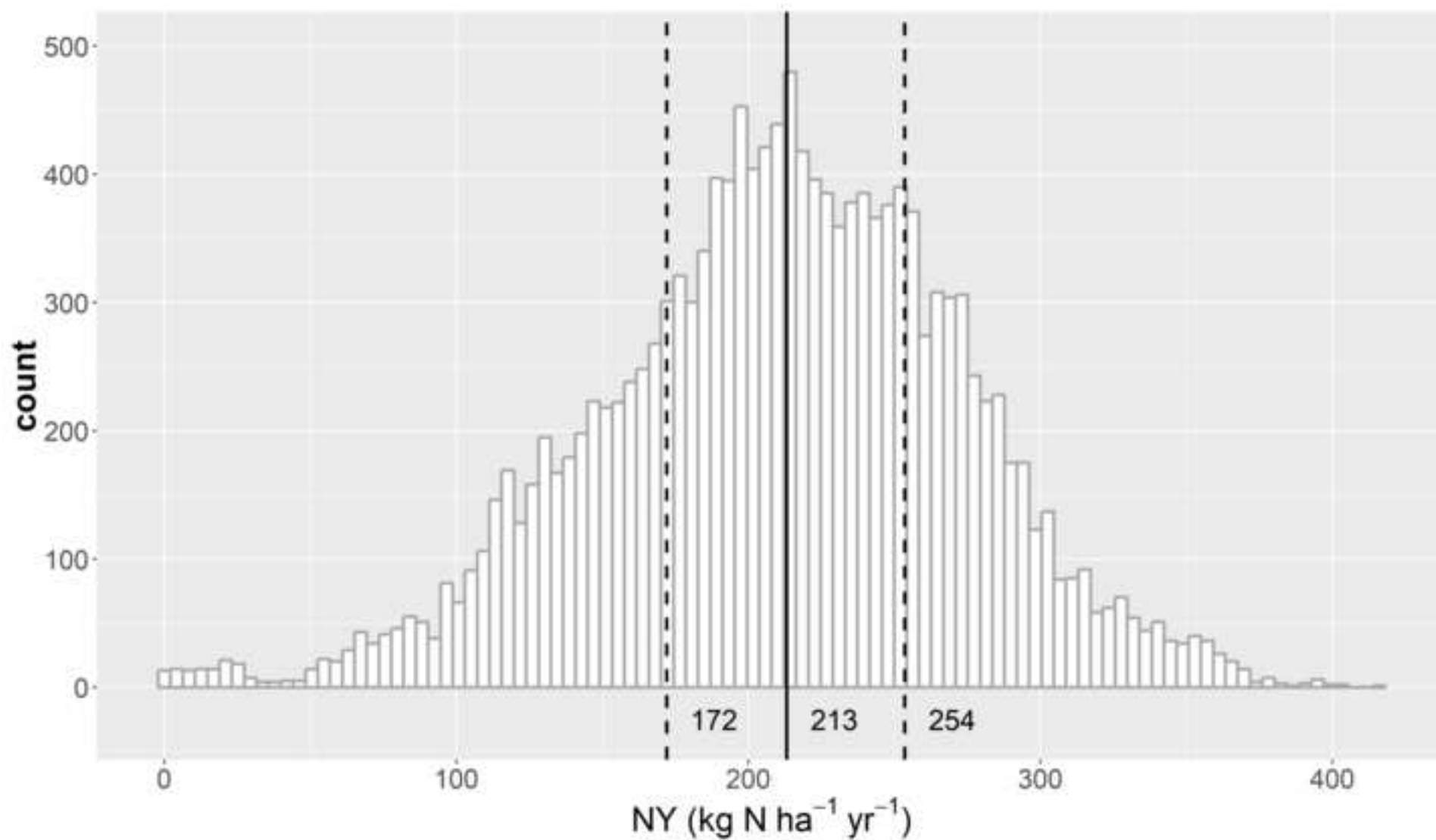
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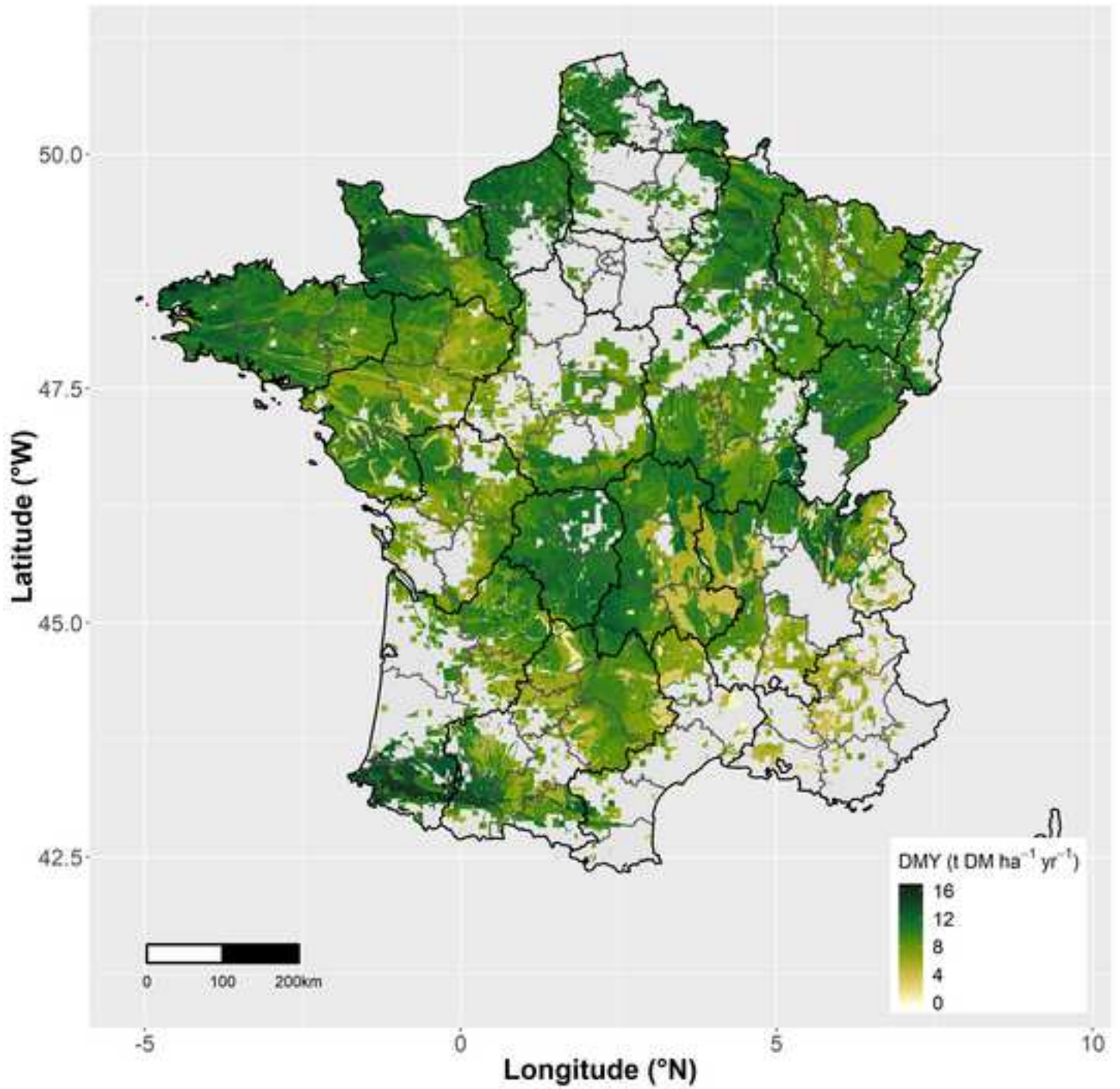
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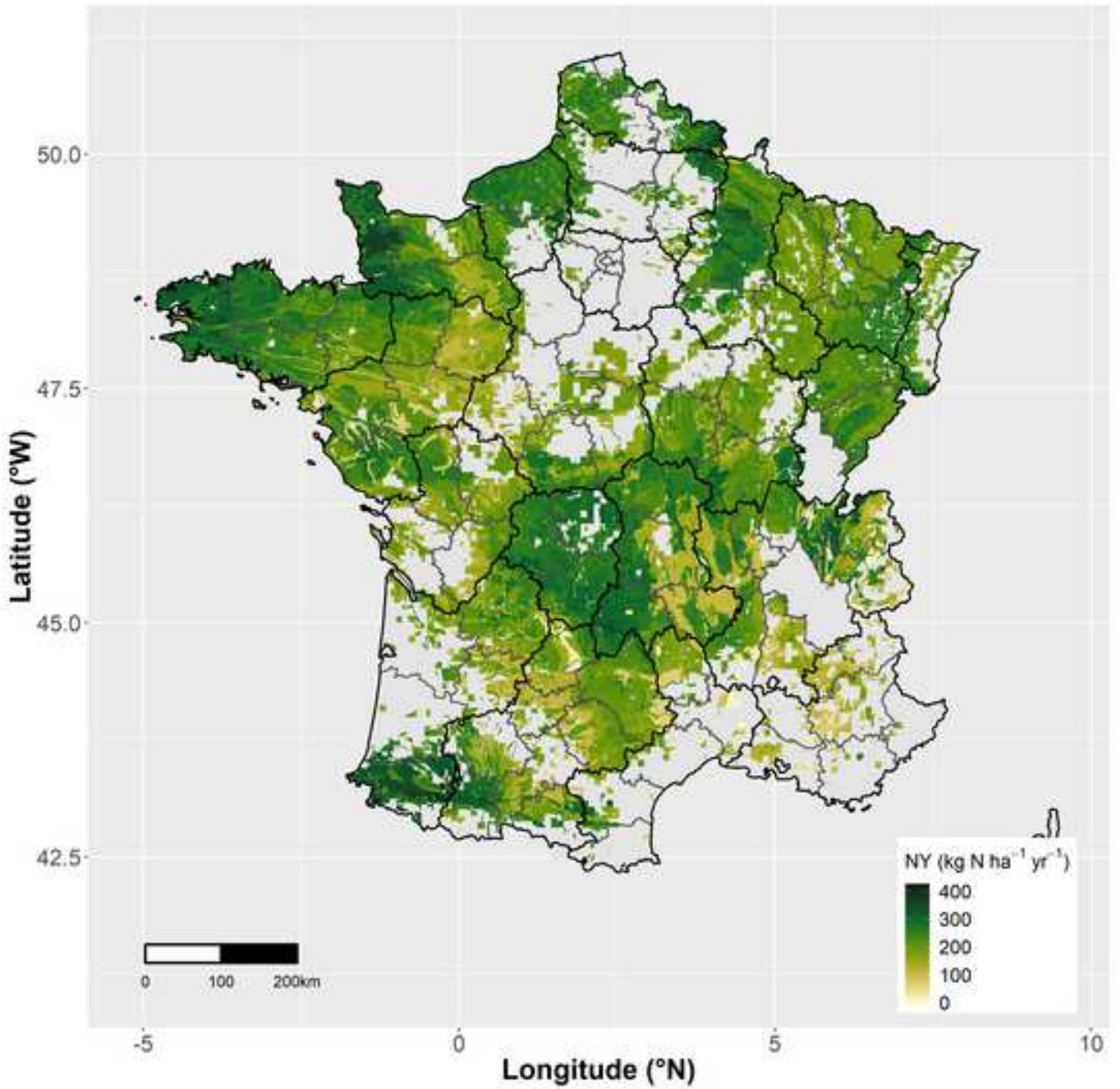
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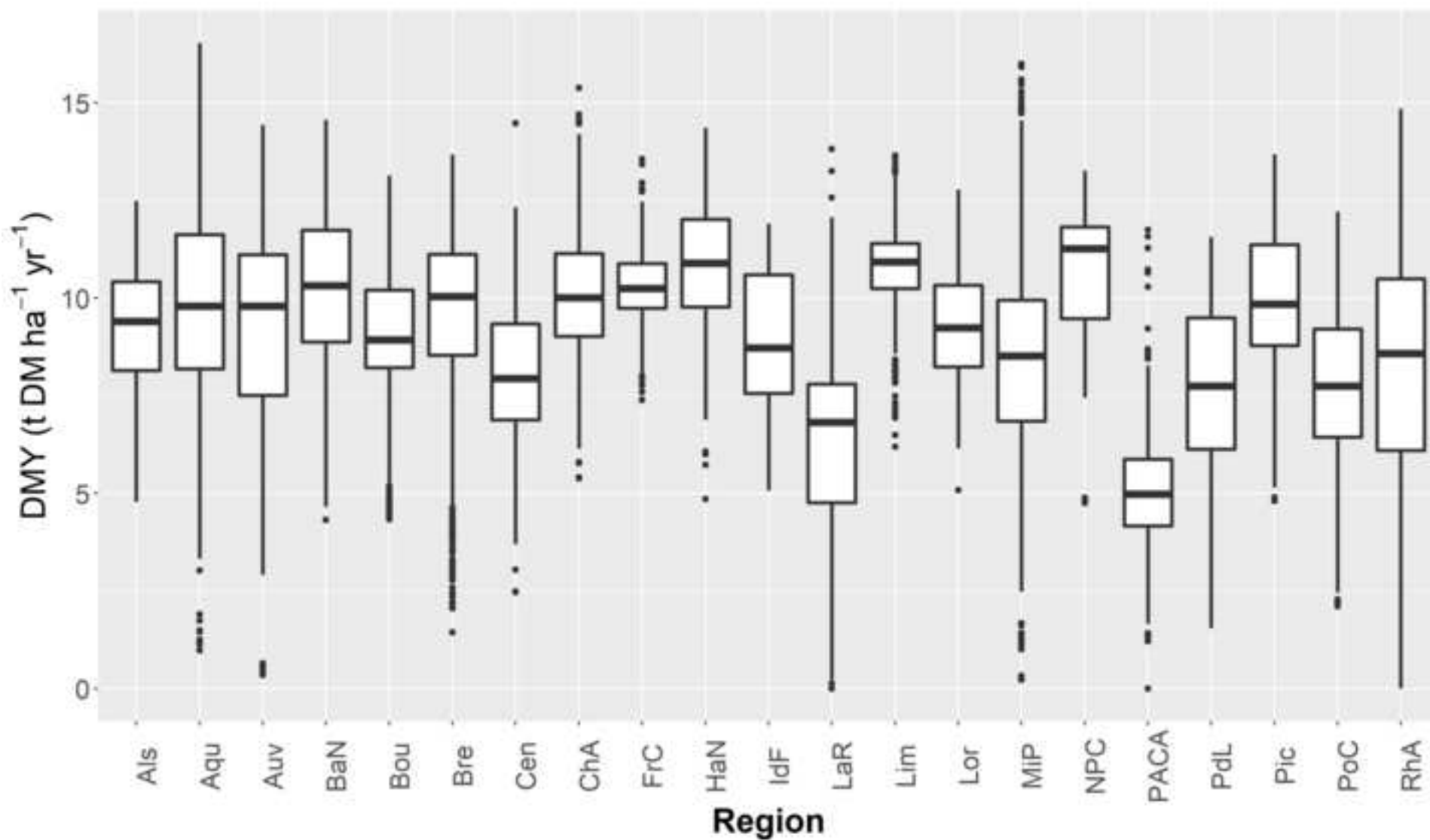


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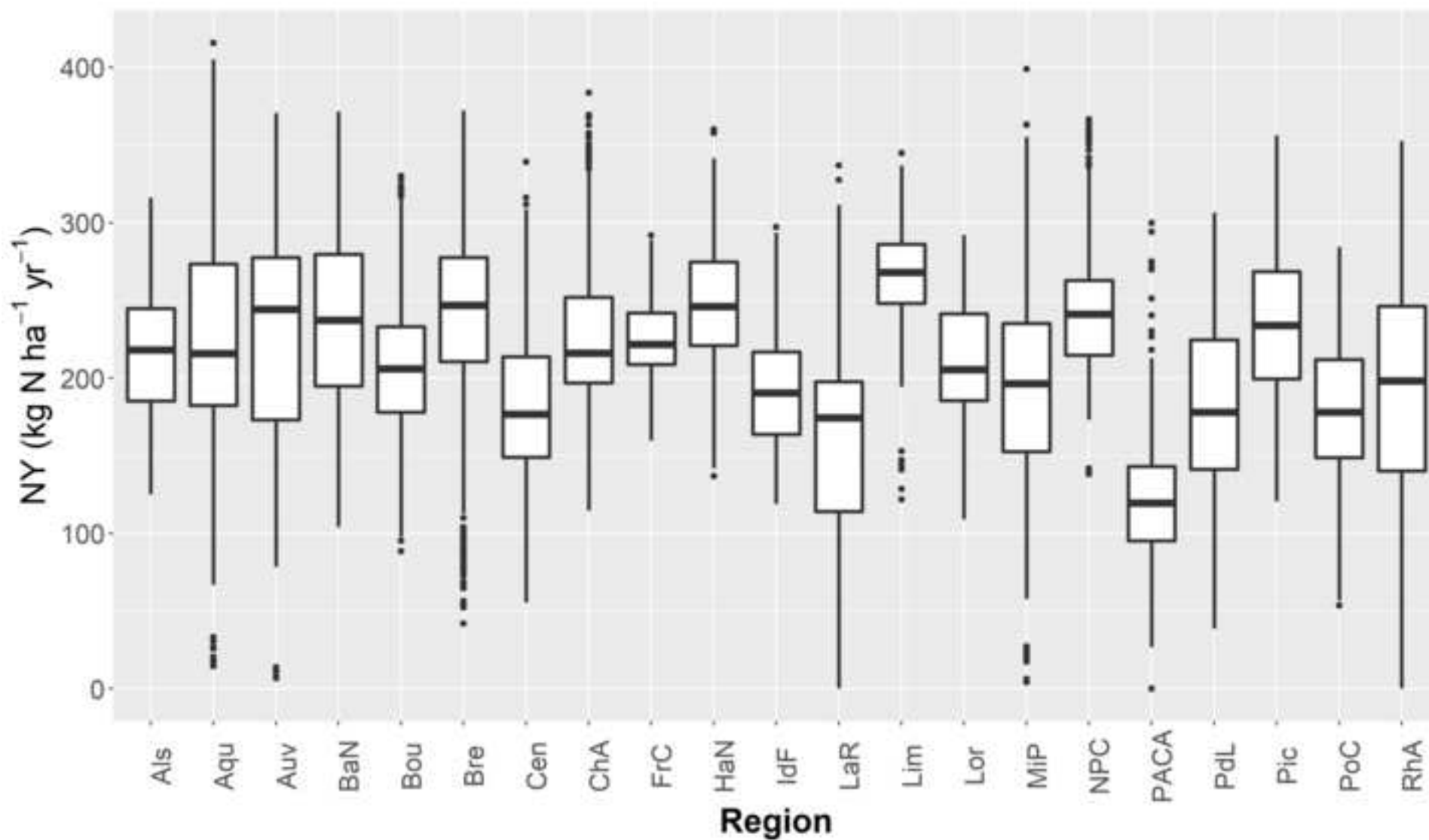






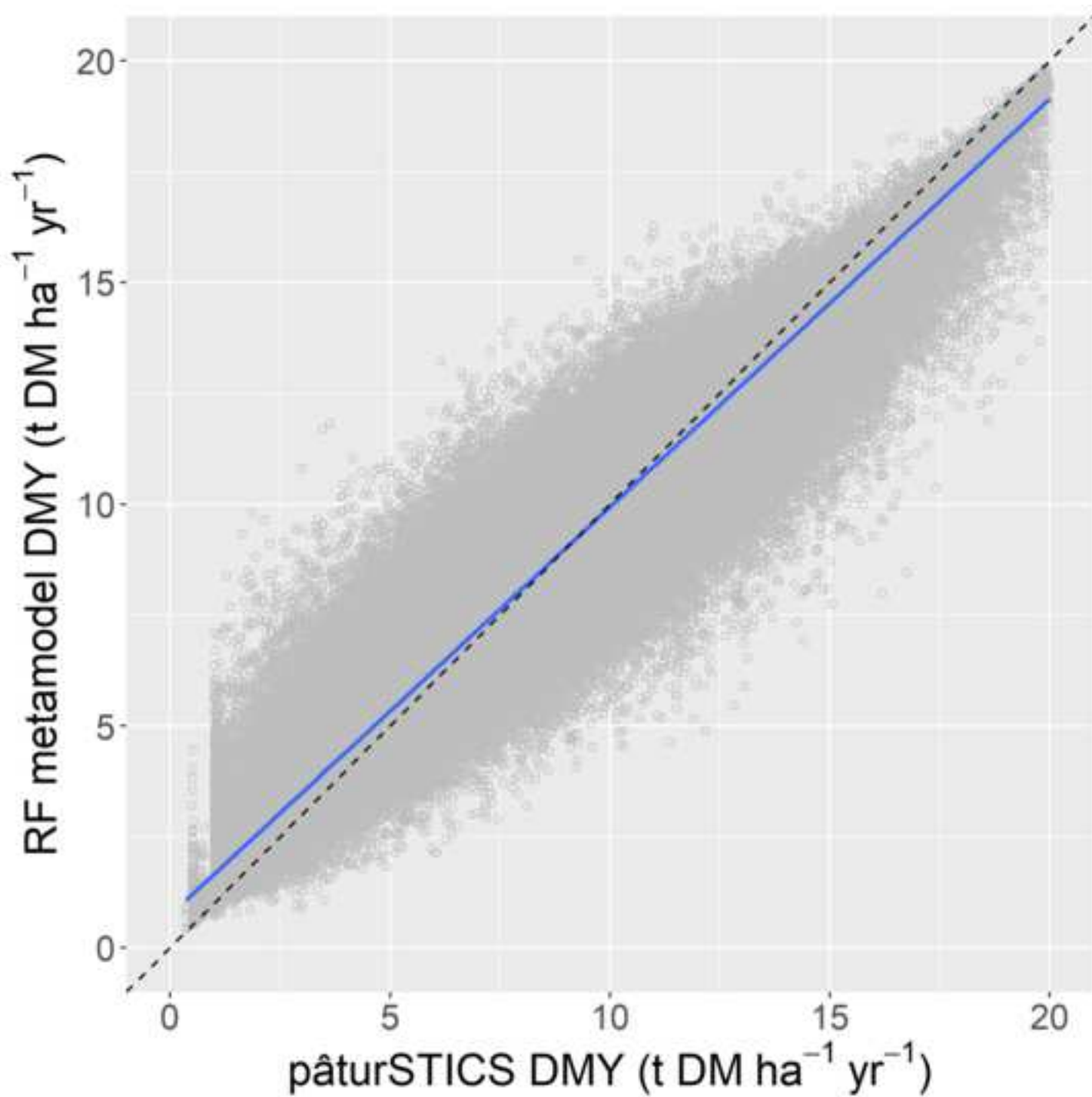
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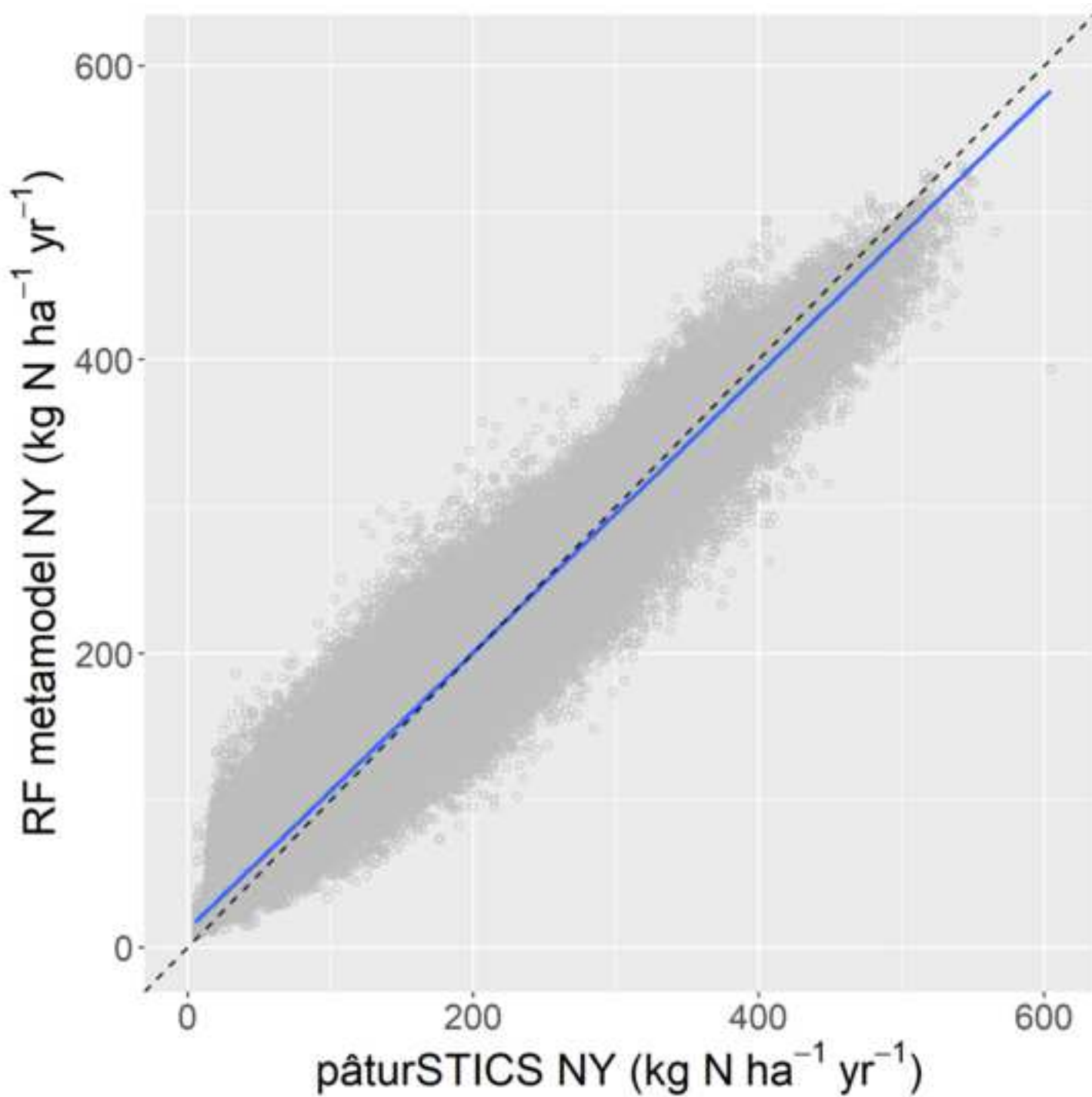
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Table 1. Description of grassland typology simulated.

Grassland type	Description	Percentage of legumes
Type 1	permanent grasslands extensively managed (not fertilised)	0
Type 2	temporary sown swards of pure legumes	100
Type 3	temporary sown pure grass or grass-legume mixtures	0 (pure swards) or 30 (mixtures)
Type 4	permanent grasslands intensively managed	0

Table 2. Mean and standard deviation (SD) of predicted DM yield (DMY, t DM ha⁻¹ yr⁻¹) and N yield (NY, kg N ha⁻¹ yr⁻¹) associated with cutting and grazing activities in grasslands in French departments simulated over the 1984-2013 period. n represents the number of pedoclimatic units simulated in a given department.

Region	Department	n	DMY		NY	
			Mean	SD	Mean	SD
Alsace	Bas-Rhin	121	8.9	1.6	202	35
	Haut-Rhin	82	9.8	1.4	233	34
Aquitaine	Dordogne	360	9.1	1.9	202	48
	Gironde	130	8.6	1.6	187	38
	Landes	87	10.4	2.2	241	47
	Lot-et-Garonne	156	7.4	2.2	158	50
	Pyrénées-Atlantiques	292	12.8	2.6	306	62
Auvergne	Allier	285	9.8	2.0	238	49
	Cantal	191	10.4	2.3	269	55
	Haute-Loire	155	7.0	2.7	179	65
	Puy-de-Dôme	260	8.5	2.9	204	74
Basse-Normandie	Calvados	242	10.4	1.7	213	37
	Manche	278	11.5	1.8	300	44
	Orne	286	8.8	1.7	201	48
Bourgogne	Côte-d'Or	299	8.9	1.6	196	36
	Nièvre	244	9.0	1.8	208	43
	Saône-et-Loire	353	9.3	2.1	225	55
	Yonne	109	8.2	1.6	178	37
Bretagne	Côtes d'Armor	281	9.8	1.7	251	44
	Finistère	296	10.9	2.2	282	54
	Ille-et-Vilaine	310	8.6	2.1	209	53
	Morbihan	353	9.5	2.0	225	47
Centre	Cher	219	8.5	1.5	188	41
	Eure-et-Loir	41	7.8	1.6	168	35
	Indre	201	9.0	1.7	213	48
	Indre-et-Loire	157	6.8	1.3	150	31
	Loir-et-Cher	79	8.0	1.5	173	38

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	Loiret	58	7.9	1.5	169	37
Champagne-Ardenne	Ardennes	222	10.5	1.6	234	42
	Aube	140	9.6	1.6	213	48
	Haute-Marne	239	9.5	1.0	199	19
	Marne	227	10.6	1.7	253	50
Franche-Comté	Doubs	204	10.2	1.1	225	32
	Haute-Saône	204	10.3	0.9	223	20
	Jura	26	10.7	1.5	235	29
	Terr. de Belfort	25	10.3	0.9	231	27
Haute-Normandie	Eure	171	10.5	1.9	229	49
	Seine-Maritime	297	11.0	1.3	254	29
Ile-de-France	Essonne	1	11.9	NA	297	NA
	Seine-et-Marne	15	8.9	2.0	184	44
	Val-D'Oise	8	8.6	2.3	208	52
	Yvelines	12	9.3	0.8	193	21
Languedoc-Rousillon	Aude	66	7.6	2.7	182	70
	Gard	38	3.7	2.7	87	66
	Hérault	42	6.1	2.3	155	60
	Lozère	117	6.5	2.4	164	62
	Pyrénées-Orientales	12	7.9	3.1	202	81
Limousin	Corrèze	178	10.9	1.2	260	38
	Creuse	123	10.9	0.9	276	25
	Haute-Vienne	189	10.4	1.3	263	27
Lorraine	Meurthe-et-Moselle	202	9.2	1.6	213	39
	Meuse	255	9.3	1.2	195	26
	Moselle	227	9.0	1.5	211	36
	Vosges	210	10.1	1.1	234	32
Midi-Pyrénées	Ariège	121	9.1	2.5	204	64
	Aveyron	316	7.8	2.4	188	59
	Gers	239	8.7	2.1	204	51
	Haute-Garonne	190	8.5	2.3	193	58
	Hauts-Pyrénées	145	11.8	2.5	279	53
	Lot	192	7.6	3.0	171	74

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	Tarn	182	7.5	1.7	168	41
	Tarn-et-Garonne	108	7.4	1.8	162	44
Nord-Pas-de-Calais	Nord	186	11.1	1.6	262	48
	Pas-de-Calais	231	10.4	1.3	227	27
Pays de la Loire	Loire-Atlantique	308	7.7	2.3	190	58
	Maine-et-Loire	310	6.8	2.3	157	52
	Mayenne	260	8.9	1.6	212	42
	Sarthe	266	6.9	1.3	149	29
	Vendée	259	7.9	2.9	195	73
Picardie	Aisne	167	9.9	2.1	243	62
	Oise	98	9.7	1.8	235	45
	Somme	113	9.9	1.2	221	28
Poitou-Charentes	Charente	165	8.0	1.6	183	42
	Charente-Maritime	143	7.3	1.5	166	36
	Deux-Sèvres	210	7.8	2.3	185	55
	Vienne	215	7.7	1.6	181	38
Provence-Alpes-Côte d'Azur	Alpes-de-Haute-Provence	81	5.3	1.4	123	41
	Alpes-Maritimes	3	6.3	0.8	173	35
	Bouches-du-Rhône	42	4.7	1.4	118	37
	Hautes-Alpes	102	5.3	2.1	128	54
	Var	18	4.9	2.2	113	60
	Vaucluse	10	5.2	1.3	118	36
Rhône-Alpes	Ain	215	10.0	2.6	228	66
	Ardèche	126	7.6	2.7	185	73
	Drôme	129	6.6	1.8	147	42
	Haute-Savoie	121	9.1	3.3	217	82
	Isère	12	8.3	3.7	192	91
	Loire	153	8.3	3.0	198	69
	Rhône	79	8.1	2.8	185	60
	Savoie	142	6.9	3.7	166	88

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Table 3. Predictors used for random forest regression models and their ranges. Ranks correspond to a variable importance measure determined by random forest models for each dataset.

	Variable	Abbreviation	Unit	Range		Rank of importance	
				Min	Max	DMY	NY
Climate	Mean annual temperature	T	°C	-2.5	17.0	3	3
	Annual global radiation	R _g	MJ m ⁻² yr ⁻¹	2849	6531	2	1
	Annual precipitation	P	mm yr ⁻¹	271	3315	5	6
Soil	Soil organic N content in the topsoil	N _{org}	% dry soil	0.068	0.40	7	4
	Soil water holding capacity	WHC	mm	7	172	4	7
Grassland	Percentage of legumes	Leg	%	0	100	10	10
	Grassland age	Age	yr	2	5	1	2
Management	Annual nitrogen fertiliser application	F _N	kg N ha ⁻¹ yr ⁻¹	0	200	6	5
	Grazing days	GD	(LSU days) ha ⁻¹ yr ⁻¹	0	1176	8	8
	Number of cutting events	CE	Dimensionless	0	4	9	9

Table 4. Evaluation statistics (root mean square error (RMSE), relative RMSE (RRMSE), and Nash-Sutcliffe model efficiency (EF)) of random forest model performance of predicted dry matter yield (DMY) and nitrogen yield (NY) on test datasets.

Variable	Unit	RMSE	RRMSE	EF
DMY	t DM ha ⁻¹ yr ⁻¹	0.77	21.8%	0.95
NY	kg N ha ⁻¹ yr ⁻¹	16.5	18.3%	0.97