



HAL
open science

Enhancing environmental models with a new downscaling method for global radiation in complex terrain

Arsène Druel, Julien Ruffault, Hendrik Davi, André Chanzy, Olivier Marloie,
Miquel de Cáceres, Florent Mouillot, Christophe François, Kamel Soudani,
Nicolas Martin-StPaul

► **To cite this version:**

Arsène Druel, Julien Ruffault, Hendrik Davi, André Chanzy, Olivier Marloie, et al.. Enhancing environmental models with a new downscaling method for global radiation in complex terrain. 2024. hal-04749982

HAL Id: hal-04749982

<https://hal.science/hal-04749982v1>

Preprint submitted on 23 Oct 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



1

Title:

2 **Enhancing environmental models with a new downscaling method**
3 **for global radiation in complex terrain**

4 **Authors / co authors:**

5 Druel, Arsène¹, Ruffault, Julien¹, Davi, Hendrik¹, Chanzy, André², Marloie, Olivier¹, De
6 Cáceres, Miquel³, Mouillot, Florent⁴, François, Christophe⁵, Soudani, Kamel⁵, and Martin-
7 StPaul, Nicolas K.¹.

8 ¹URFM, INRAE, 84000 Avignon, France; ²UMR 1114 EMMAH, INRAE, Avignon University,
9 84000 Avignon, France; ³CREAF, Centre de Recerca Ecològica i Aplicacions Forestals,
10 Bellaterra, Catalonia, Spain; ⁴UMR 5175 CEFE, Montpellier University, CNRS, EPHE, IRD,
11 Montpellier, France; ⁵UMR 8079 ESE, UPS, CNRS, AgroParisTech, Orsay, France

12 **Correspondence email:** arsene.druel@inrae.fr

13



14 **Abstract:**

15 Global radiation is a key climate input in forest process-based models (PBM) as it
16 determines photosynthesis, transpiration and the canopy energy balance. While radiation is
17 highly variable at fine spatial resolution in complex terrain due to shadowing effects, data
18 required for PBM currently available over large extents are generally at spatial resolution
19 coarser than ~9 km. Downscaling radiation from large-scale to high resolution available from
20 digital elevation models is therefore of potential importance to refine global radiation
21 estimates and improve PBM estimations. In this study, we introduce a new downscaling
22 model that aims to refine sub-daily global radiation data obtained from climate reanalysis or
23 projection at large scales to the resolution of a given digital elevation model. First,
24 downscaling involves splitting radiation into direct and diffuse fraction. Then, the influence of
25 surrounding mountains' shade on direct radiation and the "bowl" (deep valley) effect on
26 diffuse radiation is considered. The model was evaluated by comparing simulated and
27 observed radiation at the Mont Ventoux mountain study site (southeast of France) using the
28 recent ERA5-Land hourly data available at 9 km resolution as input and downscaled at
29 different spatial resolution (from 1 km to 30 m resolution) using a digital elevation model. The
30 downscaling algorithm improved the reliability of radiation at the study site in particular at
31 scales below 150 m. Finally, by using two different process based models (Castanea, a
32 process-based model simulating tree growth, and SurEau, a plant-hydraulic model
33 simulating hydraulic failure risk), we showed that accounting for fine resolution radiation can
34 have a great impact on predictions of forest functions and climatic risks.

35 **short summary:**

36 Accurate radiation data are essential for understanding ecosystem growth. Traditional large-
37 scale data lack the precision needed for complex terrains, e.g. mountainous regions. This
38 study introduces a new model to enhance radiation data resolution using elevation maps,
39 which accounts for sub-daily direct and diffuse radiation effects caused by terrain features.
40 Tested on Mont Ventoux, this method significantly improves radiation estimates, benefiting
41 forest growth and climate risk models.



42 1. INTRODUCTION

43 Studies assessing the impacts of climate change on forest ecosystem functions increasingly
44 rely on high resolution spatial and temporal climate data. For example, process-based
45 models that aim to evaluate the effect of climate on forest functions and services require
46 daily or sub-daily temporal resolution meteorology as input (e.g., Davi et al., 2006; De
47 Cáceres et al., 2023; Granier et al., 2007; Ruffault et al., 2013, 2022, 2023) to simulate key
48 ecophysiological processes (transpiration, photosynthesis or water potential). Yet, even
49 relatively fine-grained (*i.e.*, 1 km) historical or projected climate products (Hijmans et al.,
50 2005; Brun et al., 2022) do not correspond to the "topographic scale" and cannot reproduce
51 fine-scale patterns observed in heterogeneous landscapes. Moreover, employing spatially-
52 coarse climatic projections can lead to biased and irrelevant inferences of local ecological
53 patterns (Bedia et al., 2013) or to substantial errors in impact studies (e.g., Patsiou et al.,
54 2014; Randin et al., 2009). Improving methodologies to provide climatic data at high spatio-
55 temporal resolution variation is therefore crucial to better understand and forecast the spatial
56 heterogeneity in forest structure and functions.

57 Among climate variables, radiation is a key driver of plant functioning and productivity
58 globally (Churkina and Running, 1998) through two main mechanisms. On one hand, global
59 radiation determines the photosynthetically active radiation (PAR), *i.e.*, the available energy
60 for photosynthesis and thus plant productivity. Numerous studies have shown the
61 relationship between the amount of solar radiation and the distribution of plant species or
62 communities worldwide (Dirnbock et al., 2003; Franklin, 1998; Meentemeyer et al., 2001;
63 Tappeiner et al., 1998; Zimmermann and Kienast, 1999). On the other hand, the radiation
64 reaching a vegetation surface is an important component of the canopy energy balance,
65 driving surface temperature and vapour pressure deficit (Monteith, 1981). Radiation is thus a
66 key driver of evapotranspiration which enters in most potential evapotranspiration
67 formulations (Fisher et al., 2011) and water balance models (Granier 1999; Ruffault et al.
68 2013; De Cáceres et al., 2015). Through its effect on leaf-temperature and vapour pressure
69 deficit, radiation also influences the water-status of the leaves which in turn will drive many
70 plant functions including growth, stomatal aperture and desiccation (Martin-StPaul et al.,
71 2023).

72 In regions with a complex orography, climatic variations can occur over distances ranging
73 from a few metres to a few kilometres. This phenomenon, referred to as topoclimate (Bramer
74 et al., 2018), can play a crucial role in shaping flora and fauna habitat as well as a multitude
75 of ecosystem processes related to climatic variability (Austin, 2002; Piedallu & Gégout,



76 2008; Randin et al., 2009). Accounting for topographic effects on spatial radiation patterns
77 has been well studied with the purpose, for instance, of improving niche models in
78 mountainous areas (Piedallu & Gégout, 2008; Randin et al., 2009). So far, such radiation
79 data are measured or computed from local meteorological stations, or from coarse-scale
80 global meteorological products such as reanalyses (e.g. De Cáceres et al., 2018).

81 Direct radiation is a primary driver of topoclimate variations, as it can undergo changes at a
82 very local scale due to several processes. At the scale of a massif, the surrounding
83 topography can cast shadows on a given point because the sun rays can be physically
84 interrupted. In other words, the presence of nearby high peaks will impact the rays directly
85 coming from the sun. At the scale of a point in space, the slope and aspect, will in addition
86 modify the direct radiation intensity received. In the northern hemisphere, a south face will
87 receive more radiation than a north face, and this will be modulated by the angle between
88 the sun rays and the slope at the point. Similarly, the surrounding topography will affect
89 diffuse luminosity (e.g., on cloudy days) anisotropically (at 360°), leading to lower luminosity
90 in valley bottoms (*i.e.*, the “bowl effect”).

91 Historically, the primary method for accounting for the effects of topography on radiation has
92 been to rely on slope or aspect. Indeed, these parameters are relatively simple to measure
93 (e.g., through GIS) and the global radiation flux at the surface can be easily derived from
94 those (Austin et al., 1990; Carroll et al., 1999; Clark et al., 1999; Pierce et al., 2005).
95 However, this downscaling approach overlooks a significant portion of the processes
96 involved in radiation attenuation due to sky obstruction by surrounding topography. Regional
97 climate models (RCMs), on the other hand, calculate radiation by accounting for atmospheric
98 processes in relation to land-surface processes (energy balance etc...). Nevertheless, they
99 typically operate on fixed grids, usually at scales of several kilometres (Bailey et al., 2023),
100 which is not precise enough for operational use at point level. More recently, another method
101 employed is statistical downscaling, which is empirical and based on regressions (Davy &
102 Kusch, 2021; Fealy & Sweeney, 2008) or machine learning techniques (Hernanz et al.,
103 2023). However, this requires a lot of field data in different contexts to elaborate an empirical
104 model.

105 Piedallu & Gégout (2008) proposed one method using the slope and the aspect of the point
106 to compute the sun intensity and taking into account the surrounding topography to compute
107 radiation accounting for direct shadowing. They produced a fine scale map (50 * 50 m) over
108 France which is dedicated to statistical niche modelling or mortality risk assessment
109 (Piedallu & Gégout, 2008). However, in the case of process-based vegetation models this



110 has several limitations. Firstly, their approach relies on interpolated meteorological station
111 data to compute the radiation correction at a monthly time step and is thus limited in terms of
112 temporal and spatial accuracy, leading to significant biases in vegetation growth or the
113 smoothing of climatic extremes. Secondly, they do not separate diffuse and direct radiation
114 using clouds but only use an empirical correction of the total radiation using cloud cover.
115 Finally, the “bowl effect” on diffuse radiation is not taken into account. This method based on
116 measurements is thus limited for projection purposes and requires a large network of
117 equipped stations, resulting in uncertainty. Moreover, it has been applied only to France and
118 has not been generalised to other regions or periods.

119 In this study we present a process-based method to downscale coarse resolution (0.1° at
120 best in general) global radiation data (such as global reanalysis or climate projections) made
121 on flat surfaces down to the level of 1 km to 30 m resolution Digital Elevation Model (DEM)
122 by accounting for slope, aspect and the shadowing effect on direct radiation and for the bowl
123 effect on diffuse radiation. The method can be applied at any resolution, depending on the
124 choice of the DEM. Moreover, it relies on any type of radiation data, making it applicable to
125 any region in the world and to historical periods as well as future projections. The possibility
126 to use reanalyses-derived radiation furthermore ensures physical consistency between the
127 different climate variables used in process-based models. The algorithm was tested on the
128 Mont Ventoux and compared with PAR measurements recorded during 2 years at 7 sites on
129 this complex topographic area. Finally we evaluated how this new radiation product can
130 impact ecological patterns by simulating the gross primary productivity (GPP) and the risk of
131 hydraulic failure for *Fagus sylvatica* using two process-based models.

132 **2. METHODS**

133 **2.1. Radiation downscaling model**

134 The proposed radiation downscaling model aims to refine sub-daily global radiation data
135 obtained from reanalysis at large scales to the resolution of a given DEM. This process-
136 based method can be adapted depending on the input dataset and accounts for the
137 shadowing effect on direct radiation and the bowl effect on diffuse radiation. In order to
138 ensure its versatility and applicability, we reduced the need for external data that can be
139 challenging to obtain at the local scale, such as cloudiness (Dubayah and Loechel, 1997;
140 Piedallu and Gégout, 2007). The only required input is a DEM whose resolution must match
141 the desired final spatial resolution of the radiation data.

142 Our methodology involves four distinct steps, outlined as follows (see Fig. 1 for



143 visualisation):

144 i. Splitting direct and diffuse radiation from a large-scale global radiation dataset (optional if

145 the data already contain direct and diffuse radiation).

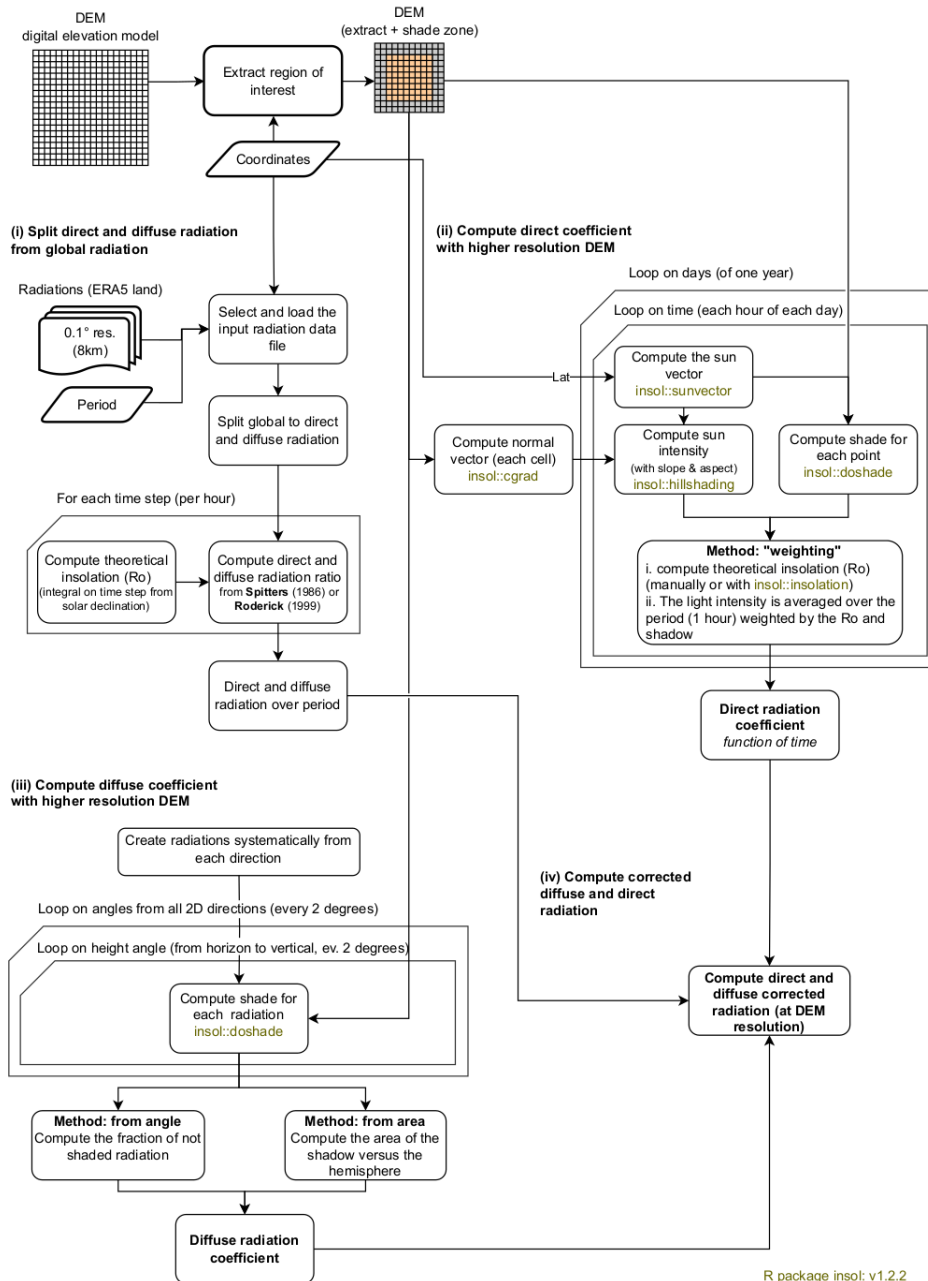
146 ii. Downscaling direct radiation by considering local topography and shadowing effects.

147 iii. Downscaling diffuse radiation by estimating the proportion of diffuse radiation that

148 reaches the target point relative to the surrounding topography.

149 iv. Summing the downscaled direct and diffuse radiation components.

150 These steps are described in detail in the subsequent sections.



151 **Figure 1: Simplified workflow of radiation downscaling, showing the four different**
 152 **steps of the procedure. The bold boxes at the top left show the data required as**
 153 **inputs (DEM, coordinates, period and large scale radiation), the green boxes show the**
 154 **functions of the external R package used (insol), the truncated boxes show the loops**
 155 **and the rounded boxes show the various stages.**



156 **2.1.1. Splitting direct and diffuse radiation**

157 In cases where only global radiation is available from the input dataset, as in products like
158 ERA5-Land (Muñoz-Sabater et al., 2021), a first step involves extracting hourly direct and
159 diffuse radiation (Fig. 1.i). Various methods exist for this purpose (Oliphant & Stoy, 2018). In
160 this study, we adopted the approach proposed by Spitters et al. (1986). This choice was
161 driven by the relative simplicity of this approach and the fact that it was originally developed
162 for European landscapes. Additionally, we explored other methods, such as the one
163 proposed by Roderick (1999) and the one proposed by Bird and Hulstrom (1981). Results
164 obtained using the Roderick (1999) method align consistently with those presented herein
165 (results not displayed). Unlike the method by Spitters et al. (1986), the method by Bird and
166 Hulstrom (1981) does not rely on global radiation values but instead aims to derive the
167 values of direct and diffuse radiation from theoretical radiation, temperature, humidity,
168 among other factors. However, the outcomes generated by this model significantly deviated
169 from those obtained using the Spitters et al. (1986) method and exhibited inconsistency with
170 available measurements (not shown).

171 The method of Spitters et al. (1986) that was used in this study is an empirical computation
172 technique based on the ratio between theoretical extraterrestrial irradiance (R_o) and the
173 observed value of global radiation (R_g). Specifically, it operates on the assumption that as
174 the ratio of R_g to R_o decreases, the proportion of diffuse radiation (R_{diff}) relative to direct
175 radiation (R_{dir}) increases - an effect attributed to cloud cover.

176 To compute R_o (in $J.m^{-2}.s^{-1}$), a common physically-based approach involves using the
177 radiation incident on a plane parallel to the Earth's surface and the sine of solar elevation
178 (which is dependent on latitude and solar time), as follows:

a. $R_o = R_{sc} [1 + 0.033 \times \cos(doy \times 360/365)] \times \sin(\beta)$
179 b. $\sin(\beta) = \sin(\lambda) \times \sin(\delta) + \cos(\lambda) \times \cos(\delta) \times \cos(15 \times (t_h - 12))$ (1)
c. $\delta = \frac{\pi \times 23.45}{180} \times \sin\left(2 \times \pi \times \frac{doy + 284}{365}\right)$

180 With R_{sc} representing the solar constant ($1\,370\, J.m^{-2}.s^{-1}$, I.E.A., 1978), doy the day of the
181 year, $\sin(\beta)$ the sine of the solar elevation angle, λ the latitude of the site (in radian), δ the
182 solar declination angle (in degrees) approximated using the Fletcher method as described in
183 Eq. (1.c) and t_h the hour (in solar time).

184 It's important to note that in this study, global radiation is not treated as a singular value but
185 rather as an accumulation over a short period of time (e.g., between h_t and h_{t+1} , using an
186 hourly time step with ERA5-Land). Thus, $\sin(\beta)$ needs to be integrated:



$$187 \int_{h_t}^{h_{t+1}} \sin(\beta) = \sin(\lambda) \times \sin(\delta) + \dot{\lambda} \dot{\delta} \quad (2)$$

$$\cos(\lambda) \times \cos(\delta) \times \frac{15 \times \pi}{180} \times \left[\sin\left(\frac{\pi}{180} \times 15 \times (h_{t+1} - 12)\right) - \sin\left(\frac{\pi}{180} \times 15 \times (h_t - 12)\right) \right]$$

188 Then, we used the relationship between the fraction of diffuse radiation (R_{diff}) compared to
 189 global radiation data (R_g) and the fraction of global radiation data (R_g) compared to
 190 theoretical radiation (R_0), as recommended by de Jon (1980) (described in Spitters et al.,
 191 1986):

$$192 \frac{R_{diff}}{R_g} = 1 \quad \text{for} \quad \frac{R_g}{R_0} \leq 0.22$$

$$193 \frac{R_{diff}}{R_g} = 1 - 6.4 \times \left(\frac{R_g}{R_0} - 0.22 \right)^2 \quad \text{for} \quad 0.22 < \frac{R_g}{R_0} \leq 0.35 \quad (3)$$

$$194 \frac{R_{diff}}{R_g} = 1.47 - 1.66 \times \frac{R_g}{R_0} \quad \text{for} \quad 0.35 < \frac{R_g}{R_0} \leq K$$

$$195 \frac{R_{diff}}{R_g} = L \quad \text{for} \quad K < \frac{R_g}{R_0}$$

$$196 \text{ With } L = 0.847 - 1.61 \times \sin(\beta) + 1.04 \times \sin^2(\beta) \text{ and } K = \frac{1.47 - L}{1.66}.$$

197 Following Spitters et al. (1986), the final step involves subtracting the circumsolar
 198 component (R_{circum}) of diffuse radiation from the direct flux.

$$199 R_{circum} = \cos^2\left(\frac{\pi}{2} - \beta\right) \times \cos^3(\beta) \quad (4)$$

200 To determine the corresponding fraction of diffuse radiation under intermediate sky
 201 conditions, we adopt the interpolation method introduced by Klucher (1978):

$$202 \frac{R_{diff}}{R_g} = \frac{R_{diff}}{R_g} \div \left[1 + \left(1 - \left(\frac{R_{diff}}{R_g} \right)^2 \right) \times R_{circum} \right] \quad (5)$$

203 Finally, considering that global radiation (R_g) comprises both diffuse (R_{diff}) and direct (R_{dir})
 204 radiation components, the value of R_{dir} can be directly inferred from the other two
 205 components.

206 **2.1.2. Downscaling direct radiation**

207 To downscale direct radiation (Fig. 1.ii.), two distinct processes were considered. Firstly, the
 208 path of sun rays was examined to determine if any obstruction in the topography may block
 209 them. Secondly, if unobstructed, the slope and aspect of the pixel are used to compute the
 210 radiation intensity relative to a horizontal surface.



211 For both processes, the initial step involved computing the sun vector in three dimensions.
212 This was achieved using the R package "insol" (version 1.2.2, Corripio, 2020) and
213 specifically the "sunvector" function, which defines the vector based on longitude, latitude,
214 and time (day, hour, minute). To assess whether radiation is obstructed by a summit, the
215 close topography derived from a DEM is computed using the "doshade" function within the
216 "insol" package. To determine sun intensity, the "hillshading" function from the same
217 package is utilised, requiring both the sun vector and the topography (previously normalised
218 into unit vectors using the "cgrad" function).

219 Considering that the input radiation is accumulated over a specific period (e.g., 1 hour in
220 ERA5-Land), and to account for spatial variations in radiation intensity (primarily due to the
221 angle of the sun rays) and shadow projections, several time steps are employed for
222 downscaling the direct radiation. In this study, the default value of three time steps per hour
223 ($n = 3$) was adopted. Additionally, to aggregate the values while considering temporal
224 variations in radiation intensity, each value is weighted by the theoretical extraterrestrial
225 irradiance (R_0 in Eq. (1)). This yields a corrected direct radiation (R_{dir_cor}):

$$226 \quad R_{dir_cor} = R_{dir} \times \frac{\sum_{t_1}^{t_n} \left(R_0 \times S \times \frac{I_{slope}}{I_{vert}} \right)}{\square} \quad (6)$$

227 Where S represents the shadow parameter (with a value of 0 indicating shadow and 1
228 indicating no shadow), and I_{slope} and I_{vert} denote the illumination intensity over the slope and a
229 vertical surface, respectively, to derive the relative intensity of sunlight over the slope.

230 **2.1.3. Downscaling diffuse radiation**

231 Diffuse radiation is independent of the sun's inclination. It emanates uniformly from all
232 directions within the skydome, limited in this study to the top half-sphere. Therefore, its
233 downscaling (Fig. 1.iii) relies on the 360° horizontal surrounding topography, particularly the
234 proportion of diffuse radiation from all directions that can reach the point under study.

235 Various methods exist to compute this fraction, including employing numerous random rays
236 or determining, for regular 3D distributed vectors, the level of shadow. In this study, a
237 specific method was devised. It involves computing, for each azimuth angle (with fixed steps
238 of 2°), the minimum unshaded radiation using the "doshade" R function described previously
239 and a DEM.

240 Subsequently, these values are utilised to calculate the shaded area of the top half-sphere
241 and thus the proportion of diffuse radiation reaching the focal point. Finally, this proportion is
242 applied to the diffuse radiation computed in Sect. 2.1.1 to derive the corrected diffuse
243 radiation (R_{diff_cor}).



244 The corrected diffuse and direct radiation can then be directly employed or recombined into
245 corrected global radiation ($R_{g,corr}$), e.g., to serve as input to a model of forest function or
246 dynamics.

247 **2.1.4. Digital elevation model data**

248 In various steps of the radiation downscaling, the utilisation of a DEM is imperative (Sect.
249 2.1.2 and 2.1.3). In this study, we evaluated radiation downscaling using different DEMs
250 characterised by varying resolutions.

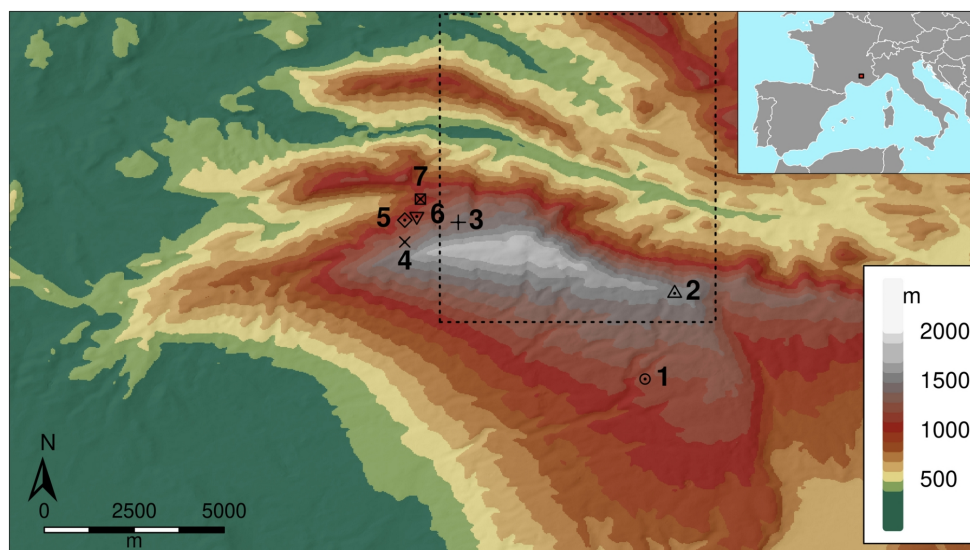
251 The first dataset is the DEM provided by the Shuttle Radar Topography Mission (SRTM,
252 2013), offering a resolution of 1 arc-second (approximately 30 m). In order to clarify the
253 impact of using different resolutions, the resolution of the SRTM product was downgraded to
254 obtain products with resolutions of 60, 90, 125, 185, 250 and 500 metres using the
255 aggregate function (R, terra 1.7.23 library).

256 An additional series of DEMs was employed: the Global Multi-resolution Terrain Elevation
257 Data 2010 (GMTED2010, Danielson and Gesch, 2011), which encompasses spatial
258 resolutions of 30, 15, and 7.5 arc-seconds, corresponding approximately to resolutions of 1
259 km, 500 m, and 250 m, respectively. These datasets were compiled from diverse sources.
260 However, for the metropolitan France region, the primary source of the dataset was the 1
261 arc-second SRTM DEM.

262 The interest of these DEMs lies in their applicability beyond the geographic scope covered in
263 this study. Their availability at a global terrestrial scale renders them suitable for use in
264 various locations worldwide (with the exception of SRTM, which is limited to latitudes
265 between 60° north and 56° south).

266 **2.2. Study area**

267 The study area is Mont Ventoux, a mountain located in southeastern France, with its highest
268 point reaching an elevation of 1912 metres (44.174° N - 5.27794° E) (Fig. 2). While Mont
269 Ventoux is predominantly oriented in an east-west direction, it exhibits notable variations in
270 slopes and orientations. The southern flank is characterised by gradual inclines, whereas
271 steeper slopes are evident on its northern side. Mont Ventoux presents a predominantly
272 wooded landscape, featuring a mixed beech-fir forest on its northern side, and a mixed
273 European beech-black pine forest on its southern side, particularly above an elevation of 800
274 metres (Jean et al., 2023). Below this elevation, the dominant species are more typical of the
275 Mediterranean biome and include coppices of *Quercus pubescens*, *Quercus ilex*, *Pinus*
276 *halepensis* as well as as natural regeneration of *Cedrus atlantica* from old plantation trials of
277 the early 20th century.



278 **Figure 2: Map of the study area (Mont Ventoux). Mont Ventoux is located in**
279 **southeastern France (see in the inset). Observation points (one symbol with**
280 **associated number) and the ERA5-Land tile (in dottle line) used in this study are**
281 **indicated.**

282 **2.3. Radiation measurements**

283 On June, 27 2016, we installed seven mini-weather stations at different strategic elevations
284 and locations on the north face of Mont Ventoux (Table 1), each equipped with loggers
285 (YBdesign) and sensors for photosynthetically active radiation (PAR, 400-700 nm),
286 temperature and relative humidity. The sensors were installed on a vertical pole and
287 positioned horizontally (levelled with a spirit level). The PAR sensors (CBE80, brand
288 Solems) and the thermo-hydrometers (EE07-PFT, brand E+E) were calibrated using a
289 reference weather station at the INRAe campus of Avignon before the beginning of the
290 experiment. The mini-weather stations were positioned in clearings with forest edges
291 extending beyond 30 m from the station. The data were recorded at one hour timestep. The
292 photosynthetic flux density delivered by the sensors were converted into $W.m^{-2}$ of global
293 radiation using an empirical relationship calibrated on the ICOS Font-Blanche experimental
294 site (Moreno et al., 2021).



N°	Site	Latitude (°)	Longitude (°)	Elevation (m)	Slope (°)	Aspect(°)
1	Les Tournières	44.129646	5.320524	1159	5.5	250.1
2	Col de la fache	44.157819	5.331975	1575	6.2	201.2
3	Mont Serein	44.182886	5.257725	1413	4.0	234.1
4	dvx5	44.176758	5.238861	1320	20.8	347.2
5	Tc2	44.184014	5.239161	1116	33.1	351.0
6	dvx2	44.185142	5.243383	1074	28.0	355.1
7	142	44.190856	5.244869	1050	23.0	188.4

295 **Table 1. List and main characteristics of the observation sites in Mont Ventoux where**
296 **radiation measurements were performed. Slope and aspect was computed from a 30**
297 **m resolution SRTM digital elevation model.**

298 The observed radiation is compared with the radiation from ERA5-Land before and after
299 downscaling using DEMs at different resolutions. In order to facilitate the comparison
300 between the ERA5-Land reanalysis dataset and observations, which may contain some
301 gaps due to power failure, we aggregated radiation data over various periods (annually or
302 seasonally). This approach involves excluding time steps with missing data, separately for
303 each site. Moreover, to compare with these observations, the correction of the light intensity
304 due to the angle of the direct light rays in relation to the slope and orientation (Sect. 2.1.2,
305 the 'hillshading' function) was deactivated (in Sect. 3.1), as the measurements were carried
306 out on a device placed horizontally.

307 **2.4. Modelling the effect of radiation downscaling on plant functions**

308 To quantify the influence of downscaled radiation on specific applications, we assessed the
309 impact of radiation downscaling on beech (*Fagus sylvatica*) forest functioning using process-
310 based vegetation modelling on the mountainous area of the Mont Ventoux massif (where
311 radiation measurements were located).

312 We employed two complementary forest vegetation models to quantify how radiation
313 downscaling affects the spatial patterns of both Gross Primary Productivity (GPP) and
314 drought-induced hydraulic failure. These models are, respectively, the forest growth model
315 CASTANEA (Dufrêne et al., 2005) and the plant hydraulic model SurEau (Cochard et al.,
316 2021; Ruffault et al., 2022).

317 CASTANEA is a comprehensive forest soil-vegetation-atmosphere model coupled with a
318 growth module. It simulates carbon (photosynthesis and respiration) and water fluxes



321 (transpiration, soil water content, soil water potential) at a half-hourly to daily time step for an
322 average tree in a homogeneous forest stand. A carbon allocation module assigns a
323 proportion of the daily Net Primary Productivity (NPP) toward various plant compartments
324 (stem, roots, fine roots, flowers, acorn, leaves, and storage) using empirical coefficients.
325 Carbon and water fluxes, including gross and net ecosystem photosynthesis, respiration,
326 transpiration, latent heat fluxes, soil water content, and plant water potential, have been
327 validated on different species and sites, including beech on Mont Ventoux (Davi et al., 2005;
328 Cailleret et al., 2011; Delpierre et al., 2012). In this study, canopy Gross Primary Productivity
329 (GPP) was used to demonstrate the effects of radiation downscaling on potential
330 productivity.

331 SurEau is a plant-hydraulic model that simulates water fluxes and water potential through
332 various compartments of the soil-plant hydraulic continuum (Cochard et al 2021). At each
333 time step (typically 30 minutes), the model computes leaf stomatal and cuticular transpiration
334 as the product between leaf-to-air vapour pressure deficit (VPD) and stomatal and cuticular
335 conductance. Then, stomatal and cuticular fluxes are used to compute water potential in the
336 different plant compartments, while accounting for the symplasmic capacitance and the
337 hydraulic conductance losses due to xylem embolism. Stomatal closure is regulated in a
338 feedback manner based on leaf water potential through empirical relationships (Klein, 2014;
339 Martin-StPaul et al., 2017). Soil water potential and hydraulic conductance are also
340 computed from soil water content. The model is parameterized with various measurable
341 plant traits previously collected for the target species (Ruffault et al., 2022). In this study,
342 drought-induced embolism (or the percentage loss of hydraulic conductance) in the vascular
343 system was used as a proxy for hydraulic risk during a given summer.

344 We conducted spatial simulations for one pixel at 0.1° resolution (~ 11 km * 8 km at these
345 coordinates), covering a large part of the Mont Ventoux northern face where the
346 measurements were conducted. The simulations covered the years 2016 and 2017,
347 encompassing the same geographical area as outlined in Sect. 2.3, spanning a segment of
348 Mont Ventoux ranging from 5.25° W to 5.35° W and from 44.15° N to 44.25° N.

349 Climate data were directly sourced from the ERA5-Land hourly dataset (Muñoz-Sabater et
350 al., 2021), including temperature, precipitation, wind speed, relative humidity, and global
351 radiation. The latter was downscaled using the method presented in Sect. 2.1, employing
352 one of the DEMs discussed in Sect. 2.1.4.

353 To maintain consistency and avoid introducing uncertainty from disparate datasets, all other
354 non-climatic inputs were set constant across the study area, as described hereafter. The



355 species selected, *Fagus sylvatica* (European beech), is one of the most common species
356 present on Mont Ventoux (Lander et al., 2021) and its traits are already available for the two
357 models (Cailleret & Davi, 2011; Cailleret et al., 2013 ; Davi & Cailleret, 2017; Ruffault et al.,
358 2022), with a Leaf Area Index set at 3.5. The soil characteristic corresponds to the median
359 value extracted from the whole studied area from the SoilGrids database (Poggio et al.,
360 2021).

361 3. **RESULTS**

362 3.1. **Comparison between simulated and observed global radiation**

363 The comparison of ERA5-Land global radiation, both uncorrected and corrected, with
364 observed global radiation across the 7 studied sites shows the benefit of our downscaling
365 method in accurately estimating local global radiation (Fig. 3).

366 Specifically, the correlation between observed and simulated yearly mean global radiation
367 increases from $r^2 = 0.59$ to $r^2 = 0.93$, while the RMSE decreases from 33.5 to 8.6 Wh.m², for
368 the raw ERA5-Land radiation and ERA5-Land radiation corrected with a 30 m resolution
369 DEM, respectively (Figs 3a and 3b). However, this increase in the performance of estimating
370 global radiation does not progress consistently as the resolution of our downscaling
371 approach increases. We observe a slight and heterogeneous improvement in the corrected
372 radiation from 1 km to 250 m resolution compared to the raw ERA5-Land resolution (around
373 9 km). It is not until the resolution reaches around 200 metres that a significant and
374 continuous improvement is observed (decrease in RMSE, increase in r^2) until 30 m
375 resolution (Fig. 3 c).

376 Our results further show that the absolute performance of radiation models (in terms of r^2)
377 and their relative differences remain consistent across the different studied seasons (Fig. 3a
378 and 3b), despite some particularities. During winter, ERA5-Land raw data shows weak
379 relationship with observations (r^2 at 0.37 and RMSE at 38 Wh.m²), which substantially
380 improves with correction ($r^2 = 0.90$, RMSE = 11 Wh.m²). Similarly, but more pronounced, in
381 autumn correlations and RMSE are considerably enhanced (respectively r^2 from 0.21 to 0.91
382 and RMSE from 45 to 9 Wh.m²). In summer, the correlation is almost zero with the ERA5-
383 Land data, whereas it exceeds 0.5 with the corrected radiations. In contrast, the correlation
384 is stable in spring but high (at 0.85), while RMSE is improved with correction (32 to 23
385 Wh.m²). Further analysis also reveals that, contrary to Fig. 3 (a), the equations of the
386 seasonal curves for corrected ERA5-Land radiation closely align with the 1/1 line, in
387 accordance with an important decrease in RMSE (Fig. 3 b). It is noteworthy that most of the



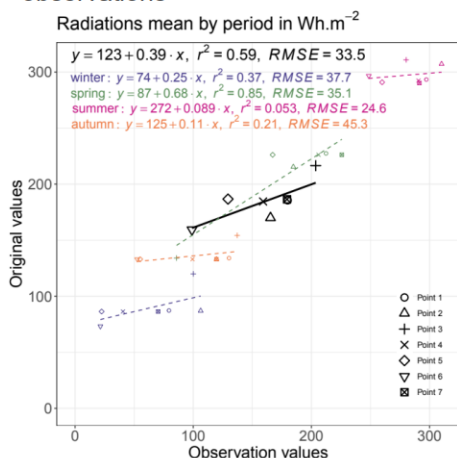
388 improvement comes from points located on northern slopes (points 4, 5 and 6, Fig. 3).

389 Accordingly, the daily bias from those points is reduced compared to uncorrected data, while

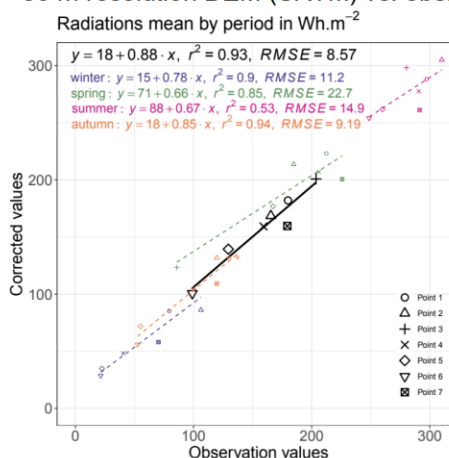
390 points located on flat surfaces or southern slopes show similar limited bias (not shown).



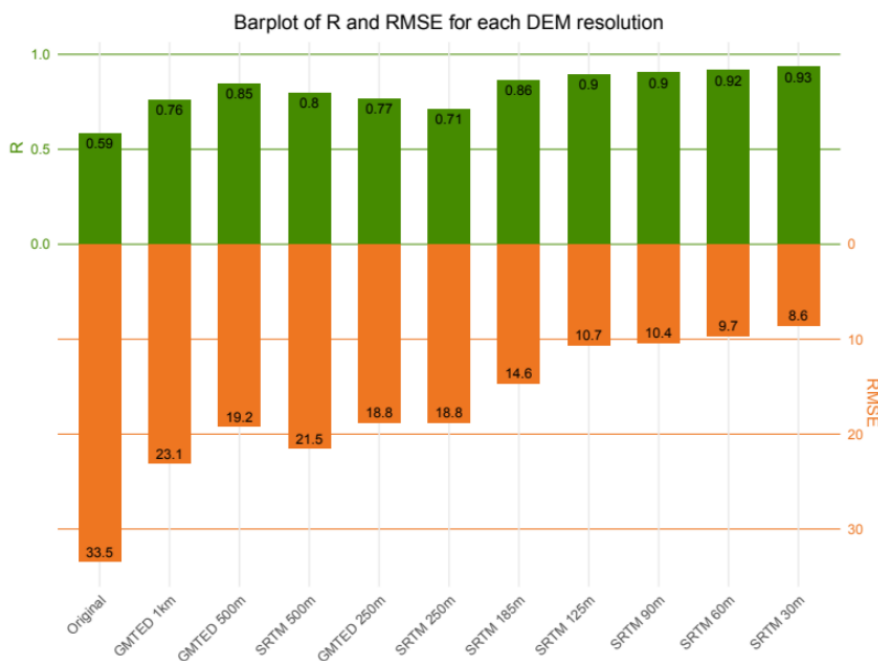
(a) Radiation ERA5-Land versus observations



(b) Radiation ERA5-Land corrected with 30 m resolution DEM (SRTM) vs. obs.



(c) Performances of ERA5-Land correction with different DEM versus observations



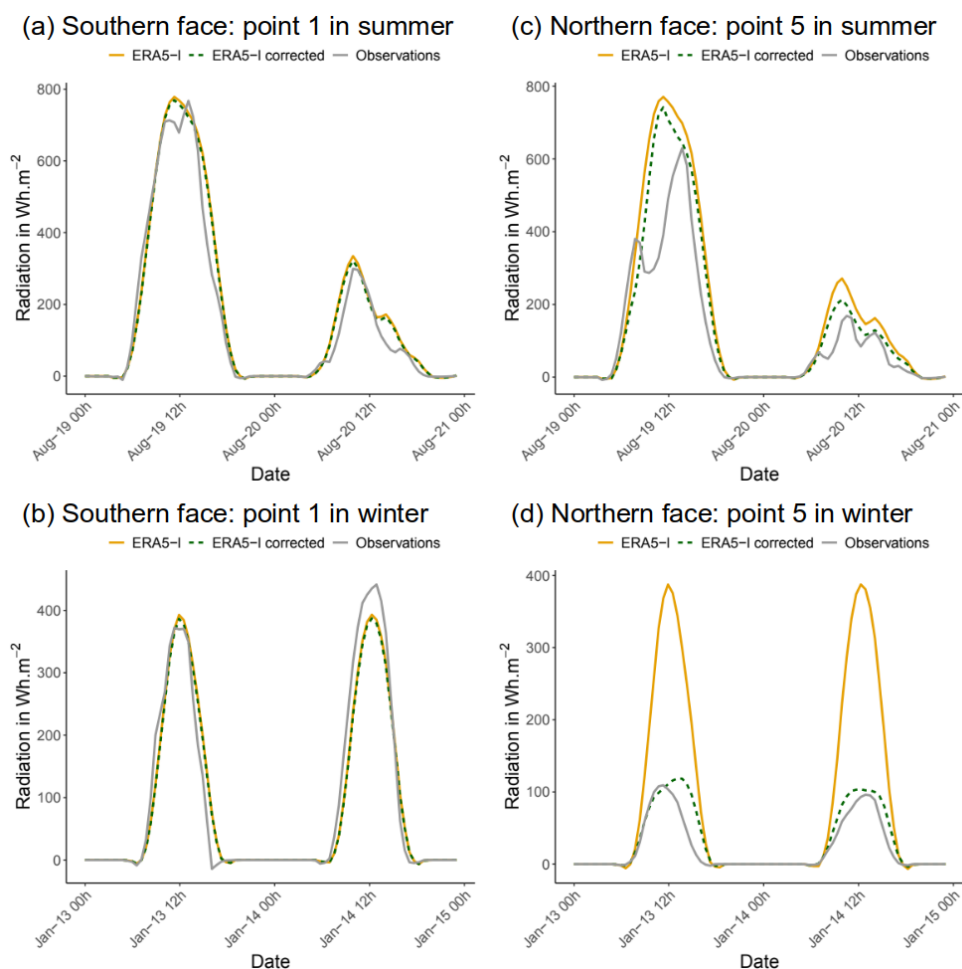
391 Figure 3: Comparison of the observed radiation with the ERA5-Land product and with
 392 corrected radiation from ERA5-Land using different DEMs. (a) and (b) represent the
 393 annual and seasonal correlation r^2 and RMSE (Wh.m^2) for each point. (c) shows the
 394 annual r^2 and RMSE (in black in (a) and (b)), for the original ERA5-Land data and each
 395 of the corrections obtained with the different DEMs



396 Figure 4 depicts the global radiation values for two distinct sites during two different periods.
397 Site 1 (refer to Table 1) represents a slightly south-facing location with little shade from
398 topographical features, particularly evident in winter. Site 5, on the other hand, is situated on
399 a north-facing slope (slightly west-facing) affecting sunlight exposure, especially during
400 winter months. Two two-day periods were selected for analysis: one in summer (19 and 20
401 August 2016) to observe the impact during peak sun exposure and a rainy day (20 August),
402 and another in winter (13 and 14 January 2017) to assess the effect of the downscaling on
403 low-inclination radiation in a mountainous region. Three types of radiation values are
404 presented: observed values (Sect. 2.3), original ERA5-Land values (9 km resolution, tile
405 indicated on Fig. 2), and values following the application of the radiation downscaling with
406 the SRTM DEM (~30 m resolution) (as described in Sect. 2.1, but without “hillshading”
407 function to be comparable with measurement).

408 At site 1 (Fig. 4.a-b), where surrounding topographical features have minimal impact on
409 radiation, the values from ERA5-Land are close to the observations and there is no
410 significant change after radiation downscaling. These trends hold for both clear and cloudy
411 days, and for both winter and summer periods. At site 5, disparities between original and
412 corrected ERA5-Land values are more significant due to topographical influences. In
413 summer (Fig. 4.c), discrepancies exist between original and corrected ERA5-Land values.
414 Corrected values more closely represent measured values but still struggle to replicate sub-
415 daily variations. Particularly, a dip in the curve around 10am appears to be present on both
416 days, possibly indicating a shadow, but not represented in the corrected radiation. In winter
417 (Fig. 4.d), downscaling markedly impacts radiation values, with corrected values nearly four
418 times lower than ERA5-Land values, closely aligning with observed values.

419 Note that if the effect of the slope and orientation were activated, the effect of the light
420 intensity would be to potentially increase the corrected radiation on the south faces, mainly
421 on clear days and in winter (e.g. +10 % for point 1), and on the contrary to considerably
422 reduce the corrected radiation on cloud-free day (e.g. by two for 19 August at point 5).



423 **Figure 4: Radiation of original ERA5-Land data in orange, after downscaling with the**
 424 **SRTM DEM (30 m resolution) in dotted dark green and the observations in grey, for**
 425 **site 1 (a and b) and site 5 (c and d) and for two different dates: one in summer (19-20**
 426 **August 2016 in a and c) and one in winter (13-14 January 2017 in b and d)**

427 **3.2. Application on Mont Ventoux massif**

428 **3.2.1. Heterogeneity of global radiation**

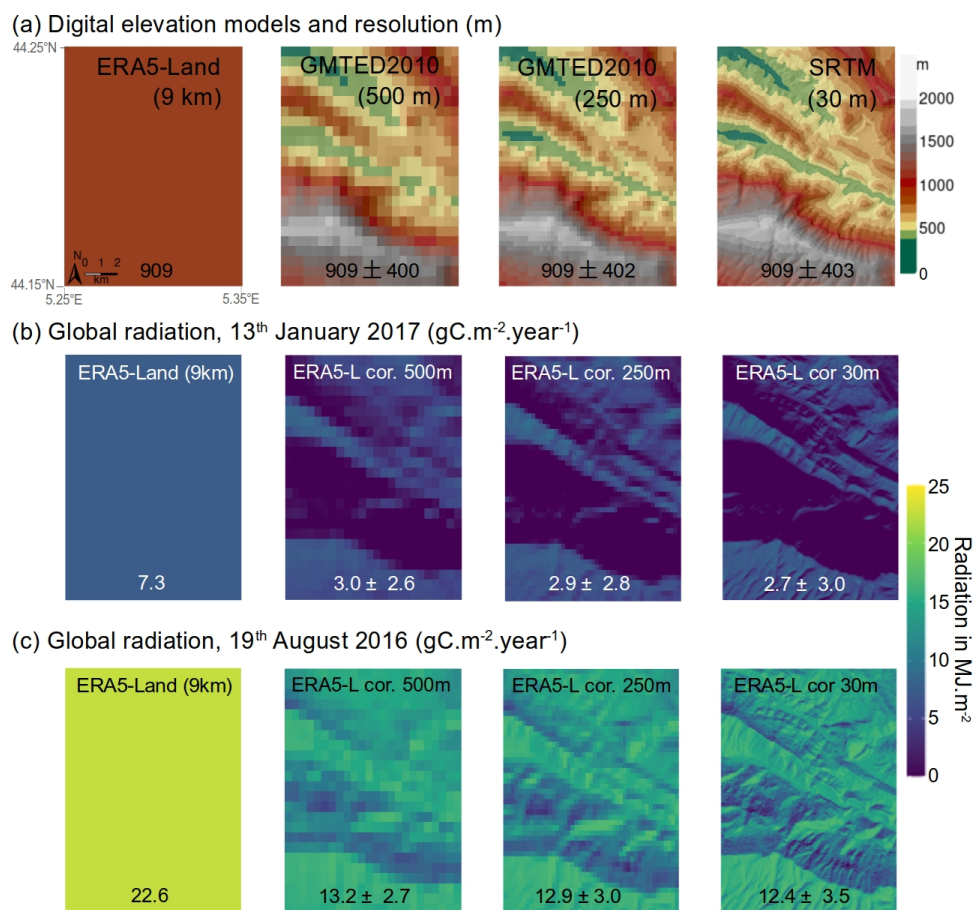
429 Applying our approach across a heterogeneous geographical area illustrates the spatial and
 430 temporal variability in global radiation introduced by downscaling (Fig. 5).

431 Radiation downscaling exerts a clear impact in the mountainous region under study, halving
 432 original ERA5-Land global radiation. An evident differentiation emerges between south-
 433 facing slopes, which receive more radiation, and north-facing slopes, which exhibit minimal
 434 radiation levels in winter (approaching zero). Mean radiation values decrease with increasing



435 resolution of the three DEM used, indicating an average decrease of 10.7 % on 13 January
436 2017 and 5.9 % on 19 August 2016 when transitioning from the GMTED DEM at
437 approximately 500 metres to the SRTM at approximately 30 metres resolution. Conversely,
438 standard deviation increases with resolution, rising by 13.5 % and 30.0 %, respectively.
439 However, during winter, the standard deviation mirrors the magnitude of the mean due to low
440 radiation values, whereas in summer, it accounts for 20 to 25 % of the mean.

441 These differences in standard deviation due to topography imply significant differences
442 between the different DEMs, as well as with the original ERA5-Land values. For instance,
443 the maximum radiation value recorded on January 13th totals 7.3 MJ.m^{-2} in the reanalysis,
444 whereas it reaches 9.3 MJ.m^{-2} with downscaling conducted using the 250 m DEM. Similarly,
445 on January 13th (Fig. 5.b), the spatial pattern representing a denser "line" denoting stronger
446 radiation values around 5.3° E and 44.19° N is relatively narrow with the 30 m DEM
447 (approximately 200 meters wide), whereas it doubles in width with the 500 m DEM.



448 **Figure 5: Global radiation from ERA5-Land and resulting from downscaling obtained**
 449 **from different resolution DEMs. (a) ERA5-Land tile (left) and DEM resolution (500,**
 450 **and 30 metres, from left to right). Global radiation for two distinct dates, (b) in winter**
 451 **(13 January 2017) and (c) in summer (19 August 2016). Regional mean values and**
 452 **standard deviations are indicated on the bottom of each map.**

453 **3.2.2. Modelling the influence of radiation downscaling on vegetation**
 454 **functioning**

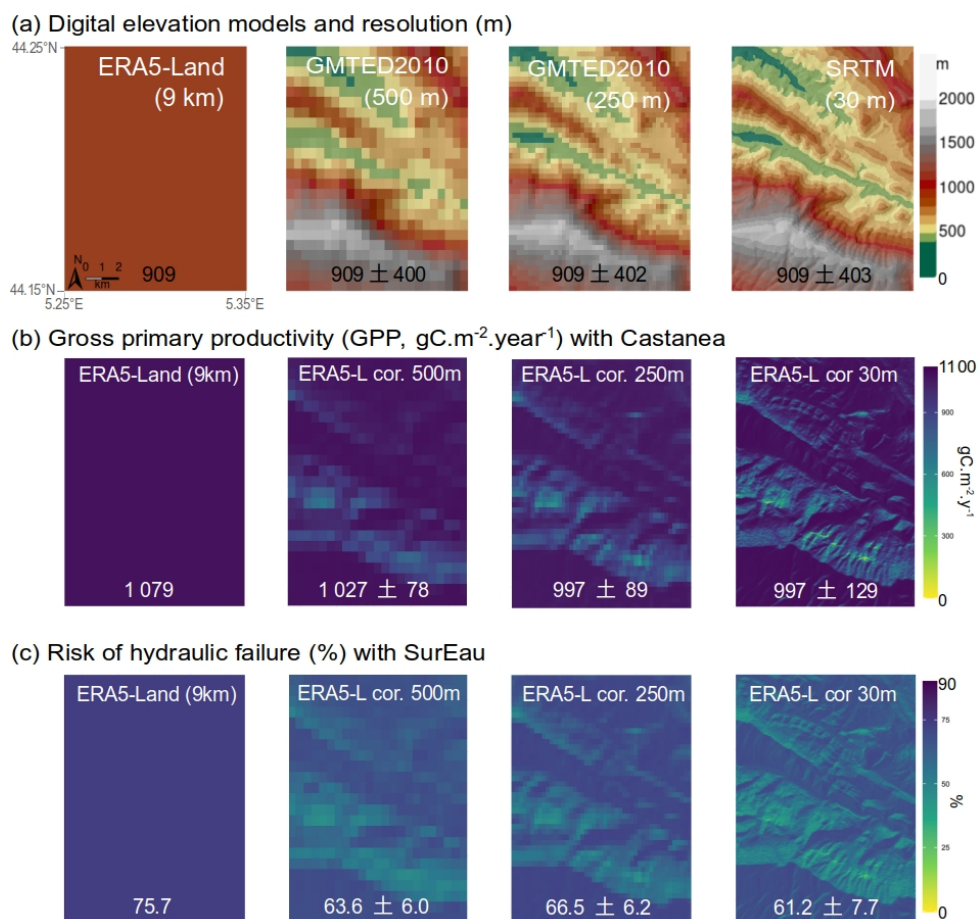
455 Modifying radiation across the entire area according to each DEM has a tangible impact as
 456 presented on models output as shown in Fig. 6. In general, the simulations remain
 457 consistent across the studied area, despite potential variations introduced by the different
 458 topographies used during downscaling. With downscaling, there is a discernible reduction in
 459 Gross Primary Productivity (GPP) ranging between 5 % and 8 %, as well as in the risk of



460 hydraulic failure, which decreases between 14 % and 23 %. Moreover, the standard
461 deviation introduced between the values is quite significant, varying between 8 % and 13 %
462 for the two outputs studied.

463 Upon comparing the patterns obtained with the corresponding DEMs, it becomes evident
464 that south-facing slopes tend to exhibit higher annual productivity (Fig. 6.b) but are
465 susceptible to greater hydraulic stress (as indicated by darker colours in Fig. 6.c).
466 Conversely, north-facing slopes generally manifest lower GPP as simulated by the Castanea
467 model, yet exhibit a reduced risk of hydraulic failure.

468 To evaluate the potential impact of these discrepancies on mortality risk, we computed the
469 risk of hydraulic failure from the embolism simulations. The relationship between mortality
470 and embolism level water stress is often conceptualised as a threshold effect (Choat et al.,
471 2018), although this notion is occasionally questioned (Hammond et al., 2021). Setting the
472 threshold at which mortality occurs to 50 % of risk of hydraulic failure, we obtain mortality
473 percentages in term of surface of 100 %, and 97 %, 98 % and 89 % for the original ERA5-
474 Land tile, and the data downscaled to 500 m, 250 m and 30 m, respectively. Given that the
475 useful reserve used in this study comes from a single value taken from the median over the
476 area of the SoilGrids database (Poggio et al., 2021), and that this value is open to question,
477 these results must be compared relatively to each other.



478 **Figure 6: Gross primary productivity and risk of hydraulic failure simulated with,**
 479 **respectively, Castanea and SurEau, from ERA5-Land and resulting from global**
 480 **radiation downscaling obtained from different resolution DEMs. (a) ERA5-Land tile**
 481 **(left) and DEM resolution (500, 250, and 30 metres, from left to right). (b) Gross**
 482 **primary productivity simulated with Castanea. (c) Risk of hydraulic failure simulated**
 483 **with SurEau. Regional mean values and standard deviations are indicated on the**
 484 **bottom of each map.**

485 4. DISCUSSION

486 4.1. Performance of the downscaling method

487 The results of our study indicate that the radiation downscaling method developed in this
 488 study effectively captures the overall trend of radiation distribution across mountainous
 489 regions. The daily patterns are effectively represented, however sub-daily variations may not



490 fully account for microclimatic variations, especially considering the spatial heterogeneity
491 within a grid pixel at the resolution of climate data. This is the case for example with cloud
492 cover, which can be highly variable in mountainous regions.

493 However, our findings suggest that, overall, radiation downscaling significantly reduces
494 radiation levels on the north-facing side, particularly during winter, as a result of the
495 obstruction of direct radiation by surrounding mountains. Conversely, this radiation decrease
496 on north-facing slopes is compensated by an increase on south-facing slopes. Consequently
497 our method improves methods already available to downscale radiation (Piedallu & Gégout,
498 2008).

499 The results of our radiation downscaling method reveal a significant improvement of the
500 representation of radiation from 9 km reanalysis, for all seasons, but especially on north-
501 facing slopes and more pronounced in winter. The impact of radiation downscaling is
502 therefore primarily observed in regions with significant shadow casting, and it becomes more
503 pronounced with the sun's zenithal angle. This emphasises the necessity to correct the
504 radiation to accurately depict the dynamics of radiation in mountainous regions.
505 Nevertheless, the method has its limitations, as it is linked to the quality of DEM and does
506 not take into account climatic heterogeneity, which can explain cloud cover on a smaller
507 scale than the reanalysis data. Thus in Figure 4.c, the dip at around 10am may indicate the
508 presence of micro-climatic conditions, such as fog, an effect that was not considered in our
509 downscaling method.

510 Additionally, our analysis revealed intriguing results concerning the impact of different DEM
511 resolutions. While no clear improvement was observed with a resolution greater than 250 m,
512 a clear gradual improvement appears for resolutions finer than 250 m (up to 30 m). This
513 suggests that higher resolutions are crucial for effectively capturing the nuances of radiation
514 dynamics. We hypothesise that insufficient improvement in resolution during the
515 downscaling introduces some variance which is not adequately compensated by
516 improvements in radiation representation at the site level.

517 **4.2. Implications of downscaling for modelling studies**

518 The application of downscaling with the SurEau and CASTANEA models provides an
519 overview of the impact that downscaling can have on different parameters, such as GPP or
520 tree mortality risk due to hydraulic failure. Mont Ventoux was used as a benchmark site for
521 testing applications. The impact of downscaling on these parameters is most pronounced in



522 areas with significant topographic features, such as mountainous regions or canyons, with
523 lower radiation levels on north-facing slopes due to shading and higher radiation levels on
524 south-facing slopes due to sun intensity.

525 These findings have to be taken with caution as only radiation was downscaled making the
526 other forcing variables (temperature, VPD, rainfall) decorrelated which partly limits the
527 interpretation. However, with these limits in my mind and assuming impact models can be
528 used to assess climate products in this context (Stephanon et al., 2015), it appears that
529 radiation downscaling has profound implications on impact simulation (Fig. 6). In particular
530 when considering processes that are based on threshold, such as the mortality risk
531 associated with hydraulic failure, in our example, the mortality rate can go from 100 % to 89
532 %. Thus, assessing the spatial heterogeneity of radiation, through its interaction with
533 topography, seems crucial for accurately assessing ecological responses and potential
534 threshold effects in complex terrain. Future studies could benefit from these methods to
535 improve the prediction of species distribution or ecosystem functions at local level.

536 **5. CONCLUSION**

537 In this study, we developed a process-based method to downscale global radiation data
538 made on flat surfaces, such as coarse spatial resolution global reanalysis data. The method
539 builds upon existing research and goes further than traditional process-based radiation
540 downscaling methods, by accounting for the shadowing effect on direct radiation and for the
541 bowl effect on diffuse radiation (Piedallu & Gégout, 2008). The recent ERA5-Land hourly
542 data available at 9 km resolution was used to compare on the Mont Ventoux the impact of
543 radiation downscaling computed from different digital elevation models.

544 The radiation downscaling method effectively captures the overall trend of radiation
545 distribution across mountainous regions. Downscaled radiation is improved compared to
546 original ERA5-Land data, especially during winter months, due to the higher zenithal angle.
547 However, the improvement is significant only after a certain spatial resolution (~ 150 m) and
548 gradually increases thereafter. The implications of downscaling for modelling studies was
549 further investigated using two different process-based models representing gross primary
550 productivity and risk of hydraulic failure. The impact of downscaling on those is most
551 pronounced in areas with significant topographic features, such as mountainous regions or
552 canyons. Assessing the spatial heterogeneity of radiation, through its interaction with
553 topography, is crucial for accurately addressing ecological responses and potential threshold
554 effects in complex terrain.



555 The method can be applied at any resolution, depending on the choice of the DEM.
556 Moreover, it relies on any type of radiation data, making it applicable to any region in the
557 world and to historical periods as well as future projections. Finally, the method could involve
558 other types of climatic data from the same input dataset, such as temperature or
559 precipitation, thereby ensuring physical consistency between the variables. In the future
560 such methods could be included in more generic climate downscaling tools (e.g. Meteoland,
561 De Cáceres et al., 2018) to facilitate the application of process based models at fine
562 resolution.

563 **Code availability**

564 The scripts corresponding to the method developed in this article is available on GitLab at
565 https://forgemia.inra.fr/urfm/modeldata_toolkit (commit `afc05ed2`) with the prefix
566 “RadDownscaling”.

567 The SurEau model code presented in section 2.4 and whose results are presented in section
568 3.2 is available on GitLab at <https://forgemia.inra.fr/urfm/sureau> (commit `ca19abfb`), while the
569 CASTANEA version is available on the capsis platform (<https://capsis.cirad.fr/>, lasted access
570 the 12/06/2024) and can be downloaded from the "download" menu.

571 **Data availability**

572 Data from Mont Ventoux (2016-2017) at the seven sites are provided by URFM-INRAE
573 Avignon. The full dataset and site information can be accessed from
574 <https://doi.org/10.57745/B22AUG>.

575 DEM data are freely accessible and can be downloaded from <https://earthexplorer.usgs.gov/>
576 (last accessed 12/06/2024): the Global Multi-resolution Terrain Elevation Data 2010
577 (GMTED2010) (<https://doi.org/10.5066/F7J38R2N>) and the Shuttle Radar Topography
578 Mission (SRTM) 1 Arc-Second Global (<https://doi.org/10.5066/F7PR7TFT>).

579 Climate ERA5-Land data (<https://doi.org/10.24381/cds.e2161bac>), including global radiation,
580 are provided by Copernicus and can be directly downloaded from
581 <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=form> (last
582 accessed 12/06/2024).

583 **Author contribution**

584 Druel, A., Ruffault, J., Davi, H. and Martin-StPaul, N.K. designed the research and
585 performed the research. Druel, A. developed the scripts and the figures. Marloie, O. and
586 Martin-StPaul, N.K. collected the data on Mont Ventoux. Druel, A., Ruffault, J., Davi, H., De
587 Cáceres, M., Mouillot, F., François, C. and Martin-StPaul, N.K. interpreted the results. Druel,



588 A. led the writing of the manuscript with inputs from Ruffault, J., Chanzy, A., Marloie, O., De
589 Cáceres, M., Mouillot, F., François, C., Soudani, K., and Martin-StPaul, N.K.

590 **Competing interests**

591 The authors declare that they have no conflict of interest.

592 **Acknowledgements**

593 This project received funding from the European Union's Horizon 2020 research and
594 innovation program under Grant Agreement No. 862221 (FORGENIUS). The authors would
595 also like to thank William Brunetto (URFM, INRAE, Avignon, France) for his help with data
596 acquisition on Mont Ventoux and Deborah Verfaillie for her help with proofreading.



597 References

598 Austin, M.P., Nicholls, A.O. and Margules, C.R.: Measurement of the realised qualitative
599 niche: Environmental niches of five Eucalyptus species. *Ecological Monographs*, 60(2): 161-
600 177, <https://doi.org/10.2307/1943043>, 1990.

601 Bailey, M. D., Nychka, D., Sengupta, M., Habte, A., Xie, Y., and Bandyopadhyay, S.:
602 Regridding uncertainty for statistical downscaling of solar radiation. *Adv. Stat. Clim.*
603 *Meteorol. Oceanogr.*, 9, 103–120, <https://doi.org/10.5194/ascmo-9-103-2023>, 2023

604 Bedia, J., Herrera, S. and Gutiérrez, J.M.: Dangers of Using Global Bioclimatic Datasets
605 for Ecological Niche Modeling. Limitations for Future Climate Projections. *Global and*
606 *Planetary Change*, 107, 1-12, <http://dx.doi.org/10.1016/j.gloplacha.2013.04.005>, 2013.

607 Bird, R. E., and Hulstrom, R. L.: A simplified clear sky model for direct and diffuse
608 insolation on horizontal surfaces. *Solar Energy Research Institute*, TR-642-761, 1981.

609 Bramer, I., Anderson, B.J., Bennie, J., Bladon, A.J., De Frenne, P., Hemming, D., Hill,
610 R.A., Kearney, M.R., Körner, C., Korstjens, A.H., Lenoir, J., Maclean, I.M.D., Marsh, C.D.,
611 Morecroft, M.D., Ohlemüller, R., Slater, H.D., Suggitt, A.J., Zellweger, F. and Gillingham,
612 P.K.: Advances in monitoring and modelling climate at ecologically relevant scales.
613 *Advances in Ecological Research*, 58, 101–161. <https://doi.org/10.1016/bs.aecr.2017.12.005>,
614 2018.

615 Brun, P., Zimmermann, N. E., Hari, C., Pellissier, L. and Karger, D. N.: CHELSA-
616 BIOCLIM+ A novel set of global climate-related predictors at kilometre-resolution. *EnviDat.*,
617 <https://www.doi.org/10.16904/envidat.332>, 2022.

618 Cailleret, M. and Davi, H.: Effects of climate on diameter growth of co-occurring *Fagus*
619 *sylvatica* and *Abies alba* along an altitudinal gradient. *Trees*, 25:265–276.
620 <https://doi.org/10.1007/s00468-010-0503-0>, 2011.

621 Cailleret M., Nourtier M., Amm A., Durand-Gillmann M. and Davi H.: Drought-induced
622 decline and mortality of silver fir differ among three sites in Southern France. *Annals of*
623 *Forest Science*, 71, 643–657, 2013.

624 Carroll, C., Zielinski, W.J. and Noss, R.F.: Using presence-absence data to build and test
625 spatial habitat models for the Fisher in the Klamath region, U.S.A. *Conservation Biology*,
626 13(6): 1344-1359, <https://doi.org/10.1046/j.1523-1739.1999.98364.x>, 1999.

627 Clark, D.B., Palmer, M.W. and Clark, D.A.: Edaphic factors and the landscape-scale
628 distributions of tropical rain forest trees. *Ecology*, 80(8): 2662-2675,
629 [https://doi.org/10.1890/0012-9658\(1999\)080\[2662:EFATLS\]2.0.CO;2](https://doi.org/10.1890/0012-9658(1999)080[2662:EFATLS]2.0.CO;2), 1999.

630 Choat, B., Brodribb, T. J., Brodersen, C. R., Duursma, R. A., López, R. and Medlyn, B. E.:
631 Triggers of tree mortality under drought. *Nature*, 558(7711), 531–539.
632 <https://doi.org/10.1038/s41586-018-0240-x>, 2018.

633 Churkina, G., and Running, S. W.: Contrasting Climatic Controls on the Estimated



- 634 Productivity of Global Terrestrial Biomes. *Ecosystems*, 1(2), 206–215.
635 <https://doi.org/10.1007/s100219900016>, 1998.
- 636 Cochard, H., Pimont, F., Ruffault, J. & Martin-StPaul, N.: SurEau: a mechanistic model of
637 plant water relations under extreme drought. *Ann. For. Sci.*, 78,
638 <https://doi.org/10.1007/s13595-021-01067-y>, 2021.
- 639 Danielson, J.J., and Gesch, D.B.: Global multi-resolution terrain elevation data 2010
640 (GMTED2010): U.S. Geological Survey Open-File Report 2011–1073, 26 p.,
641 <https://doi.org/10.5066/F7J38R2N> (Downloaded on <https://earthexplorer.usgs.gov/> the 15-
642 10-2021), 2011.
- 643 Davi, H., Dufrêne, E., Granier, A., Le Dantec, V., Barbaroux, C., François, C. and Bréda,
644 N. Modelling carbon and water cycles in a beech forest: Part II.: Validation of the main
645 processes from organ to stand scale. *Ecological Modelling*, 185, 387–405.
646 [doi:10.1016/j.ecolmodel.2005.01.003](https://doi.org/10.1016/j.ecolmodel.2005.01.003), 2005.
- 647 Davi, H., Dufrêne, E., Francois, C., Le Maire, G., Loustau, D., Bosc, A., Rambal, S.,
648 Granier A. and Moors E.: Sensitivity of water and carbon fluxes to climate changes from
649 1960 to 2100 in European forest ecosystems. *Agric. For. Meteorol.*, 141, 35–56,
650 <https://doi.org/10.1016/j.agrformet.2006.09.003>, 2006.
- 651 Davi, H. and Cailleret, M.: Assessing drought-driven mortality trees with physiological
652 process-based models. *Agricultural and Forest Meteorology*, 232, 279–290,
653 <https://doi.org/10.1016/j.agrformet.2016.08.019>, 2017.
- 654 Davy, R. and Kusch, E.: Reconciling high resolution climate datasets using KrigR.
655 *Environ. Res. Lett.*, 16, 124040, <https://doi.org/10.1088/1748-9326/ac39bf>, 2021.
- 656 De Cáceres, M., Martínez-Vilalta, J., Coll, L., Llorens, P., Casals, P., Poyatos, R.,
657 Pausas, J.G. and Brotons, L.: Coupling a water balance model with forest inventory data to
658 predict drought stress: the role of forest structural changes vs. climate changes. *Agricultural
659 and Forest Meteorology*, 213: 77-90, <https://doi.org/10.1016/j.agrformet.2015.06.012>, 2015.
- 660 De Cáceres, M., Martin-StPaul, N., Turco, M., Cabon, A. and Granda, V.: Estimating daily
661 meteorological data and downscaling climate models over landscapes. *Environmental
662 Modelling and Software*, 108: 186-196, [doi:10.1016/j.envsoft.2018.08.003](https://doi.org/10.1016/j.envsoft.2018.08.003), 2018.
- 663 De Cáceres M, Molowny-Horas R, Cabon A, Martínez-Vilalta J, Mencuccini M, García-
664 Valdés, R., Nadal-Sala, D., Sabaté, S., Martin-StPaul, N., Morin, X., D'Adamo, F., Batllori, E.
665 and Améztegui, A.: MEDFATE 2.9.3: A trait-enabled model to simulate Mediterranean forest
666 function and dynamics at regional scales. *Geoscientific Model Development*, 16, 3165–3201,
667 <https://doi.org/10.5194/gmd-16-3165-2023>, 2023.
- 668 De Jong, J.B.R.M.: Een karakterisering van de zonnestraling (A characterization of solar
669 radiation) in Nederland. Doctoral report, Eindhoven University of Technology, Netherlands,
670 97 + 67 pp., 1980.



- 671 Delpierre, N., Soudani, K., Francois, C., Le Maire, G., Bernhofer, C., Kutsch, W.,
672 Misson, L., Rambal, S., Vesala, T., and Dufrene, E.: Quantifying the influence of climate and
673 biological drivers on the interannual variability of carbon exchanges in European forests
674 through process-based modelling. *Agric. For. Meteorol.*, 154–155, 99–112,
675 <https://doi.org/10.1016/j.agrformet.2011.10.010>, 2012.
- 676 Dirnbock, T., Dullinger, S., Gottfried, M., Ginzler, C. and Grabherr, G.: Mapping alpine
677 vegetation based on image analysis, topographic variables and Canonical Correspondance
678 Analysis. *Applied Vegetation Science*, 6: 85-96, <https://doi.org/10.1111/j.1654->
679 [109X.2003.tb00567.x](https://doi.org/10.1111/j.1654-109X.2003.tb00567.x), 2003.
- 680 Dubayah, R. and Loechel, S.: Modeling topographic solar radiation using GOES data. *J.*
681 *Appl. Meteor.*, 36, 141–154, <https://doi.org/10.1175/1520->
682 [0450\(1997\)036<0141:MTSRUG>2.0.CO;2](https://doi.org/10.1175/1520-0450(1997)036<0141:MTSRUG>2.0.CO;2), 1997.
- 683 Dufrene, E., Davi, H., Francois, C., Maire, G. I., Dantec, V. L., and Granier, A.: Modelling
684 carbon and water cycles in a beech forest: Part I: Model description and uncertainty analysis
685 on modelled NEE. *Ecol. Model.*, 185, 407–436,
686 <https://doi.org/10.1016/j.ecolmodel.2005.01.004>, 2005.
- 687 Fealy, R. and Sweeney, J.: Statistical downscaling of temperature, radiation and potential
688 evapotranspiration to produce a multiple GCM ensemble mean for a selection of sites in
689 Ireland. *Irish Geography*, 41:1, 1-27, DOI: <https://doi.org/10.1080/00750770801909235>,
690 2008.
- 691 Fisher, J. B., Whittaker, R. J., and Malhi, Y.: ET come home: Potential evapotranspiration
692 in geographical ecology: ET come home. *Global Ecology and Biogeography*, 20(1), 1–18.
693 <https://doi.org/10.1111/j.1466-8238.2010.00578.x>, 2011.
- 694 Franklin, J.: Predicting the distribution of shrub species in southern California from climate
695 and terrain-derived variables. *Journal of Vegetation Science*, 9(5): 733-748,
696 <https://doi.org/10.2307/3237291>, 1998.
- 697 Corripio, J.G.: insol: Solar Radiation. R package version 1.2.2,
698 <https://www.meteoexploration.com/R/insol/> (last access 27/05/2024), 2020.
- 699 Granier, A., Breda, N., Biron, P. and Villette, S.: A lumped water balance model to
700 evaluate duration and intensity of drought constraints in forest stands. *Ecol. Model.*,
701 116:269–283, [https://doi.org/10.1016/S0304-3800\(98\)00205-1](https://doi.org/10.1016/S0304-3800(98)00205-1), 1999.
- 702 Granier, A., Reichstein, M., Bréda, N., Janssens, I. A., Falge, E., Ciais, P., Grünwald, T.,
703 Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Facini, O., Grassi, G., Heinesch, B.,
704 Ilvesniemi, H., Keronen, P., Knohl, A., Köstner, B., Lagergren, F., Lindroth, A., Longdoz, B.,
705 Loustau, D., Mateus, J., Montagnani, L., Nys, C., Moors, E.J., Papale, D., Peiffer, M.,
706 Pilegaard, K., Pita, G., Pumpanen, J., Rambal, S., Rebmann, C., Rodrigues, A., Seufert, G.,
707 Tenhunen, J., Vesala, T. and Wang, Q.: Evidence for soil water control on carbon and water



708 dynamics in European forests during the extremely dry year: 2003. *Agricultural and Forest*
709 *Meteorology*, 143(1-2), 123-145. <https://doi.org/10.1016/j.agrformet.2006.12.004>, 2007.

710 Hammond, W. M., Yu, K., Wilson, L. A., Will, R. E., Anderegg, W. R. L. and Adams, H. D.:
711 Dead or dying? Quantifying the point of no return from hydraulic failure in drought-induced
712 tree mortality. *New Phytologist*, 223(4), 1834–1843, <https://doi.org/10.1111/nph.15922>,
713 2019.

714 Hernanz, A., Correa, C., Domínguez, M., Rodríguez-Guisado, E. and Rodríguez-Camino,
715 E.: Comparison of machine learning statistical downscaling and regional climate models for
716 temperature, precipitation, wind speed, humidity and radiation over Europe under present
717 conditions. *International Journal of Climatology*, 43, 13, 6065-6082,
718 <https://doi.org/10.1002/joc.8190>, 2023.

719 Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G. and Jarvis, A.: Very high-
720 resolution interpolated climate surfaces for global land areas. *International Journal of*
721 *Climatology*, 25(15):1965-1978, <https://doi.org/10.1002/joc.1276>, 2005.

722 I.E.A. (International Energy Agency): An Introduction to Meteorological Measurements
723 and Data. Handling for Solar Energy Applications, Handbook Int. Energy Agency, Dept.
724 Energy U.S.A., Washington D.C, 1978.

725 Jean, F., Davi, H., Oddou-Muratorio, S., Fady, B., Scotti, I., Scotti-Saintagne, C., Ruffault,
726 J., Journe, V., Clastre, P., Marloie, O., Brunetto, W., Correard, M., Gilg, O., Pringarve, M.,
727 Rei, F., Thevenet, J., Turion, N. and Pichot, C.: A 14-year series of leaf phenological data
728 collected for European beech (*Fagus sylvatica* L.) and silver fir (*Abies alba* Mill.) from their
729 geographic range margins in south-eastern France. *Annals of Forest Science*, (2023)80:35,
730 <https://doi.org/10.1186/s13595-023-01193-9>, 2023.

731 Klein, T.: The variability of stomatal sensitivity to leaf water potential across tree species
732 indicates a continuum between isohydric and anisohydric behaviours. *Funct. Ecol.*, 28,
733 1313–1320, <https://doi.org/10.1111/1365-2435.12289>, 2014.

734 Klucher, T.M.: Evaluation of models to predict insolation on tilted surfaces. Division of
735 *solar energy*, N.A.S.A. TM-78842, [https://doi.org/10.1016/0038-092X\(79\)90110-5](https://doi.org/10.1016/0038-092X(79)90110-5), 1978.

736 Lander, T.A., Klein, E.K., Roig, A. and Oddou-Muratorio, S.: Weak founder effects but
737 significant spatial genetic imprint of recent contraction and expansion of European beech
738 populations. *Heredity (Edinb)*, 126(3):491-504, doi: 10.1038/s41437-020-00387-5, 2021.

739 Martin-StPaul, N., Delzon, S. and Cochard, H.: Plant resistance to drought depends on
740 timely stomatal closure. *Ecology Letters*, 20(11), 1437–1447.
741 <https://doi.org/10.1111/ele.1285>, 2017.

742 Martin-StPaul, N., Ruffault, J., Guillemot, J., Barbero, R., Cochard, H., Cailleret, M.,
743 Cáceres, M. D., Dupuy, J.-L., Pimont, F., Torres-Ruiz, J. M., and Limousin, J.-M.: How much
744 does VPD drive tree water stress and forest disturbances? *Authorea*, Preprints.



- 745 <https://doi.org/10.22541/au.168147010.01270793/v1>, 2023.
- 746 Meentemeyer, R.K., Moody, A. and Franklin, J.: Landscape-scale patterns of shrub-
747 species abundance in California chaparral: The role of topographically mediated resource
748 gradients. *Plant Ecology*, 156: 19-41, <https://doi.org/10.1023/A:1011944805738>, 2001.
- 749 Monteith, J. L.: Evaporation and surface temperature. *Quarterly Journal of the Royal*
750 *Meteorological Society*, 107(451), 1–27. <https://doi.org/10.1002/qj.49710745102>, 1981.
- 751 Moreno, M., Simioni, G., Cailleret, M., Ruffault, J., Badel, E., Carrière, S., Davi, H.,
752 Gavinet, J., Huc, R., Limousin, J.-M., Marloie, O., Martin, L., Rodríguez-Calcerrada, J.,
753 Vennetier, M. and Martin-StPaul, N.: Consistently lower sap velocity and growth over nine
754 years of rainfall exclusion in a Mediterranean mixed pine-oak forest. *Agricultural and Forest*
755 *Meteorology*, 308–309, 108472. <https://doi.org/10.1016/j.agrformet.2021.108472>, 2021.
- 756 Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G.,
757 Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles,
758 M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., and Thépaut, J.-N.: ERA5-Land:
759 a state-of-the-art global reanalysis dataset for land applications. *Earth Syst. Sci. Data*, 13,
760 4349–4383, <https://doi.org/10.5194/essd-13-4349-2021>, 2021.
- 761 Oliphant, A. J., & Stoy, P. C.: An evaluation of semiempirical models for partitioning
762 photosynthetically active radiation into diffuse and direct beam components. *Journal of*
763 *Geophysical Research: Biogeosciences*, 123, 889–901,
764 <https://doi.org/10.1002/2017JG004370>, 2018.
- 765 Patsiou, T.S., Conti, E., Zimmermann, N.E., Theodoridis, S. and Randin, C.F.: Topo-
766 climatic microrefugia explain the persistence of a rare endemic plant in the Alps during the
767 last 21 millennia. *Global Change Biology*, 20(7):2286–2300,
768 <https://doi.org/10.1111/gcb.12515>, 2014.
- 769 Piedallu, C. and Gégout, J.-C.: Multiscale computation of solar radiation for predictive
770 vegetation modelling. *Ann. For. Sci.*, 64, 899-909, DOI: 10.1051/forest:2007072, 2007.
- 771 Piedallu, C. and Gégout, J.-C.: Efficient assessment of topographic solar radiation to
772 improve plant distribution models. *Agricultural and Forest Meteorology*, 148 (11), pp.1696-
773 1706., <https://doi.org/10.1016/j.agrformet.2008.06.001>, 2008.
- 774 Pierce, K.B., Lookingbill, T. and Urban, D.: A simple method for estimating potential
775 relative radiation (PRR) for landscape-scale vegetation analysis. *Landscape Ecology*, 20(2):
776 137-147, <https://doi.org/10.1007/s10980-004-1296-6>, 2005.
- 777 Poggio, L., De Sousa, L. M., Batjes, N. H., Heuvelink, G. B. M., Kempen, B., Ribeiro, E.,
778 and Rossiter, D.: SoilGrids 2.0: Producing soil information for the globe with quantified
779 spatial uncertainty. *Soil*, 7(1), 217–240. doi: 10.5194/soil-7-217-2021, 2021.
- 780 Randin, C. F., Engler, R., Normand, S., Zappa, M., Zimmermann, N. E., Pearman, P. B.,
781 Vittoz, P., Thuiller, W. and Guisan, A.: Climate change and plant distribution: local models



782 predict high-elevation persistence. *Global Change Biology*, 15(6), 1557-1569.

783 <https://doi.org/10.1111/j.1365-2486.2008.01766.x>, 2009.

784 Roderick, M. L.: Estimating the diffuse component from daily and monthly measurements
785 of global radiation. *Agricultural and Forest Meteorology*, 95, 169-185,
786 [https://doi.org/10.1016/S0168-1923\(99\)00028-3](https://doi.org/10.1016/S0168-1923(99)00028-3), 1999.

787 Ruffault, J., Martin-StPaul, N.K., Rambal, S. et Mouillot, F.: Differential regional
788 responses in drought length, intensity and timing to recent climate changes in a
789 Mediterranean forested ecosystem. *Climatic Change*, 117, 103–117,
790 <https://doi.org/10.1007/s10584-012-0559-5>, 2013.

791 Ruffault, J., Pimont, F., Cochard, H., Dupuy, J.-L., and Martin-StPaul, N.: SurEau-Ecos
792 v2.0: a trait-based plant hydraulics model for simulations of plant water status and drought-
793 induced mortality at the ecosystem level, *Geosci. Model Dev.*, 15, 5593–5626,
794 <https://doi.org/10.5194/gmd-15-5593-2022>, 2022.

795 Ruffault, J., Limousin, J.-M., Pimont, F., Dupuy, J.-L., De Cáceres, M., Cochard, H.,
796 Mouillot, F., Blackman, C.J., Torres-Ruiz, J.M., Parsons, R.A., Moreno, M., Delzon, S.,
797 Jansen, S., Olioso, A., Choat, B. and Martin-StPaul, N.: Plant hydraulic modelling of leaf and
798 canopy fuel moisture content reveals increasing vulnerability of a Mediterranean forest to
799 wildfires under extreme drought. *New Phytologist*, 237, 4, 1256-1269,
800 <https://doi.org/10.1111/nph.18614>, 2023.

801 Spitters, C.J.T., Toussaint, H.A.J.M., and Goudriaan, J.: Separating the diffuse and direct
802 component of global radiation and its implications for modeling canopy photosynthesis Part I.
803 Components of incoming radiation. *Agr. and Forest Met.*, 38(1-3), 217-229,
804 [https://doi.org/10.1016/0168-1923\(86\)90060-2](https://doi.org/10.1016/0168-1923(86)90060-2), 1986.

805 Shuttle Radar Topography Mission (SRTM): 1 Arc-Second Global (2013).
806 <https://doi.org/10.5066/F7PR7TFT> (Downloaded on <https://earthexplorer.usgs.gov/> the 15-
807 10-2021), 2013.

808 Stéfanon, M., Martin-StPaul, N. K., Leadley, P., Bastin, S., Dell'Aquila, A., Drobinski, P.,
809 and Gallardo, C.: Testing climate models using an impact model: What are the advantages?
810 *Climatic Change*, 131(4), 649–661, <https://doi.org/10.1007/s10584-015-1412-4>, 2015.

811 Tappeiner, U., Tasser, E. and Tappeiner, G.: Modelling vegetation patterns using natural
812 and anthropogenic influence factors: preliminary experience with a GIS based model applied
813 to an Alpine area. *Ecological Modelling*, 113(1-3): 225-237, [https://doi.org/10.1016/S0304-
814 3800\(98\)00145-8](https://doi.org/10.1016/S0304-814-3800(98)00145-8), 1998.

815 Zimmermann, N.E. and Kienast, F.: Predictive mapping of alpine grasslands in
816 Switzerland: Species versus community approach. *Journal of Vegetation Science*, 10(4):
817 469-482, <https://doi.org/10.2307/3237182>, 1999.