1 **Will climate change affect sugar beet establishment of the 21st century?**

2 **Insights from a simulation study using a crop emergence model**

3 Jay Ram Lamichhane[1*], Julie Constantin[1], Jean-Noël Aubertot[1], Carolyne Dürr[2]

4 [1]INRA, Université Fédérale de Toulouse, UMR 1248 AGIR, F-31326 Castanet-Tolosan,

5 France

6 [2]INRA, IRHS 1345, 42 rue George Morel, F-49071 Beaucouzé, France

7 *Corresponding author: jay-ram.lamichhane@inra.fr

8 Tel: +33 (0)5 61 28 52 50; Fax: +33 (0)5 61 28 55 37

Abstract

10 Ongoing climate change has been reported to have far-reaching impact on crop

11 development and yield in many regions of the globe including Europe. However, little is

12 known about the potential impact of climate change on specific stages of the crop cycle

13 including crop establishment, although it is a crucial stage of the annual crop cycles. For

14 the first time, we performed a simulation study to pinpoint how sugar beet sowing

15 conditions of the next eight decades will be altered under future climate change and if

16 these variations will affect sowing dates, germination and emergence as well as bolting

17 rates of this crop. We chose Northern France as an important study site, representative of

18 sugar beet growing basin in Northern Europe. Sugar beet emergence simulations were

19 performed for a period between 2020 and 2100, taking into account five sowing dates

20 (mid-February, 1st March, mid-March, 1st April and mid-April). Soil water contents and

21 temperatures in the 0-10 cm soil horizon were first simulated with the STICS soil-crop

22 model using the most pessimistic IPCC scenario (RCP 8.5) to feed the SIMPLE crop

23 emergence model. We also evaluated the probability of field access for the earlier sowings,

24 based on the amount of cumulated rainfall during February and March. When analyzed

25 by sowing date and for successive 20-year period from 2020 to 2100, there was a

26 significant increase in seedbed temperatures by 2°C after 2060 while no change in

27 cumulative rainfall was found before and after sowings, compared with the past.

28 Emergence rate was generally higher for 2081-2100, while time to reach the maximum

29 emergence rate decreased by about one week, compared with other periods, due to higher

30 average seedbed temperatures. The rate of non-germinated seeds decreased, especially

31 for the earlier sowing dates, but the frequency of non-emergence due to water stress

32 increased after 2060 for all sowing dates, including the mid-February sowing. Bolting

33 remains a risk for sowings before mid-March although this risk will be markedly

34 decreased after 2060. The changes in seedbed conditions will be significant after 2060 in

35 terms of temperatures. However, the possibility of field access will be a main limiting

36 factor for earlier sowings, as no significant changes in cumulative rainfall, compared with

37 the past, will occur under future climate change. When field access is not a constraint, an

38 anticipation of the sowing date, compared to the currently practiced sowing (i.e. mid-

39 March), will lead to decreased risks for the sugar beet crop establishment and bolting. The

40 use of future climate scenarios coupled with a crop model allows a precise insight into the

41 future sowing conditions, and provide helpful information to better project future farming

42 systems.

43 **Key words:** adaptation, seed germination, seedling emergence, seedling mortality, soil-

44 surface crust, temperature, water stress

45   **1. Introduction**

46 Seed germination and seedling emergence are critical phases of a crop cycle that affect

47 the success or failure of any crop establishment (Villalobos et al. 2016). These early

48   phases of crop cycle are affected by several biotic and abiotic factors that may reduce seed

49   germination and seedling emergence rates (Lamichhane et al. 2018). More specifically to

50   abiotic stresses, many factors including seedbed water content, temperature, and the

51   frequency and quantity of cumulated rainfall profoundly impact crop establishment

52   (Gallardo-Carrera et al. 2007; Constantin et al. 2015; Dürr et al. 2016). Several studies

53   reported that climate change will result in increased mean temperature and higher

54   precipitation variability in many regions of the globe including Europe (Pendergrass et al.

55   2017; Kjellström et al. 2018). The effects of ongoing climate change on crop yield have

56   been extensively studied (Lobell et al. 2008; Challinor et al. 2014). For instance, climate

57   change from 1980 to 2008 has resulted in reduced global production of maize by 3.8%

58   and wheat by 5.5% compared with a counterfactual without climate change (Lobell et al.

59   2008). A recent meta-analysis (Challinor et al. 2014) -- based on 1,700 published

60   simulation studies on climate change impacts on yields and adaptation -- showed that

61   without adaptation, there will be losses in production for wheat, rice and maize in both

62   temperate and tropical regions by 2 °C of local warming.

63   While many studies assessed the impact of climate change on crop yields, there is less

64   detailed information about the potential effect of climate change on crop establishment,

65   although it is a crucial stage for annual crops. This prevents stakeholders from mobilizing

66   adaptation strategies that may be helpful to attenuate climate change effects. Rather small

67   adjustments (e.g. changes in varieties, sowing date and density, tillage or tactical pest

68   management) in contrast to more systemic changes (e.g. changes in crop sequences;

69   moving from dryland to irrigated systems or from spring to autumn sowings), may ensure

70   successful crop establishment with positive impacts on crop yield (reviewed by

71   Lamichhane et al. 2018). Indeed, either a lack or an excess of soil temperature, water

72   content or rainfall may be detrimental to crop establishment. For example, if no

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73 precipitation occurs after sowing the seed imbibition process is hindered and seeds

74 cannot germinate. In contrast, if heavy rainfall occurs following sowing soil crusting will

75 occur preventing seedlings from being emerged (Gallardo-Carrera et al. 2007). Spring

76 crops are more sensitive to seedbed sowing conditions than winter crops. The risk of poor

77 crop establishment is higher for these crops also because most of them are not able to

78 compensate a lower plant density via tillering or ramification during their development.

79 Sugar beet (*Beta vulgaris* L.) is a typical example of spring crop highly sensitive to seedbed

80 sowing conditions. In Northern Europe, these conditions are frequently unfavorable, with

81 low temperatures, heavy rainfall followed by dry periods leading to soil surface crusting

82 on loamy soils (Durr and Boiffin 1995). Sugar beet growers have to optimize sowing dates

83 and seedbed preparations to ensure successful crop establishment. In addition, sugar beet

84 is subject to bolting, if cold temperatures occur following early sowings (Longden et al.

85 1975; Milford et al. 2010), with negative impact on its yield and volunteer plant's control.

86 Simulation studies are useful to help decision-making process. Exploration of adaptation

87 strategies to climate change using process-based models allows crop-level evaluation and

88 adaptation of existing cropping systems (Challinor et al. 2014). While numerous crop

89 models have been developed and used to facilitate decision-making during the crop

90 development phase, only few models focus on the crop establishment phase.

91 The objective of this simulation study was to pinpoint whether sowing conditions of the

92 next decades (2020-2100) will be altered under climate change and if these variations

93 will affect germination and emergence, as well as bolting rates of sugar beet in Northern

94 Europe. A total of 405 sugar beet emergence simulations were performed taking into

95 account five sowing dates. To this aim, we first mobilized the STICS soil-crop model

96 (Brisson et al. 1998, 2003) to generate soil water content and temperature in the seedbed

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97 (0–10 cm) using the most pessimistic IPCC scenario. We then used the data obtained as

98 input variables to feed the SIMPLE crop emergence model (Dürr et al. 2001; Constantin et

99 al. 2015). The emergence courses and final rates, and causes of no-seedling emergence

100 are analyzed and discussed. In addition, the possibility of field access was evaluated

101 comparing historical records in relation to future climatic conditions.

2. Materials and methods

2.1. Description of the SIMPLE crop emergence model

104 A comprehensive description including the functioning of the SIMPLE model and the list

105 of equations and input variables has been previously provided (Dürr et al. 2001). Briefly,

106 the model predicts the germination and emergence process and their final rates in

107 relation to environmental conditions during sowing. The model has previously been

108 parameterized for a number of crop species -- including wheat, sugar beet, flax, mustard,

109 French bean, oilseed rape (Dürr et al. 2001; Dorsainvil et al. 2005; Moreau-Valancogne et

110 al. 2008 ; Dürr et al. 2016), and a plant model *Medicago truncatula* (Brunel et al. 2009) -

111 which allows to compare a range of plant species using the same set of parameters

112 (Gardarin et al. 2016).

113 SIMPLE creates 3D representations of seedbeds with sowing depth distribution and the

114 size, number, and position of soil aggregates as input variables. Daily soil temperature and

115 soil water potential in several layers are also used as input variables for simulations, along

116 with plant characteristics for germination and seedling growth. The model predicts

117 germination and emergence, seed by seed, at daily intervals. The time required for

118 germination of the seed i is chosen at random in the distribution of thermal times that

119 characterizes the seed lot used. Cumulative thermal time from sowing is calculated above

120 the base temperature (Tb) for germination, provided that the soil water content at the

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121 seed sowing depth is above the base water potential (Ψb). The Tb and Ψb thresholds for

122 germination are input variables. If seed i has not germinated after a given time (usually

123 fixed at 30 days for the simulation), the model considers that the seed will never

124 germinate. If the seed germinates, then a seedling grows from the seed. Time is expressed

125 as thermal time using the Tb value. To better include the effect of early water stress on

126 seedling growth, we added a water stress function to the SIMPLE model, which reduces

127 emergence after germination (Constantin et al. 2015). With this function, the fate of

128 seedlings is determined by considering soil water potential in the soil layer in which the

129 radicle grows in the two days following germination. During this period, if soil water

130 potential is lower than Ψb, the seedling does not emerge and dies the following day. If this

131 is not the case, the time it takes for the seedling to reach the soil surface after germination

132 is calculated by SIMPLE based on the seed's sowing depth, the length of the pathway the

133 shoot takes through the aggregates, and the shoot's elongation function, whose

134 parameters are input variables. The probability of the seedlings remaining blocked under

135 aggregates depends on the size and position of the clods in the seedbed, i.e. laying on the

136 surface or below it. Soil surface crusting depends on cumulative rainfall after sowing; a

137 proportion of seedlings remain blocked under the crust depending on daily crust water

138 content (no seedlings are blocked if the crust is wet). Simulations at the individual seed

139 level are run 1000 times to predict the emergence rate and final emergence percentage.

140 The causes of non-emergence simulated by SIMPLE are (i) non-germination, (ii) death of

141 seedlings caused by water stress after germination and (iii) mechanical obstacles (clods

142 or a soil crust). The SIMPLE model does not consider biotic stresses, such as pests and

143 diseases or the effect of high temperatures, which could inhibit germination or cause

144 young seedling death.

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145 Bolting risk is represented by a function that was not initially presented in the seminal

146 paper describing the SIMPLE model (Dürr et al, 2001). This function was derived from

147 Longden et al (1975) and the probability of bolting μ_b is calculated as:

148 $\mu_b = c_1 \left(1 - e^{-c_2 n_{ccd}^{c_3}} \right)$ Equation 1

149 where c_1, c_2, c_3 dimensionless coefficients (Table 1); n_{ccd} is the number of cumulative cold

150 days from sowing to the end of June and is calculated as follows:

151 $n_{ccd} = \sum_{i=1}^{i=i_{max}} \delta_{\alpha_i \beta_i}$ Equation 2

152 where i is a daily index ranging from 1 (sowing day) to i_{max} (day corresponding to the end

153 of June) and $\delta_{\alpha_i \beta_i}$ is the Kronecker symbol with:

154 $\alpha_i = \beta_i$ if $\theta_i < \theta_b$ and $\alpha_i \neq \beta_i$ otherwise Equation 3

155 where θ_i is the maximum daily temperature at 2 m, and θ_b is the maximum threshold air

156 temperature to define whether a given day is considered as cold or not with regard to

157 bolting **(Table 1)**.

158 More recent studies (Fauchère et al 2003; Milford 2010) suggested that devernalization

159 can occur if plants are exposed to high temperatures during a specific period of the crop

160 cycle. Based on this information, we analyzed the number of days with Tmax >25°C

161 between 60 to 120 days post sowing (dps). Finally, we established that if this number was

162 >7, the potential risk of having bolted plants became zero.

163 **2.2. Climate scenarios and simulations of the seedbed climate**

164 We used the RCP 8.5 emission scenario to generate soil temperature and water content of

165 the seedbed using the STICS soil-crop model (Brisson et al. 2003). This model daily

166 simulates soil water contents and temperatures, according to daily weather and soil

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167 characteristics. Variations in soil moisture were predicted using STICS at 0-2, 2-4, 4-6 and

168 6-10 cm. We selected Estrées-Mons (49°52′44″N 3°00′27″E), located in the typical sugar

169 beet growing regions of Northern France, as study site. We chose Northern France as

170 representative sugar beet growing basin of Northern Europe. The soil type considered

171 had the following soil granulometry and chemical characteristics at the 0-30 cm soil

172 horizon: 0.197 g.g^{-1} clay, 0.747 g.g^{-1} silt and 0.056 g.g^{-1} sand; 0 g.g^{-1} CaCO$_3$, 0.095 g.g^{-1} C,

173 0.001 g.g^{-1}N, C/N ratio 9.3, and pH 7.7.

174 Four weather and soil parameters were analyzed for the year 2020-2100: average soil

175 temperature at sowing, average soil and maximum air temperature 30 dps, and cumulated

176 rainfall 30 dps. The average weather data of the last 19 years (2000-2018) registered at

177 the weather station of the study area were calculated to compare the trend with the

178 simulated weather data of the next 81 years.

179 **2.3. Sugar beet sowing scenarios**

180 Values of plant input variables of SIMPLE for sugar beet crop are reported in **Table 1**. The

181 seedbed considered in this study is typical of that prepared by growers and was

182 characterized by 15-25% of soil aggregates >20mm in diameter and 70-85% of its

183 aggregates having <20mm in diameter. The simulated sowing depths were 2.5 ± 0.4 cm.

184 A total of 405 sugar beet emergence simulations was performed for a period between

185 2020 and 2100, taking into account five sowing dates: mid-February, 1st March, mid-

186 March, 1st April, and mid-April. Farmers in Northern France most often practice mid-

187 March sowing of sugar beet crop but we included both earlier (mid-February and 1st

188 March) and late (1st April and mid-April) sowing dates taking into account a possible shift

189 in future sowing dates due to climate change.

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2.4. Analysis of simulation results

Climatic data were pooled and analyzed by sowing date and 20-year period (2000-2018 for the past and 2020-2040, 2041-2060, 2061-2080, and 2081-2100 for the future). When data were analyzed by sowing date, the 100 years were treated as replicates. When data were analyzed by 20-year period, the 20 years x five sowing dates (i.e. 100) were treated as replicates. ANOVA was used to determine the potential effect of sowing dates and periods, and their interaction on the four average weather and soil parameters mentioned above.

The variability of germination and emergence rates and their duration was analyzed by establishing three classes of rate or duration, expressed as the frequency of each class over the 20-year period for germination and emergence rates, and their duration. For germination rate, thresholds were poor germination when germination rate was <75% and sufficient germination above 75%. For emergence rate, thresholds were poor emergence when the emergence rate was <50%, and sufficient over 50%. For germination duration, thresholds were low duration when the number of days required to reach maximum germination (NGmax) was < 14 days and high when NGmax was >14 days. For emergence duration, thresholds were low duration when the number of days required to reach maximum emergence (NEmax) was < 28 days, and high when NEmax was >28 days. The frequency of poor germination (<75%) and emergence (<50%) rates as well as high NGmax (>14 days) and NEmax (>28 days) duration were analyzed as they could lead to crop emergence failure and potential re-sowing.

The variability of causes of non-emergence was analyzed by establishing two classes of seed and seedling mortality rates for each mortality cause. For non-germination, the two classes were low with <25% and high with >25% non-germinating seeds. For seedling

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214   mortality due to clod, crust and drought, the two classes were low with <15%, and high

215   with >15% of seedling mortality. Frequency of high risks of non-germination (>25%) and

216   seedling mortality due to clod, crust, and drought (each >15%) cases are presented for

217   the same reason as described above.

218   The variability of bolting rates was presented as the average predicted percentages of

219   bolted plants over the 20-year periods. This variability was also analyzed by establishing

220   three classes of bolting rates : <0.5%, 0.5-1%, and >1% rate.

221   To determine significant effects on germination, emergence and bolting rates, and

222   duration as well as on causes of non-emergence, in addition to the same statistical analysis

223   performed for weather data (i.e. only by sowing date and 20-year period pooling all the

224   data), we also analyzed the data by sowing date for each 20-year period separately

225   (hereafter referred to as period). All statistical analyses were conducted using software R

226   (Hothorn and Everitt 2009).

227   **2.5. Technical feasibility of sowing**

228   An earlier sowing than the currently practiced sowing (mid-March) may be possible

229   under future climate change. This shift in sowing date however depends on field access

230   for sowing. We determined whether farmers will have technical possibility for sowing for

231   the simulated sowing dates and years using two following approaches.

232   i) based on a past historical data set (1987-2005), we observed a correlation between the

233   quantity of total cumulative rainfall during the sowing in March and the percentage of

234   sugar beet surface sown in France at the end of this month **(Figure 1)**. We then compared

235   these past observations with the predicted cumulative future rainfall of the same months

236   (i.e. February and March).

237   ii) we supposed that >1 mm rainfall on sowing day will not technically allow field access

238   for farmers for the sowings in February and March because the soil surface is wet and

239   evapotranspiration low. Based on this, we calculated the frequency of days >1 mm rainfall

240   for February and March.

3. Results

3.1. Sowing conditions and their variability under future scenario

243   When analyzed by sowing date, differences between the average soil temperature at

244   sowing, average soil and maximum air temperature 30 dps were statistically significant

245   (P < 0.001) **(Table 2).** When analyzed by period of time, all average weather values

246   related to temperature increased with time with statistically significant differences (P <

247   0.001). In contrast, no differences statistically significant were found for average rainfall

248   30 dps (P = 0.220).

249   As expected, average soil temperature at sowing increased with later sowing dates. The

250   trend was similar for average soil and maximum air temperatures 30 dps. Overall, average

251   soil temperature at sowing ranged between 5 °C for the mid-February sowing to 11 °C for

252   the mid-April sowing, while average soil temperature 30 dps ranged from 6 °C for the mid-

253   February sowing to 13 °C for the mid-April sowing. Also average maximum air

254   temperature 30 dps was the lowest (9 °C) for the mid-February sowing while it was the

255   highest (16 °C) for the mid-April sowing. In contrast to the three temperature factors,

256   average rainfall 30 dps did not follow the same pattern: it was high (45-52 mm) for the

257   first four sowing dates with no significant differences, and then decreased drastically for

258   the mid-April sowing (28 mm).

259 When analyzed by period, average soil sowing day temperature was the lowest (7 °C) for

260 the 2020-2040 and 2041-2060 periods, and increased progressively for the 2061-2080

261 and 2081-2100 periods by 8 and 9 °C, respectively. The trend was the same also for

262 average soil temperature 30 dps, which ranged from 9 °C for the 2020-2040 period to 11

263 °C for the 2081-2100 period. These differences were significant between the first two and

264 the last two periods. These changes became significant after 2060. In contrast, mean

265 average maximum air temperature 30 dps varied over periods but with no regular

266 increase. Mean cumulated rainfall 30 dps ranged from 39 to 47 mm, with a high variability

267 between individual years, but without any significant differences until 2100. There was

268 no significant effect of the sowing date x period interaction on any of the analyzed weather

269 data **(Table 2).**

270 **3.2. Emergence rate, duration and frequency**

271 Year-to-year emergence rate variability for all five sowing dates is described in **Figure 2**.

272 Results on the effect of sowing date for each period and their interaction on emergence

273 rate, duration and frequency are reported in **Table 3**. Results on the effect of sowing date

274 and period separately, and their interaction on emergence rate and duration are

275 presented in **Supplementary Table 1**.

276 Year-to-year variability in emergence rate was very high for all sowing dates over the 81

277 simulated years ranging from 0 to 85%. Emergence rate most often registered between

278 50 and 85%, but emergence rate <50% were observed in many cases. Simulated average

279 emergence rate by "sowing date × period" ranged from less than 50% for the mid-

280 February sowing in 2020-2040 to more than 70% for different sowing dates. The

281 frequency of poor emergence rate (<50%) ranged from 14 to 48% depending on sowing

282   date × period. The mid-February sowing in the 2020-2040 period not only had the lowest

283   average emergence rate but also a high frequency of poor emergence rate.

284   When data were analyzed by sowing date for each period, the interaction effect of sowing

285   date x period on emergence rate was not statistically significant (P = 0.08). In contrast,

286   the interaction effect was statistically significant (P < 0.001) when all data were pooled

287   and analyzed only by sowing date or period **(Supplementary Table 1)**.

288   Simulated mean NEmax by sowing date × period ranged from 20 days for the mid-April

289   sowing in the 2081-2100 period to 50 days for the mid-February sowing in the 2041-2060

290   period **(Table 3)**. Mean NEmax decreased over sowing dates and also over periods, by

291   more than one week for the earlier sowing dates and to a lower extent for later sowings.

292   Within each period, mean NEmax was almost no significantly different between the five

293   sowing dates. However, there were statistically significant differences when the data were

294   analyzed only by sowing date (P < 0.001) or period (P < 0.001**; Supplementary Table 1)**.

295   The frequency of high NEmax (>28 days) ranged from 15 to 100% by sowing date ×

296   period. This frequency was higher for earlier sowing dates and also for earlier periods

297   **(Table 3)**.

298   **3.4. Causes of non-emergence rates and frequencies**

299   Results on the main causes of non-emergence are reported in **Table 4**. The major causes

300   of non-emergence were non-germination, followed by soil surface crusting and seedling

301   death due to drought while seedling death due to clod was the least important. Results on

302   the effect of sowing date for each period and their interactions on germination rate,

303   duration and frequency are reported in **Table 5.** Outcomes on the overall effect of sowing

304   date and period, and their interactions on germination rate and duration are presented in

305   **Supplementary Table 1**.

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3.4.1. Non-germination

The mean non-germination rate ranged from less than 5% for several sowing dates after the mid-March sowing to 37% for the mid-February sowing in the 2020-2040 period. When data were analyzed by sowing date for each period, and their interaction, no statistically significant effect of the sowing date, period, or their interaction was found on non-germination rate except between the 2020-2040 and 2081-2100 periods for the mid-February sowing. In contrast, non-germination rate differences were statistically significant when the data were combined and analyzed by sowing date (P < 0.001), period (P < 0.01), and their interaction (P < 0.001; **Supplementary Table 2)**. The frequency of high non-germination (>25%) ranged from 0 to 48% **(Figure 3)** depending on sowing date x period and was higher for earlier sowings.

Simulated average NGmax values ranged from 14 to 22 days when data were analyzed by sowing date for each period. These values generally decreased with later sowing dates and periods **(Table 5)**. The frequency of high NGmax (>14 days) ranged from 8 to 21% which generally decreased with later sowings and over the periods. No statistically significant effect of sowing date, period and their interaction (P = 0.98) was found on mean NGmax values when data were analyzed by sowing date for each period. In contrast, when data were analyzed only by sowing date or period, there were statistically significant effects of sowing date (P < 0.001) and period (P < 0.01), but not of their interaction on mean NGmax **(Supplementary Table 1).**

3.4.2. Seedling mortality due to crust

Seedling mortality rate due to soil surface crust ranged from 6 to 15% **(Table 4).** Average mortality rate was generally lower for the 2020-2040 period until the mid-March sowing, as soil surface crust prevents emergence only when it becomes dry. No statistically

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330 significant effect of sowing date (P = 0.48) or period (P = 0.24) or their interaction was

331 observed on seedling mortality rate either when the data were analyzed by sowing date

332 for each period (P = 0.76) or only by sowing date and period (P = 0.22) **(Supplementary**

333 **Table 2)**. The frequency of high seedling mortality rate (>15%) ranged from 19 to 45%

334 **(Figure 3)**. This frequency was lower for the 2020-2040 period until mid-March sowing.

335 **3.4.3. Seedling mortality due to drought**

336 Seedling mortality rate due to drought ranged from 1 to 14%, and increased with later

337 sowing dates and periods, with some exceptions **(Table 4)**. When data were analyzed by

338 sowing date for each period, no significant effect of sowing date, period or their

339 interaction (P = 0.276) was found on seedling mortality rate. In contrast, when the data

340 were pooled and analyzed only by sowing date and period, statistically significant effect

341 of sowing date (P < 0.001), period (P < 0.001) and their interaction (P < 0.05) was found

342 on seedling mortality rate **(Supplementary Table 2)**. The frequency of high mortality

343 due to drought (>15%) ranged from 0 to 40% **(Figure 3)**. This frequency increased with

344 later sowing dates and periods. It is however remarkable that seedling mortality due to

345 drought appeared for the 2081 – 2100 period even for sowings as early as mid-March or

346 even before.

347 **3.4.4. Seedling mortality due to clod**

348 Seedling mortality rate due to clod ranged from 9 to 12% **(Table 4)** with little variability

349 among the sowing dates or periods. This was expected because this mortality mostly

350 depends on seedbed structure, which was the same for all simulations, independent of the

351 sowing date and period.

352 **3.5. Risks of bolting**

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353   When data were analyzed by sowing date for each 20-year period, significant effect of

354   sowing date, period or their interaction (P < 0.001) was found on potential bolting rate

355   and devernalization conditions. The average predicted potential bolting rates ranged

356   from 0.04% to 1.65%. As expected, bolting rates were higher for sowings in February and

357   decreased with later sowing dates. Our results showed that the predicted bolting rates

358   decreased progressively and significantly after 2060 for all simulated sowing dates

359   **(Table 6**). Likewise, the potential for devernalization highly increased due to an increased

360   number of days with Tmax > 25°C at the end of spring **(Table 6)**. Based on these results,

361   the average risk of bolting will be lower after 2060, even for the earliest sowing dates.

362   **3.6. Technical feasibility of sowing**

363   Results on the probability of field access for February and March over periods are

364   reported in **Table 7**. When considering cumulated rainfall over one month or the number

365   of days >1 mm rainfall in February or March (i.e. the earliest sowing periods), there were

366   no statistically significant differences between the two months and over the 20-year

367   periods. This means that the technical feasibility of sowings will remain the same as

368   nowadays, as shown in **Figure 1.**

369   # 4. Discussion

370   **4.1. Seedbed micro-climatic conditions under future scenarios**

371   We used the STICS soil-crop model based on the RCP 8.5 emission scenario to generate

372   climate data. This model has been reported to be sensitive enough to generate realistic

373   soil data such as soil moisture (Constantin et al. 2015; Dürr et al. 2016; Tribouillois et al.

374   2018). Predictions of the STICS soil-crop model showed that during the sowing period of

375   sugar beet, mean seedbed temperatures will increase over time and that a higher

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376 variability of rainfall will occur, without an overall increase of its cumulated values. The

377 trends we found here are coherent with those generally expressed for global climate

378 changes, and the use of the STICS model allows to evaluate more precisely these changes

379 specifically in the seedbed and for the sowing period of sugar beet in Northern France or

380 Europe.

381 Under the most pessimistic climate scenario that we used, the predicted rise in mean soil

382 temperature at sowing remained 0 °C until 2060 and became +2 °C after 2080. When

383 climatic data of the next eight decades were compared with the past two decades, we

384 found that average soil temperature 30 dps of the last 19 years were similar to those

385 predicted until 2060, but higher over the last two periods. This highlights that the impact

386 of climate change will become more remarkable after 2060 with warmer soil

387 temperatures during the last two decades of the 21st century. Interestingly, when

388 maximum air temperature at sowing was considered, mean values 30 dps showed a very

389 high year-to-year variability, but without any regular increase over the years.

390 In contrast to predicted seedbed temperatures, cumulative rainfall did not change over

391 time and were more or less the same for the first four sowing dates. A delay of two weeks

392 in sowing from 1st to mid-April resulted in an increased drought risk under future climate

393 change.

4.2. Sugar beet crop establishment under future climate

395 Several previous studies compared results of field observation and simulation using the

396 SIMPLE crop emergence model and found its prediction similar to observed data

397 (Dorsainvil et al. 2005; Brunel-Muguet et al. 2011; Constantin et al. 2015; Dürr et al.

398 2016). Therefore, prediction of germination and emergence rates reported in this study

399 can be considered reliable. Even by using the most pessimistic climate scenario,

17

400   predictions based on the SIMPLE crop emergence model showed that, in most cases, there

401   will be a sufficient level of sugar beet crop emergence in Northern France and Europe

402   under future climate change.

403   Despite performing simulation studies using only one climate scenario, the results of this

404   study represent an important outcome for decision making related to sugar beet sowing

405   not only in Northern France, but in Northern Europe in general due to similar climatic

406   conditions and sowing dates. The inclusion of the most pessimistic climate scenario for

407   simulation did not render necessary the use of other less pessimistic climate scenarios

408   (i.e. RCP 2.6, 4.5 and 6). This is because we did not find any dramatic changes in sugar

409   beet emergence rate which would have been less impacted with simulation studies

410   including less drastic future climate scenarios. Nevertheless, our results are based on only

411   one study site which represents a limit and thus future studies taking into account several

412   study sites over space could shed more light in this regard.

413   The most important finding of this study is that there are no important variability in terms

414   of emergence rate among sowing dates, except for the earliest one for which emergence

415   rate was predicted to be higher and less variable after 2060. Sowing date adaptation is,

416   by far, the most frequently investigated climate change adaptation option (White et al.

417   2011). Sugar beet farmers in France and Northern Europe, who currently practice the

418   mid-March sowing, may thus anticipate sowing under future climate scenarios, given that

419   earlier sowing provides higher yield benefits. This is due to a prolonged vegetation period

420   and the higher amount of intercepted solar radiation, as it is the case for many field crops

421   (Van Ittersum and Rabbinge 1997).

422   Bolting causes yield penalties in sugar beet , and contribute to gene flow, seed dispersion,

423   and volunteer plant development in the next crops (Longden et al 1975; Sester et al 2008).

424 Therefore, bolting risks could be a limiting factor even when there are possibilities for

425 earlier sowing. Our results showed that the predicted bolting risk will decrease over time

426 and will become reduced for the mid-February sowing and very limited for the 1st March

427 sowing, especially after 2060.

4.3. Causes of non-emergence of seedlings under future scenarios

429 In terms of the total percentage of emergence failure, the one due to non-germination was

430 the most important followed by soil surface crusting and drought. Seedling mortality rates

431 under clod did not vary over sowing dates or periods since it strictly depends on the

432 seedbed structure chosen for simulations. It is also the reason why the maximum

433 simulated emergence rate remained always around 85%, due to about 5% non-

434 germinating seeds in the simulated seed lot and about 10% non-emerging seedlings due

435 to the simulated seedbed structure. Both germination and emergence were affected by

436 the considered abiotic stresses. At the germination stage, very low temperature with

437 earlier sowings, and very low or no rainfall during the later sowings affected the seed

438 germination process. During the emergence phase, the frequency of emergence failure

439 was either related to seedling mortality due to a soil surface crust with all sowing dates,

440 or to water stress with later sowings. The average risk of crop emergence failure remains

441 similar with sowing dates or periods but the prevalence of individual stress factor changes

442 according to sowing dates and periods. After 2060 and to a greater extent after 2080,

443 higher risks of seedling mortality due to drought appear even for the earliest sowing date.

444 Such an analysis of non-emergence results can be obtained only with a simulation

445 approach. Even in the current situation, field observations are rarely undertaken since

446 they are difficult, time consuming and cannot be performed in a high number of fields.

19

447   Although the SIMPLE model does not consider the effect of high temperatures that could

448   inhibit germination, we exclude the impact of this stress, given that all sowing were

449   performed in spring and under North European conditions.

450   Seed germination and seedling emergence rates of sugar beet simulated by the SIMPLE

451   crop emergence model could be overestimated because this model does not take into

452   account the effect of biotic stresses (Constantin et al. 2015). Nevertheless, the risk related

453   to biotic stress could be still limited under current cropping practices for two reasons.

454   First, pelleting of sugar beet seeds containing protectants (fungicides, insecticides, and

455   nematicides) and biostimulants -- is performed to date on 100% seeds (Agreste 2014)

456   which may limit risks of the sugar beet crop establishment due to biotic stresses. Although

457   several diseases of sugar beet caused by soil-borne pathogens, including Rhizoctonia root

458   rot and damping-off, have been reported in Northern France (Motisi et al. 2009), the

459   disease pressure is generally low when seeds are treated. Secondly, sugar beet crop is

460   often rotated with other crops including wheat, to reduce pest inocula *sensu lato*, although

461   some of the crops introduced into the rotation scheme may also be affected by the same

462   soil-borne pathogens affecting sugar beet (Motisi et al. 2009). This is due to a wide host

463   range of most soil-borne pathogens affecting the crop establishment phase (Lamichhane

464   et al. 2017). Therefore, risks related to biotic stresses may be a limiting factor to sugar

465   beet crop establishment under two conditions: i) when seeds are not treated with

466   conventional pesticides and when farmers plan to anticipate sowing, especially under

467   climate change. As shown in this study, an anticipation of sowing, compared to the

468   currently practiced sowing (i.e. mid-March) may be beneficial in terms of yield, but it has

469   to take into account potential risks due to biotic stresses. The latter is generally increased

470   when crops are sown into cold and humid soil conditions and without chemical seed

471   treatment (Serrano and Robertson 2018). Therefore, future studies should integrate the

20

472 biotic determinants affecting crop establishment into the SIMPLE crop emergence model

473 since the sustainability of chemical pesticides in general and those used for seed

474 treatment in particular is increasingly questioned, especially in the European Union for

475 human health and environmental reasons (Lamichhane et al. 2016). This has led to the

476 recent ban of neonicotinoids in the EU which were widely used for seed treatment (Gross

477 2013).

478 **4.4. Technical feasibility of sowing**

479 The feasibility of technical field operations depends on water content of the soil top layers

480 and thus also on climate change and sowing dates. We evaluated the possibility to enter

481 into the field with agricultural equipments including a seeder for each simulated sowing

482 date and year, using past historical data on earlier sowing dates. Our results suggest that,

483 field access will represent the main limit for earlier sowings in the future as rainfall during

484 early spring will not decrease, compared with the past.

485 **5. Conclusions**

486 Climate impact studies are dominated by those on crop yields (Wollenberg et al. 2016).

487 Little is known about the impact of changing climate on specific stages of the crop cycle,

488 especially the crop establishment phase. To achieve an acceptable level of yield it is

489 essential to optimize conditions that favor crop establishment. Despite several

490 limitations, simulation studies represent an important means when it comes to predict

491 food security of the 21st century under future climate change. The present study provides

492 important information that was not possible without mobilizing simulation approach

493 using process-based models. Despite some possibilities of crop emergence failure, the

494 quality of crop establishment will be acceptable under future scenarios, which was not

495 easy to predict without simulations. An anticipation of sowing, compared to the currently

496 practiced sowing (i.e. mid-March), will be viable under future climate change, with

497 possibility of compensating increasing drought risks during summer. However, the

498 possibility of filed access will remain a limiting factor due to extremely variable and high

499 cumulative rainfall values in late winter across our study sites.

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Table 1. Values of the input variables of SIMPLE for sugar beet used in this study

Parameter	Value	Unit
Germination		
Base temperature, $T_{b,germ}$	3.5	°C
Germination percentages per thermal time class STT_g		°Cd (%)
20-25	3	
25-30	12	
30-35	12	
35-40	32	
40-45	15	
45-50	15	
50-55	6	
55-60	1	
Residual percentage of non-germinated seeds	4	
Base water potential $\Psi_{b,germ}$	1.94	MPa
Heterotrophic growth		
Base temperature for elongation $T_{b,elon}$	3.5	°C
Parameters of the Weibull elongation function		
(i) for hypocotyl		
a	59.06358	mm
b	0.01696	°C^{-1}d^{-1}
c	2.6095	
(ii) for radicle		
v	0.7	mm °C^{-1}d^{-1}
Mechanical obstacles - clods		
Parameters of the probability function of seedling death under clod		
(i) Buried clods		
α_b	0.031	mm^{-1}

L_{0b}	10.37	mm
ii) Clods laid on the soil surface		
α_{ss}	0.021	mm^{-1}
L_{0ss}	23.16	mm
Mechanical obstacles - soil surface crust		
Probability (p) for a seedling to emerge through a dry crust	60	%
Daily rain threshold causing the appearance of a crust	5	mm
Cumulative rain-threshold causing the appearance of a crust	12	mm
Daily rain threshold causing humidification of the crust during the last 3 days	3.5	mm
Parameters of the bolting function		
c_1	$1.407769 \cdot 10^{-1}$	
c_2	$2.500000 \cdot 10^{-5}$	
c_3	2.197334	
θ_b, threshold for the daily maximum air temperature at 2 m for bolting	12	°C

Table 2. Differences among weather data (means ± standard deviation) of the study site when analyzed by sowing date, 20-year period and their interaction

Sowing date	ASTS (°C)	AST 30 dps (°C)	ATairmax 30 dps (°C)	TR 30 dps (mm)
Mid-February	5[a] ± 3	6[a] ± 2	9[a] ± 2	46[b] ± 30
1st March	7[b] ± 3	8[b] ± 2	11[b] ± 2	45[b] ± 28
Mid-March	7[b] ± 3	9[c] ± 2	12[c] ± 2	49[b] ± 27
1st April	9[c] ± 3	11[d] ± 2	15[d] ± 2	52[b] ± 26
Mid-April	11[d] ± 3	13[e] ± 2	16[e] ± 2	28[a] ± 19
Df	4	4	4	4
Significance level	***	***	***	***
Period				
2000-2018	7[a] ± 3	9[a] ± 3	13[b] ± 4	40[a] ± 27
2020-2040	7[a] ± 4	9[a] ± 3	12[a] ± 3	43[a] ± 21
2041-2060	7[a] ± 3	9[a] ±3	12[a] ± 3	46[a] ± 27
2061-2080	8[b] ± 3	10[b] ± 3	13[b] ± 3	39[a] ± 27
2081-2100	9[b] ± 3	11[b] ± 3	14[b] ± 3	47[a] ± 33
Df	4	4	4	4
Significance level	***	***	***	NS
Sowing date X Period				
Df	12	12	12	12
Significance level	NS	NS	NS	NS

Means followed by the same letter are not significantly different within the year or sowing date categories; ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$
NS: not significant; dps: days post sowing; ASTS: average soil temperature at sowing; AST: average soil temperature; ATairmax: average daily maximum air temperature; TR: total cumulated rainfall

Table 3. Emergence rate and duration (means ± standard deviation) and frequencies with <50% emergence rate and >28 days to reach the maximum emergence when analyzed by sowing date for each 20-year period and their interaction

Sowing date	Period	Emergence (%)	Frequency (%) of emergence rate <50%	NEmax (days)	Frequency (%) of NEmax >28 days
Mid-February	2020-2040	48[a] ± 32	48	45[a] ± 24	95
	2041-2060	62[a] ± 24	25	50[a] ± 12	100
	2061-2080	63[a] ± 20	30	40[a] ± 13	80
	2081-2100	68[a] ± 20	25	37[a] ± 10	70
1st March	2020-2040	66[a] ± 20	24	43[b] ± 13	90
	2041-2060	59[a] ± 28	30	40[ab] ± 16	85
	2061-2080	60[a] ± 20	30	36[ab] ± 11	65
	2081-2100	67[a] ± 19	30	32[a] ± 12	60
Mid-March	2020-2040	73[a] ± 16	24	38[a] ± 11	81
	2041-2060	64[a] ± 21	35	35[a] ± 11	75
	2061-2080	62[a] ± 23	30	29[a] ± 11	70
	2081-2100	68[a] ± 20	35	29[a] ± 10	65
1st April	2020-2040	69[a] ± 15	14	28[a] ± 7	43
	2041-2060	70[a] ± 15	25	27[a] ± 7	40
	2061-2080	66[a] ± 21	25	26[a] ± 10	50
	2081-2100	74[a] ± 15	25	23[a] ± 8	30
Mid-April	2020-2040	74[ab] ± 14	33	23[a] ± 7	33

	2041-2060	$74^b \pm 11$	20	$24^a \pm 7$	30
	2061-2080	$66^a \pm 16$	60	$22^a \pm 7$	20
	2081-2100	$72^b \pm 15$	25	$20^a \pm 7$	15
Sowing date X Period	**Df**	12		12	
	Significance level	NS		NS	

Means followed by the same letter are not significantly different; number of days required to reach maximum emergence (NEmax); NS: not significant

Table 4. Rates of non-emergence causes (means ± standard deviation) of seedlings as analyzed by sowing date for each 20-year period and their interaction

Sowing date	Period	Non-Germination (%)	Clod (%)	Crust (%)	Drought (%)
Mid-February	2020-2040	37[b] ± 39	9[a] ± 5	7[a] ± 10	1[a] ± 3
	2041-2060	17[ab] ± 27	11[a] ± 4	11[a] ± 13	1[a] ± 2
	2061-2080	17[ab] ± 22	11[a] ± 3	9[a] ± 13	1[a] ± 1
	2081-2100	13[a] ± 17	11[a] ± 2	8[a] ± 13	2[a] ± 6
1st March	2020-2040	14[a] ± 18	11[a] ± 2	9[a] ± 12	1[a] ± 2
	2041-2060	21[a] ± 32	10[a] ± 4	10[a] ± 12	1[a] ± 1
	2061-2080	16[a] ± 24	11[a] ± 3	13[a] ± 14	2[a] ± 3
	2081-2100	12[a] ± 19	11[a] ± 2	10[a] ± 13	4[a] ± 12
Mid-March	2020-2040	9[a] ± 16	12[a] ± 2	6[a] ± 10	1[a] ± 4
	2041-2060	11[a] ± 18	12[a] ± 3	13[a] ± 14	1[a] ± 2
	2061-2080	17[a] ± 28	11[a] ± 4	10[a] ± 12	3[a] ± 6
	2081-2100	9[a] ± 14	12[a] ± 2	12[a] ± 14	7[a] ± 15
1st April	2020-2040	5[a] ± 7	12[a] ± 1	13[a] ± 12	2[a] ± 5
	2041-2060	7[a] ± 10	12[a] ± 2	11[a] ± 13	4[a] ± 10
	2061-2080	11[a] ± 22	11[a] ± 3	11[a] ± 12	5[a] ± 12
	2081-2100	6[a] ± 8	12[a] ± 1	9[a] ± 12	9[a] ± 14
Mid-April	2020-2040	4[a] ± 1	12[a] ± 1	10[a] ± 13	7[a] ± 11
	2041-2060	5[a] ± 4	12[a] ± 1	9[a] ± 9	5[a] ± 11

	2061-2080	$8^a \pm 11$	$12^a \pm 2$	$15^a \pm 14$	$14^a \pm 19$
	2081-2100	$6^a \pm 8$	$12^a \pm 1$	$10^a \pm 12$	$6^a \pm 14$
Sowing date X Period	**Df**	12	12	12	12
	Significance level	NS	NS	NS	NS

Means followed by the same letter are not significantly different within the sowing date categories; NS: not significant

Table 5. Germination rate and duration (means ± standard deviation) and frequencies with <75% germination rate and >14 days to reach the maximum germination when analyzed by sowing date for each 20-year period and their interaction

Sowing date	Period	Germination (%)	Frequency (%) of germination rate <75%	NGmax (days)	Frequency (%) of NGmax >14days
Mid-February	2020-2040	$63^a \pm 39$	48	$21^a \pm 10$	21
	2041-2060	$83^{ab} \pm 27$	15	$22^a \pm 5$	20
	2061-2080	$83^{ab} \pm 22$	25	$20^a \pm 6$	15
	2081-2100	$87^b \pm 17$	20	$18^a \pm 7$	13
1st March	2020-2040	$86^a \pm 18$	14	$22^a \pm 7$	17
	2041-2060	$79^a \pm 32$	25	$20^a \pm 8$	16
	2061-2080	$84^a \pm 24$	25	$20^a \pm 8$	13
	2081-2100	$88^a \pm 19$	15	$18^a \pm 8$	14
Mid-March	2020-2040	$91^a \pm 16$	10	$22^a \pm 7$	18
	2041-2060	$89^a \pm 18$	10	$21^a \pm 7$	16
	2061-2080	$83^a \pm 28$	20	$19^a \pm 9$	16
	2081-2100	$91^a \pm 14$	10	$19^a \pm 8$	13
1st April	2020-2040	$95^a \pm 7$	5	$17^a \pm 6$	14
	2041-2060	$93^a \pm 10$	5	$16^a \pm 5$	13
	2061-2080	$89^a \pm 22$	15	$18^a \pm 8$	14
	2081-2100	$94^a \pm 8$	5	$16^a \pm 7$	11

Mid-April	2020-2040	$96^a \pm 1$	0	$15^a \pm 8$	11
	2041-2060	$95^a \pm 4$	0	$17^a \pm 7$	12
	2061-2080	$92^a \pm 11$	10	$15^a \pm 7$	10
	2081-2100	$94^a \pm 8$	5	$14^a \pm 7$	8
Sowing date X Period	**Df**	12		12	
	Significance level	NS		NS	

Means followed by the same letter are not significantly different; number of days required to reach maximum germination (NGmax); NS: not significant

Table 6. Bolting rate (means ± standard deviation), without the devernalization effect, and frequency when analyzed by sowing date for each 20-year period and their interaction and potential devernalization due to high temperatures (7 days with Tmax > 25°C) 60 to 120 days after sowing.

Sowing date	Year categories	Potential bolting rate (%)	Frequency of potential bolting rates (%)			Number of days with Tmax > 25°C, 60-120 days after sowing
			<0.5%	0.5-1%	>1%	
Mid-February	2020-2040	$1.65^{b} \pm 0.59$	0	3	18	$3^{a} \pm 3$
	2041-2060	$1.60^{b} \pm 0.76$	2	2	16	$4^{ab} \pm 6$
	2061-2080	$0.97^{a} \pm 0.41$	4	5	11	$7^{ab} \pm 4$
	2081-2100	$0.79^{a} \pm 0.54$	7	8	5	$8^{b} \pm 7$
1st March	2020-2040	$0.89^{b} \pm 0.38$	3	9	9	$4^{a} \pm 4$
	2041-2060	$0.88^{b} \pm 0.52$	5	7	8	$7^{ab} \pm 7$
	2061-2080	$0.47^{a} \pm 0.26$	12	8	0	$13^{bc} \pm 7$
	2081-2100	$0.40^{a} \pm 0.33$	13	6	1	$15^{c} \pm 9$
Mid-March	2020-2040	$0.40^{b} \pm 0.21$	16	5	0	$6^{a} \pm 6$
	2041-2060	$0.40^{b} \pm 0.28$	13	6	1	$13^{ab} \pm 8$
	2061-2080	$0.17^{a} \pm 0.13$	20	0	0	$20^{bc} \pm 10$
	2081-2100	$0.16^{a} \pm 0.17$	19	1	0	$23^{c} \pm 12$
1st April	2020-2040	$0.11^{bc} \pm 0.08$	21	0	0	$8^{a} \pm 8$

	2041-2060	$0.13^c \pm 0.14$	19	1	0	$17^{ab} \pm 10$
	2061-2080	$0.04^{ab} \pm 0.05$	20	0	0	$26^{bc} \pm 12$
	2081-2100	$0.02^a \pm 0.03$	20	0	0	$32^c \pm 12$
Mid-April	2020-2040	$0.02^{ab} \pm 0.02$	21	0	0	$13^a \pm 11$
	2041-2060	$0.03^b \pm 0.04$	20	0	0	$26^b \pm 12$
	2061-2080	$0.01^{ab} \pm 0.01$	20	0	0	$33^{bc} \pm 12$
	2081-2100	$0.00^a \pm 0.01$	20	0	0	$42^c \pm 11$
Sowing dates X Periods	**Df**	12				12
	Significance level	***				***

Means followed by the same letter are not significantly different within the sowing dates or
periods; ***$P < 0.001$; **$P < 0.01$; *$P < 0.05$; NS: not significant

Table 7. Indicators for field accessibility for farmers to perform sowing for early sowing dates and periods

Period of time	Period	Average cumulated rainfall 30 days before sowing (mm)	Number of days with >1mm
1st February – end of February	2000-2018	38[a] ± 3	8[a] ± 0.45
	2020-2040	47[a] ± 3	11[a] ± 0.47
	2041-2060	51[a] ± 3	11[a] ± 0.48
	2061-2080	51[a] ± 4	10[a] ± 0.47
	2081-2100	52[a] ± 3	11[a] ± 0.47
1st March –end of March	2000-2018	45[a] ± 3	8[a] ± 0.43
	2020-2040	48[a] ± 3	10[a] ± 0.45
	2041-2060	50[a] ± 3	9[a] ± 0.44
	2061-2080	37[a] ± 3	7[a] ± 0.42
	2081-2100	50[a] ± 4	9[a] ± 0.45

Means followed by the same letter are not significantly different within the sowing dates or periods

Supplementary Table 1. Germination and emergence rates and duration of sugar beet (means ± standard deviation) when analyzed by sowing date and 20-year period

| Sowing date	Germination (%)	Emergence (%)	NGmax (days)	NEmax (days)
Mid-February	79[a] ± 29	59[a] ± 25	17[a]±7	26[b]±8
1st March	84[ab] ± 23	61[a] ± 22	20[b]±7	38[d]±14
Mid-March	89[bc] ± 19	64[a] ± 21	15[a]±7	22[a]±7
1st April	93[c] ± 13	64[a] ± 20	20[b]±7	43[e]±16
Mid-April	94[c] ± 7	63[a] ± 20	20[b]±8	33[c]±11
Df	4	4	4	4
Significance level	***	NS	***	***
Period				
2020-2040	86[a] ± 23	63[ab] ± 23	19[b]±8	35[b]±16
2041-2060	88[a] ± 21	63[ab] ± 21	19[b]±7	35[b]±14
2061-2080	86[a] ± 22	58[a] ± 22	18[ab]±8	31[a]±12
2081-2100	91[a] ± 14	64[b] ± 21	17[a]±7	29[a]±11
Df	3	3	3	3
Significance level	NS	*	**	***
Sowing date X Period				
Df	12	12	12	12
Significance level	***	***	NS	NS

Means followed by the same letter are not significantly different within the year or sowing date categories;
***P < 0.001; **P < 0.01; *P < 0.05; NS: not significant; NGmax and NEmax: number of days required to reach the maximum germination and emergence respectively

Supplementary Table 2. Causes of non-emergence rates of sugar beet (means ± standard deviation) when analyzed by sowing date and 20-year period

Sowing date	Non-Germination (%)	Clod (%)	Crust (%)	Drought (%)
Mid-February	$7^a \pm 13$	$10^a \pm 4$	$9^a \pm 12$	$2^a \pm 4$
1st March	$16^{bc} \pm 23$	$11^{ab} \pm 3$	$10^a \pm 12$	$3^a \pm 6$
Mid-March	$6^a \pm 7$	$11^{bc} \pm 3$	$10^a \pm 12$	$4^{ab} \pm 8$
1st April	$21^c \pm 29$	$12^c \pm 2$	$11^a \pm 12$	$6^{bc} \pm 11$
Mid-April	$11^{ab} \pm 19$	$12^c \pm 1$	$11^a \pm 12$	$9^c \pm 14$
Df	4	4	4	4
Significance level	***	***	NS	***
Period				
2020-2040	$14^a \pm 23$	$11^a \pm 3$	$9^a \pm 12$	$3^a \pm 7$
2041-2060	$12^a \pm 21$	$11^a \pm 3$	$10^a \pm 12$	$3^a \pm 7$
2061-2080	$14^a \pm 22$	$11^a \pm 3$	$11^a \pm 13$	$6^b \pm 12$
2081-2100	$9^a \pm 14$	$11^a \pm 2$	$10^a \pm 12$	$6^b \pm 12$
Df	3	3	3	3
Significance level	**	NS	NS	***
Sowing date X Period				
Df	12	12	12	12
Significance level	***	***	NS	*

Means followed by the same letter are not significantly different within the year or sowing date categories;
***$P < 0.001$; **$P < 0.01$; *$P < 0.05$; NS: not significant

Figure 1. Relationship between cumulative rainfall (measured at Estrées-Mons ; 49°52′44″N 3°00′27″E) and percentage of sown surface recorded at the end of March across the sugar beet growing area in France (1987-2005).
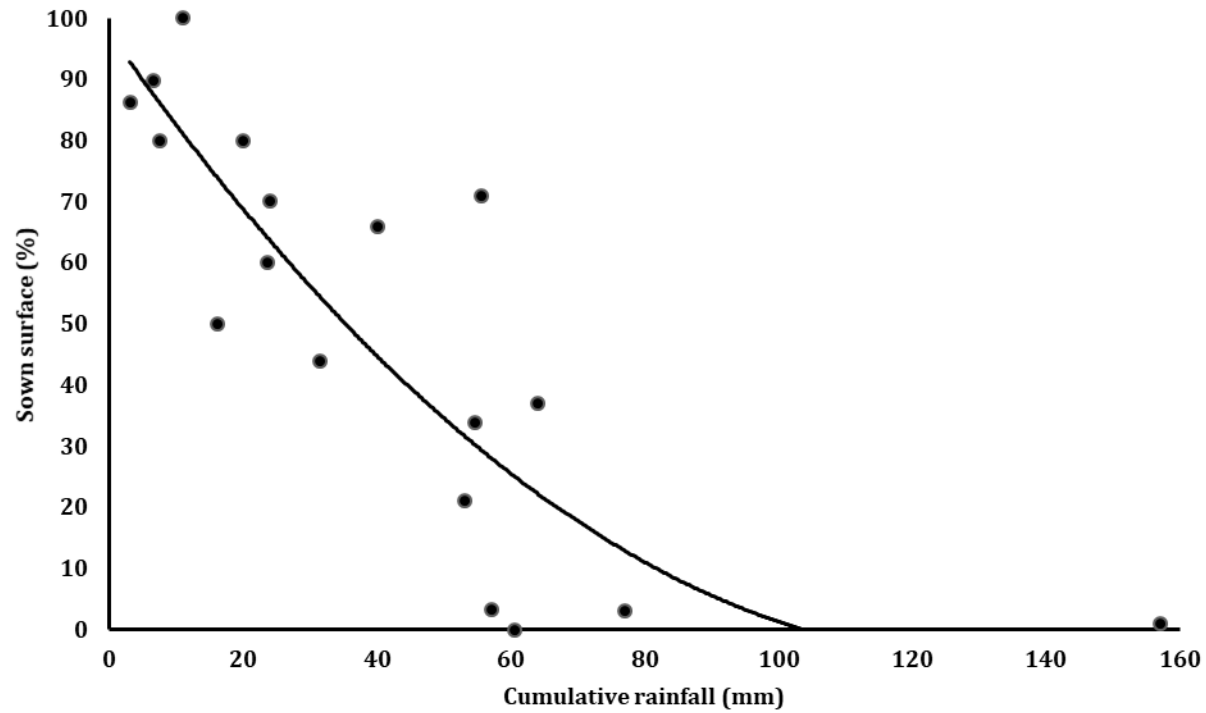
Figure. 2. Year-to-year emergence rate variability of sugar beet by sowing date under future climate scenario
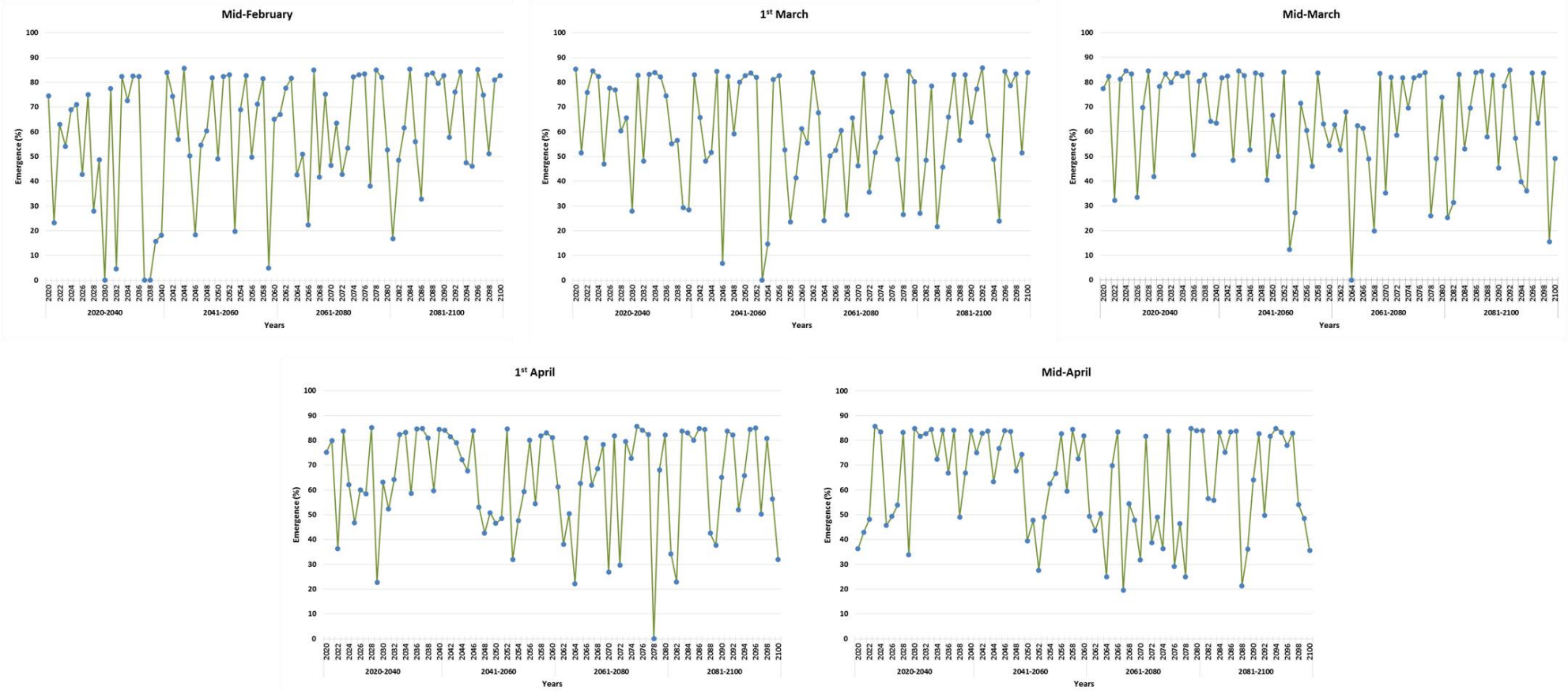
Figure 3. Frequencies (%) of non-emergence causes when analyzed by sowing date for each 20-year period. Only causes with a high frequency that could pose risks of crop emergence failure were considered which included frequency of non-germination >25% and frequency of seedling mortality due to clod, crust and drought, each >15%