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ORIGINAL PAPER

Consequences of climate change on flax fiber in Normandy by 2100: prospective bioclimatic simulation based on data from the ALADIN-Climate and WRF regional models

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Abstract

Normandy is the world's leading producer of flax fiber (*Linum usitatissimu* L.), which is mainly exported to China for textile manufacturing. Flax is a plant that is cultivated in spring and that grows in an oceanic climate with regular watering and limited thermal excesses. This article aims at projecting the impact of climate change on the phenology of this plant when subjected to climatic hazards that may occur during its development. These projections use two regional climate models (ALADIN-Climate and WRF) based on the two scenarios generated by the latest IPPC report—intergovernmental panel on climate change—(RCP 4.5 and RCP 8.5). The rise in temperatures would result in a time-cycle reduction. Consequently, flax would not be exposed to the early summer water shortage. However, thermal conditions could be unfavorable, especially due to the increased frequency of heat days. Flax is also exposed to the risk of lodging during heavy rainfall episodes; however, the results are somehow contrasted between the two climate models used. This research demonstrates the interest of multidisciplinary impact studies so as to anticipate the consequences of climate change on agricultural crops.

1 Introduction

France is the largest producer of flax fiber, accounting for 54% of the world's production over the period from 2000 to 2018, i.e., almost 500,000 tons for a world total of more than 900,000 t (FAOSTAT data). China ranks second (221,700 t), followed by Russia (45,639 t), Belarus (43,134 t), the UK (18,078 t), and the Netherlands (17,156 t). The vast majority of the world's production is concentrated along the coast of the Channel Sea, from Normandy to the Netherlands, where the temperate oceanic climate allows this plant to grow (Sultana 1992). Moreover, in Europe, the common agricultural policy encourages its cultivation (Preisner et al. 2014).

Normandy produces more than 300,000 tons of flax on average each year (AGRESTE data for the period from 2000 to 2018; Fig. 1), which represents almost two thirds of the French production (62%) and one third of the world's production (33%).

The areas dedicated to flax cultivation only represent 3% of the regional agricultural land, with approximately 55,000 ha in 2016 (data from the Parcel Register Graph in 2016), even though their number has increased in recent years.[1] This characteristic can be explained by the fact that flax follows a crop rotation of 7 years.[2] This herbaceous plant is nevertheless attractive owing to its significant added value. This crop is seeded in winter or spring. The most

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[1] The number of areas devoted to flax cultivation has increased by 96% between 2000 and 2018, from 33,030 ha to 64,810 ha according to the Agreste processed data for Normandy.

[2] Flax is planted every 6 to 7 years to avoid soil depletion and prevent diseases. This rotation crop is considered the most significant one and leads to higher yields of the following crops by 20 to 30% (according to the European Flax and Hemp Confederation (CELC, 2012).

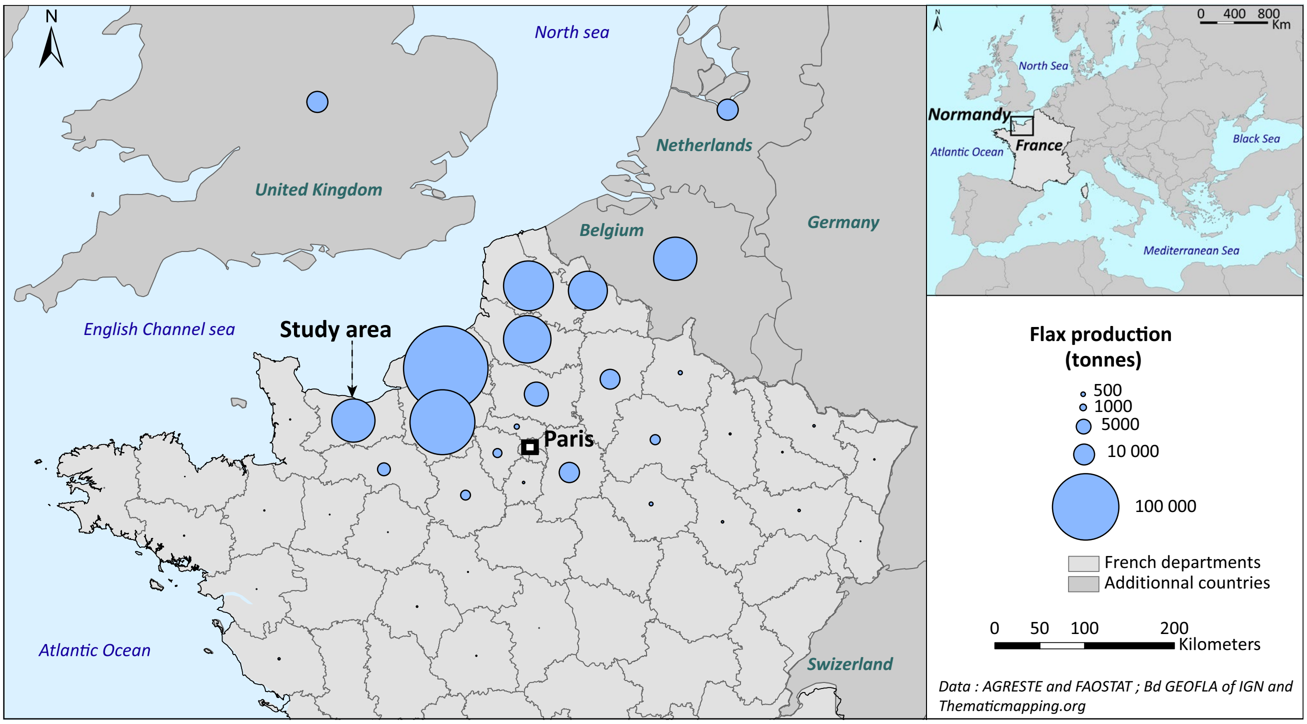


Fig. 1 Map of flax fiber production in France and location of the studied site

widely grown varieties are spring varieties whose cycle lasts about 120 days (Goudenhooft et al. 2019). The winter varieties are more marginal, raise the need to spread the workload and are particularly adapted to drying terroirs. The process to be carried out to obtain exploitable fibers requires special technical know-how. Flax is pulled up in summer, during which the seeds are harvested to be re-sown the following year while the straws are turned over several times to dry down. This is the retting process, which requires alternating episodes of rain, sun, and breeze so that the straw begins to separate from the fiber. The straws are then transferred to the flax cooperatives that are specialized in the scutching technique; this process consists of extracting the fibers from the plant. The shives — a co-product of scutching — made from straw fragments are used in many outlets (horse bedding, fuel, and chipboard). Long fibers intended for spinning mills are mainly exported to China (90%) before being sent back to Italy and Eastern European countries for weaving. A smaller proportion of the production (short fibers) is used as composite materials (CCE[3] 2008).

The great agricultural plains of Normandy are well-suited for the growing of flax fiber due to the low temperatures and the scarcity of extreme phenomena that are specific to the oceanic climate. The proximity of the English Channel makes it possible to limit the effects of frost and heat waves (Pédelaborde 1958; Trzpit 1970; Planchon 1997; Vigneau 1997; Cantat 2005, 2006). This study focuses more particularly on the agricultural plain of Caen[4] an area under the influence of a slightly altered oceanic climate (Joly et al. 2010; DREAL Normandie 2020; Beauvais et al. 2019a, b). Over the current reference period (1981–2010), the total annual rainfall is about 740 mm, including 224 mm for the months of April, May, June, and July during which flax grows. The average annual temperature is 11.2 °C and there are approximately 32 days of frost and 23 days of heat throughout the year (Fig. 2). For the 4 months of cultivation, the average temperature is 13,9 °C, with 1,2 days of frost (only in April) and 12,3 days of heat (mainly in June and more specifically in July). The regular rainfall, combined with deep, silty soils with significant useful reserves (Le Gouée and Delahaye 2008; Le Gouée et al. 2010a,b), guarantees enough water to fulfill the conditions necessary for flax production.

Moreover, the weather conditions are very diverse in Normandy (DREAL 2014; DREAL Normandie 2020; Beauvais et al. 2019a, b). Indeed, the mean annual temperature at the Météo-France station in Caen-Carpiquet

[3] Commission of the European Communities.

[4] The Plaine de Caen, with 34,000 tons produced each year, is one of the agricultural plains of Normandy that is specialized in the cultivation of spring flax fiber and has three scutching plants (Preux et al. 2020).

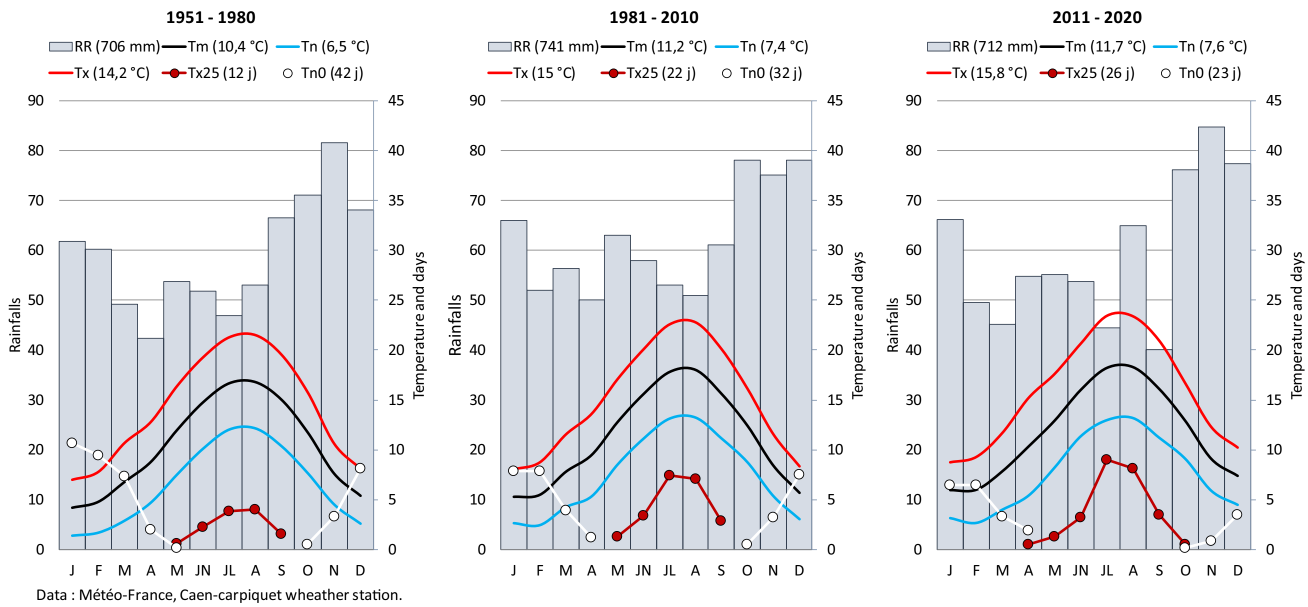


Fig. 2 Ombrothermal diagrams for the climate normals 1951–1980 and 1981–2010 and the period 2011–2019 in Caen (with RR (mm): total annual precipitation; Tm (°C): mean annual temperature; Tn (°C): minimum annual temperature; Tn0 (d): number of frost days per year; Tx25 (d): number of heat days per year)

increased by + 0.8 °C between the 1951–1980 (10.4 °C) and 1981–2010 (11.2 °C) climate normals. Over the same period, the number of frosts decreased by 10 days per year (from 42 to 32 days) while the number of heat days increased by 10 days (from 12 to 22 days). The increase in temperature is currently ongoing since the average over the last 9 years (2011–2020) is 11.7 °C. Warming has become more visible since the end of the 1980s, with an estimated break in 1987 as was evidenced by the Pettit test (Pettitt, 1979). This evolution can also be witnessed in other French regions (Bonnefoy et al. 2010; Briche et al. 2010; Madelin et al. 2010). Due to the very high interannual variability, no significant trend can be statistically demonstrated in the total annual rainfall, although the normal is increasing (Beauvais et al. 2019a, b). The same applies to the months of April, May, and June, during which flax is grown full time.

By 2100, if no effort is made to reduce greenhouse gases emissions on a global scale (IPCC scenario RCP 8.5), the average annual temperature in Caen will increase by around 3 °C compared with the period 1981–2010 according to the ALADIN-Climate and WRF regional climate models. Heat episodes would then increase by 43 days (from 14 to 57 days) (Fig. 3) and late frosts would disappear. At the same time, the ALADIN-Climate model simulates a strong reduction in spring (− 13%) and summer (− 30%) rainfall accumulation.

This study projects the bioclimatic potential of spring flax fiber in an agricultural plain in Normandy using two climate models: ALADIN-Climate and WRF. The aim is to identify future climatic constraints in order to support the agricultural sector while adapting to climate change. The temperatures of the north-western coasts would remain relatively cool in comparison with the rest of the country (Fig. 4). But will it be sufficient to generate climatic conditions that would be favorable to the cultivation of spring flax fiber? Recent work has been conducted on the evolution of the regional biopedoclimatic context (Cantat et al. 2009, 2010; Le Gouée et al. 2010a, b; Lamy et al. 2012; Beauvais, 2016; Beauvais et al. 2019a, b), but up to now, no scientific publication has focused on flax. However, Arvalis-L'Institut du Végétal has conducted research on this crop and presented it during a seminar (Gate and Deudon 2018). The authors state that flax yields in France have so far not stagnated and that the conditions would remain favorable in the short term (2050). The protocol used is the same as the one described in Beauvais et al. (2019a, b); however, it has been adapted to spring flax fiber and was supplemented with a climate model.

2 Data and methods

2.1 Data

The reference data for future climate are those of the SAFRAN reanalysis (Quintana-Segui et al. 2008; Vidal et al. 2010). It is a system of analysis that combines hourly surface observations with those of meteorological models. The

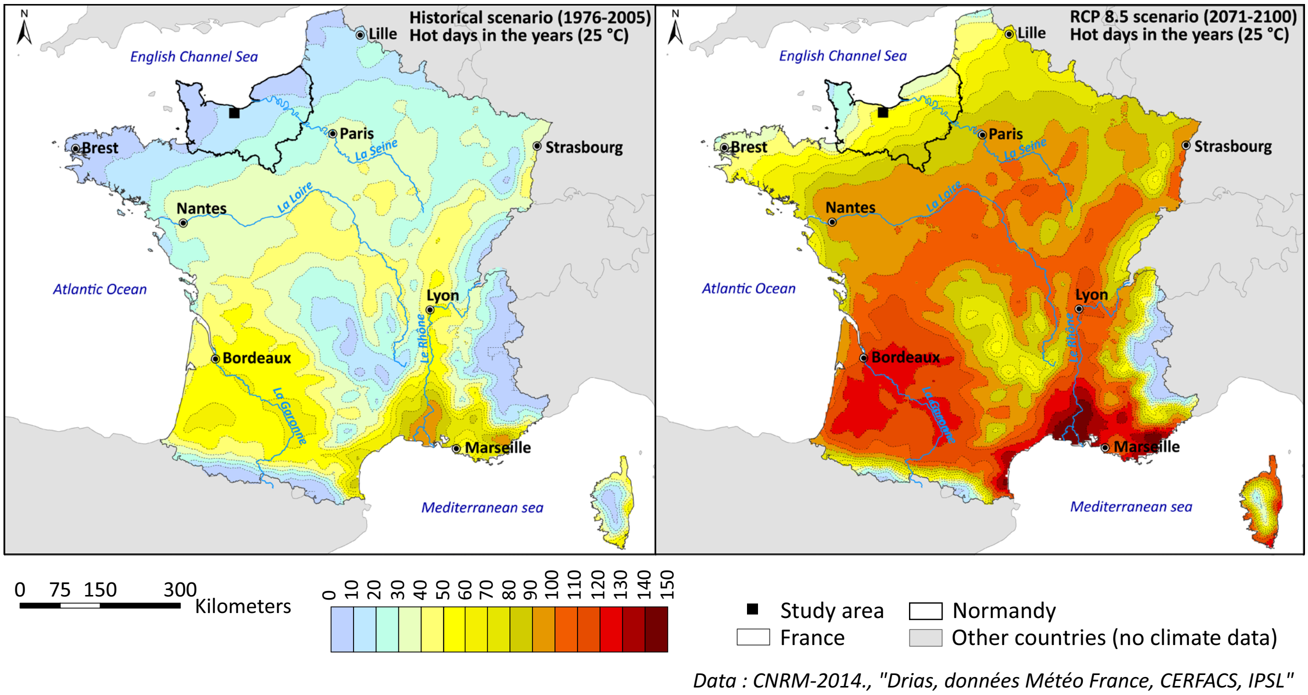
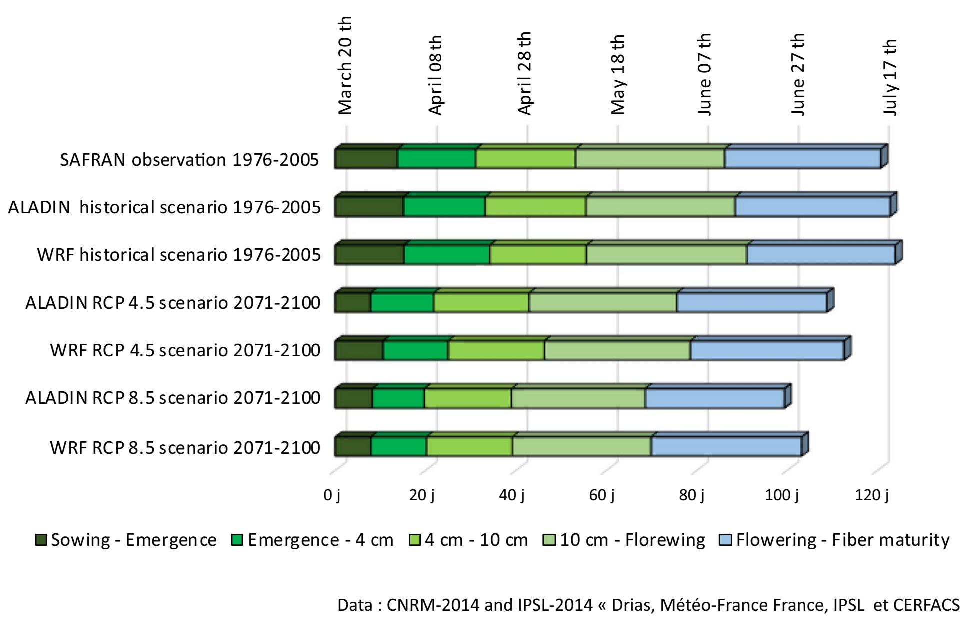


Fig. 3 Increase in the number of heat days in France by 2100 in the case of RCP 8.5 scenarios with the ALADIN-Climate model (without reduction of greenhouse gas emissions)

Fig. 4 Possible evolution of the duration of the phenological periods of spring flax fiber in the Plaine de Caen between now and 2100 with the ALADIN-Climate and WRF models



parameters are analyzed in steps of 300 m in altitude and interpolated on a horizontal grid with a spatial resolution of 8×8 km. Daily data have been collected over the period 1976–2005 so as to compare them with the CNRM-2014 and IPSL-2014 simulations on the same grid point. Only one grid point is used, given the slight difference observed between the model grids in this flat and open study area (Beauvais et al. 2019a, b). These data from the limited area regional models ALADIN-Climate (Spiridonov et al. 2005) and WRF (Skamarock et al., 2008) are available for the entire French territory on the DRIAS web portal www.drias-climat.fr/ (Ouzeau et al. 2014). The conditions at the lateral boundaries of ALADIN-Climate are derived from a first dynamic downscaling between the coupled global model CNRM-CM5 (Voldoire et al. 2013) and the ARPEGE-Climate

Table 1 Limiting factors for spring flax fiber production and associated indicators

Phenoclimatic indicators	Phenological stages	Possible consequences
-Water deficit -Water comfort (value between 0 and 1)	All stages	Difficulty to germinate, reduced growth, hollow fibers, and short fibers (Arvalis, accident sheets)
-Temperatures above 25 °C	All stages	Hollow fibers (Bert 2011), short fibers
-Heavy (RR10) and very heavy rains (RR20)	"4 cm—flowering" and "flowering-maturity"	Verse (Arvalis, accident records), threshold determined through field observation
-Duration of vegetative stages	All stages	Change in biomass accumulation time and shift of phenology in the calendar

When the water comfort level is 1, then the plant does not lack water. At level 0, on the other hand, water stress increases.

We observed flax lodging on two occasions. The lodging of June 20th, 2019 follows two rainy days with an overall rainfall of 11.3 and 14.5 mm. The lodging of June 25th, 2019 follows a daily accumulation of 25 mm which resulted in a more important flax lodging. Consequently, the thresholds of 10 mm and 20 mm are retained. The time step is daily since the hourly data are not available at the output of the climate models. RR is the abbreviation for cumulative rainfall (in mm).

model (Déqué et al. 1994). The simulation of WRF over France comes after a previous one that was carried out over Europe, succeeding that of the global model IPSL-CM5A (Dufresne 2013). The versions of the global model simulations are those of the CMIP5 experiments. The data are then corrected using the quantile–quantile method (Déqué, 2007) in relation to the SAFRAN model data (observation).

The projections used are derived from IPCC RCP 4.5 and 8.5 scenarios (Van Vuuren et al. 2011), with a longer-term horizon (2071–2100) to express the change in the radiation balance at the top of the troposphere (IPCC, 2014). The first one (RCP 4.5) reflects a stagnation in the evolution of this balance in the second half of the twenty-first century (660 ppm CO2 eq.). The second one (RCP 8.5) illustrates the possible evolution of the climate if no global climate policy is enacted (above 1370 ppm CO2 eq.). It seems relevant to note that greenhouse gas emissions have kept on increasing over the recent years (WMO, 2019; Jackson et al., 2019); the probability of the RCP 8.5 scenario is hereby confirmed. It should be noted that a cold bias of the ALADIN and WRF models is observed in the Plaine de Caen, with an under-estimation of the 1987 post-break temperatures observable by comparing the historical scenario with the SAFRAN model (observation) for the same grid point (Beauvais et al. 2019b). The minimum temperature is underestimated by 0.5 °C with both models and the maximum temperature by 0.4 °C for ALADIN and 0.6 °C for WRF. The historical scenario is therefore updated by considering the monthly mean bias of the minimum and maximum temperatures (Dubreuil et al. 2019) over the periods 1976–1987 and 1988–2005. The data from the RCP scenarios are only adjusted according to the post-outage bias.

2.2 Method

Phenology is simulated using the degree-day concept. This method is commonly used in the area of agricultural science to estimate the dates of appearance of phenological stages and their duration (Bonhomme 2000). The temperature sum is calculated on a 5 °C basis, capped at 28 °C. This means that the temperatures falling below 5 °C count as 0 while those rising above 28 °C are considered to be at the maximum height of that threshold (Durand 1969). The change in the phenological period occurs when the thermal duration requested for the appearance of the new phase of the cycle is reached. The sums of temperatures retained are those exposed by the Arvalis L'Institut du végétal (2015) of Normandy within the framework of a technical meeting. They are close to those listed in Goudenhooft et al. (2019) and to all existing flax varieties in the Visio-Lin tool of Arvalis-L'Institut du végétal. Simulations are generated for the sowing date March 20 of each year.[5] Phenoclimatic indicators are associated with these different phases of the plant's development and their occurrence triggers possible impacts on the agricultural production (Gate, 2008). Studying the impact of climate on crops by taking into account phenology and its interannual variability makes it possible to achieve more precise results than when using agroclimatic indicators for invariant dates (Holzkämper et al. 2013; Caubel et al. 2015). This method seems to be particularly appropriate since global warming causes an advance in plant phenology and acts as a bio-indicator (Rezaei et al. 2018). Several recent works have already used this dynamic process for wheat or grain maize: Gate et al., (2008); Gouache et al. (2012); Holzkämper et al. (2011, 2013, 2015); Caubel et al. (2015, 2017); Beauvais et al. (2019a, 2019b, 2020).

Phenoclimatic indicators are selected (Table 1) according to the parameters available at the climate model output. The consequences associated with their evolution or with the overrunning of the thresholds may result in a loss of production that can sometimes be significant during the cycle. These are heat days and water deficit affecting the quality of the fibers as well as heavy

[5] In France, the advised periods for sowing ranges from March 15th to April 15th for a soil temperature of between 7 and 9 °C (Sultana 1983).

rains that can cause flax to shed or the duration of the phenological stages. According to Gate and Deudon (2018), the conditions are optimal when the number of days of heat within the cycle is lower than 5, with little water deficit, for a flowering occurring after 90 to 95 days and a maturity phase reached at 115/120 days.

The lack of water for the plant is estimated via a decreasing logarithmic[6] daily water balance — using the method of Thorntwaite and Mather (1955) — in order to include the plant's progressive difficulty in mobilizing water from the useful reserve as it empties. The climatic demand is that of spring flax fiber (MET, maximum evapotranspiration) determined by the set of crop coefficients (Doorenbos and Pruitt 1975), multiplied by Thornthwaite's[7] potential evapotranspiration, which varies according to phenological periods, as described by Allen et al. (1998). When the available water is below the MET, then there is a water deficit and a degradation of the hydrological resources. The useful water reserve retained is 199 mm over 1 m of soil depth (flax rooting potential, according to Biard 2017) and corresponds to that of an agricultural plot located in the municipality of Anguerny, which is representative of the soil cover of the northern sector of Caen (thick, silty, poorly leached soils with stone-free element load and neutral, or weak alkaline pH; Le Gouée and Delahaye, 2008). This estimate is based on measurements carried out in laboratory,[8] on samples taken as a soil pit was dug in situ on April 2nd, 2019, according to the RMQS2 protocol[9] (Jolivet et al., 2018).

3 Results

In this section the results are presented for different bio-indicators that depend on seasonal changes in energy and water supply by 2100.

3.1 Cycle time reduction

Over the reference period from 1976 to 2005, and based on the meteorological data from the SAFRAN model, flowering takes place on average after 85 days, i.e., on June 12th (Fig. 4). The simulations carried out over the historical period with data from the ALADIN-Climate and WRF models lead to flowering after 88 and 90 days respectively (June 15th and 17th). Given the increase in temperature by 2100, if we consider scenario RCP 4.5, flowering would occur after 76 and 79 days (3rd and 6th June), and after 69 and 70 days (27th and 28th May) for scenario RCP 8.5.

The maturity date of the fibers would also be brought forward. Over the period from 1976 to 2005, the observed maturity date is July 18th, which corresponds to a cycle length of 121 days. According to the historical scenarios of the two models, this date could be July 21st (124 days). At the end of the century, according to the RCP 4.5 scenario, this should happen on July 6th (109 days) with ALADIN and July 10th (113 days) with WRF. If greenhouse gas emissions do not slow down (RCP 8.5), the anticipation is such that the cycle would end before July: June 26th (99 days) for ALADIN and June 30th (103 days) for WRF.

According to the ALADIN-Climate data, the interannual variability would decrease slightly. On the other hand, over the reference period ranging from 1976 to 2005, the number of years having a cycle length of less than 110 days remains low and exceptional. In 2100, these years could be the norm, so much so that this would be the case every other year, according to the ALADIN for the RCP 8.5 scenario (Fig. 5A).

Rising temperatures would therefore lead to a reduction in the length of the vegetative cycles of spring flax fiber. The anticipation of the phenological stages justifies the use of phenoclimatic indicators. Given the early arrival of phenology in the calendar, the exposure to climatic impacts could consequently be modified.

3.2 Cumulative water deficit and water comfort

Despite an increase in climate demand in spring, the cumulative water deficit over the cycle would be lower than that was measured during the reference period. Anticipating fiber maturity would reduce the window of exposure to droughts, especially since the silty soil provides water to the plant until late spring. The water deficit observed with the SAFRAN model data over the reference period is of 29 mm. It is estimated at 27 mm and 25 mm with the historical scenario of the ALADIN-Climate and WRF models. In the long term, this water deficit for the plant would decrease by 7 mm and 10 mm for the ALADIN RCP 4.5 and RCP 8.5 scenarios. With the WRF model, the reduction is of 2 mm for the first scenario and 9 mm for the second one (Fig. 5B).

[6] Although the calculations are made on a daily time step basis, the interpretation of the water balance is made on the scale of the phenological periods.

[7] Potential evapotranspiration calculated on the basis of Thornthwaite's formula, based on temperature and latitude, is considered representative in the wet temperate zone and therefore for northwestern France (Lecarpentier 1975; personal communication by V. Dubreuil). Indeed, the global solar radiation, which is useful for the calculation of the TURC potential evapotranspiration, a more precise method, is not available at the end of the IPSL-2014 simulation.

[8] The calculation of the useful water reserve corresponds to the following formula (Baize 2000) for each soil horizon:

UWR (mm) = (pF 2.0 − pF 4.2) × Da × thickness.

With UWR = useful water reserve (in mm); pF 2.0 = field capacity and pF 4.2 = wilting point; DA = soil bulk density and E = horizon thickness (in cm). Soil matrix potentials are determined by means of a membrane presser by the INRA unit in Orleans.

[9] At the same time, we assessed soil texture using Robinson's pipette method by plotting the results on the Jamagne (1977) diagram. When applying the pedotransfer rules (Bouma 1989), the useful water reserve is 185 mm.

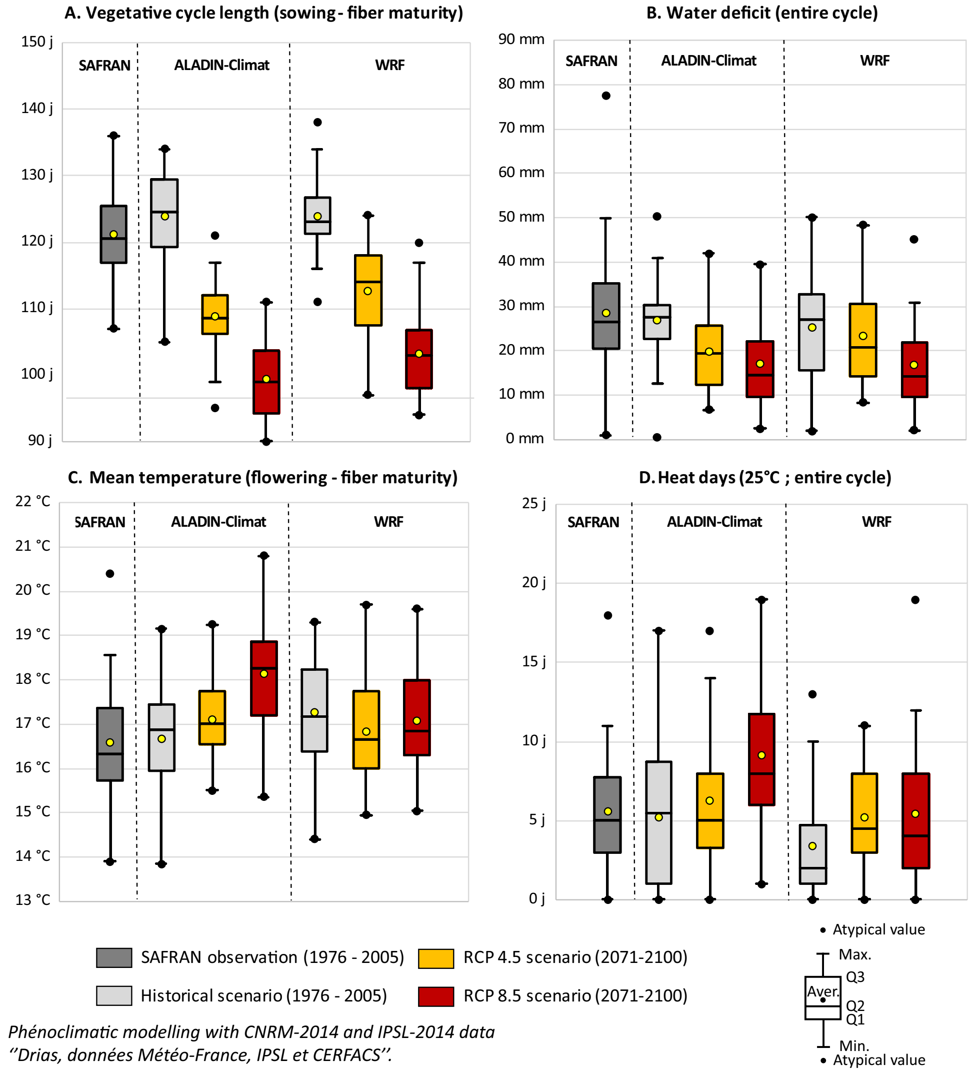


Fig. 5 Comparison of the reference period (1976–2005) with the distant period (2071–2100) of the values associated with the phenoclimatic indicators of spring flax fiber in Caen: the length of the spring flax fiber cycle, its water deficit, the number of heat days, and the average temperature during fiber maturity

There is therefore no significant change in the water deficit, nor a slight decrease in this constraint. Thus, over the reference period, the average water deficit per day is of 0.22 mm with the ALADIN model and of 0.20 mm with the WRF model. According to scenario RCP 8.5, it would be 0.17 and 0.16 mm respectively.[10] Water comfort is of 1 (optimal value) until flowering. At present, it deteriorates slightly at the end of the cycle (0.8 between flowering and fiber maturity). In the case of an anticipation of the stages, no increase is noted after flowering. On the contrary, the conditions would be even more favorable (water comfort of 0.9).

[10] Water comfort corresponds to the ratio of actual evapotranspiration to maximum plant evapotranspiration.

3.3 Temperatures

With warmer seasons, all the phenological stages would be advanced in the calendar, allowing the plant to escape the sharp rise in temperatures in early summer (vegetative cycle completed earlier). As an example, over the period from 1976 to 2005, the average temperature between flowering and fiber maturity is 16.6 °C. In 2100, in the case of scenario RCP 4.5, it would be 17.1 °C (+0.5 °C) and 16.8 °C (+0.2 °C) with the ALADIN and WRF data. For the RCP 8.5 scenario, it remains low with the WRF model (17.1 °C: +0.5 °C) but is higher with the ALADIN model (18.1 °C: +1.5 °C) (Fig. 5C).

However, the moderate increase in temperature should not overshadow the greater occurrence of heat waves that could occur as early as spring (Fig. 5D). The number of heat days experienced by the plant during its cycle would increase. This type of hazard is already present since the current average of the observation (SAFRAN model) is 5.6 days

Table 2 Possible evolution of the number of years affected by at least 1 day with rainfall greater than or equal to 10 mm and 20 mm during the "10 cm—flowering" and "flowering—ripening" periods and the average number of days

	10 cm — flowering		Flowering — ripening	
Period and scenario	RR10	RR20	RR10	RR20
SAFRAN observation 1976–2005	20/30a (1,3 j)	05/30a (0,2 j)	20/30a (1,4 j)	06/30a (0,3 j)
Model ALADIN-Climate (CNRM-2014)				
Historical scenario 1976–2005	22/30a (1,5 j)	07/30a (0,2 j)	19/30a (1,3 j)	05/30a (0,2 j)
Scenario RCP 4.5 2071–2100	21/30a (1,3 j)	06/30a (0,2 j)	23/30a (2 j)	06/30a (0,2 j)
Scenario RCP 8.5 2071–2100	17/30a (1,1 j)	06/30a (0,2 j)	20/30a (1,5 j)	07/30a (0,3 j)
Model WRF (IPSL-2014)				
Historical scenario 1976–2005	19/30a (1,1 j)	01/30a (0,003 j)	23/30a (1,6 j)	05/30a (0,2 j)
Scenario RCP 4.5 2071–2100	17/30a (0,9 j)	04/30a (0,1 j)	27/30a (2,6 j)	12/30a (0,6 j)
Scenario RCP 8.5 2071–2100	19/30a (0,9 j)	07/30a (0,3 j)	24/30a (2 j)	09/30a (0,4 j)

(compared to 5.2 days with the historical ALADIN scenario and 3.4 days with WRF). In the case of a controlled global warming by 2100 (RCP 4.5), the increase in the average number of days could be 1 day with the ALADIN and 2 days with the WRF models. In contrast, in the case of a significant warming (RCP 8.5), it would be 4 days and 2 days respectively. The interannual variability could increase slightly in the last scenario of the ALADIN model, making the overall crop conditions more uncertain from 1 year to the next.

3.4 Heavy and very heavy rains

Heavy rainfall during the phenological periods "10 cm—flowering" and "flowering—maturity" is a hazard which is commonly encountered in the lowland of Caen. It is especially damaging before flowering. Indeed, after this stage, flax has the ability to recover from heat stress if the plants are not intermingled. Twenty years out of 30 are affected by at least 1 day where rainfall is greater than or equal to 10 mm. For very high daily rainfall (20 mm), the occurrence is low (5 and 6 years out of 30). For the coming decades, the results are contrasted between the two models. ALADIN does not simulate any significant evolution. With WRF, the opposite happens, with a clear increase in very heavy rains even though they are underestimated in the reference period between the 10 cm stage and flowering. The same observation is made by looking at the average number of days of heavy and very heavy rains over the two phases (Table 2).

4 Discussion

4.1 Other indicators and other climate scenarios

If certain hazards cannot be studied via the climate model due to a lack of data (strong wind and hail, very high rainfall intensities with short intraday time steps), other indicators shall complement the analysis. Flax is also sensitive to the accumulation of excess water on the soil surface (stagnant water disrupting root development, straw rot during retting[11]). Sprouting can also occur if retting lasts until late summer and weather conditions become cool and wet. On the other hand, in case of a strong sunlight and high heat, the straws can be exposed to scalding. It is important not to neglect time cycle reduction and to check whether or not it has consequences on the constitution, filling, and quality of the fibers. Finally, the climatic conditions that are conducive to the development of diseases should not be neglected. For example, a dry soil combined with high temperatures creates a breeding ground for *verticilliosis* to develop, whereas *septoria* appears under conditions of high humidity (Arvalis, accident sheets).

The present paper presents the envelope of the most likely scenarios with RCP 4.5 and RCP 8.5. However, it is worth noting that climate change could be more moderate in the case of an international reduction of greenhouse gas emissions, to comply with the climate agreements of the COP21 that took place in Paris in 2015 (RCP 2.6). This "optimistic" scenario is not presented in this paper for inter-model comparison purposes as it is not available with the IPSL-2014 simulations. For information purposes, however, it should be noted that the RCP 2.6 simulations from NRCM-2014 show a warming of the Caen Plain that is 2.5 and 1 °C lower than those of the RCP 4.5 and 8.5 scenarios for the 2071–2100 times horizon. The number of warm days per year would increase by only 8 or 10 units, with 33 days less than in the RCP 4.5 and 8.5 scenarios. Cumulative spring and summer precipitation would remain unchanged from the 1976–2005 baseline. Therefore, the consequences for flax fiber could be much less pronounced.

[11] The retting takes place after the flax is pulled out. The stems are spread out on the ground for 5 to 8 weeks. The alternation of rain and sunshine, i.e., wet then dry and hot periods, allows the development of micro-organisms (fungi and molds) that "more or less completely destroy the intermediate lamella that connects the fibrous bundles together, thus allowing the bundles to separate and divide into technical fibers" (Charlet 2008). This step is necessary to then extract the fiber.

4.2 Collaborative approach with farmers

More broadly, this work could be deepened with collaborative approaches. A survey will be carried out to identify, together with a farmer, the climatic conditions that he considers favorable or unfavorable for the cultivation of flax fiber, which should lead to new indicators. The stresses identified in unfavorable years (in terms of quality and quantity) could be used as references. It will also be an opportunity to take stock of the hazards that have increased over the last few decades and to compare these field observations with the meteorological changes measured. Consequently, this work will incorporate the way in which farmers adjust their agricultural practices and production techniques to prevailing climatic changes (sowing dates, varieties, crop rotations, work organization, etc.). In this respect, farmers from the south of the department, where soils are thin and heat days are more frequent, now use winter flax to respond to climate change. Consequently, the climate history of recent years in this area is already an indicator of what could be done today.

4.3 Extension of the analysis to other agricultural plains

Flax is also cultivated in other agricultural plains of northwestern France with an oceanic climate ("Seine-Maritime" and "Somme" departments), but also in areas where the oceanic influence is reduced (Department of "Eure"), which demonstrates a certain phenotypic plasticity of this plant. These areas should be subject to the same analysis. In the perspective of climate change, some other northwestern French agricultural regions ("Manche" and "Finistère" departments) — where flax does not grow currently — could be the basis of more focused research to assess the future feasibility of this crop. In addition, it will be necessary to check if new climatic potentials that would be favorable to flax production could emerge in northwestern Europe. If so, these regions could be serious competitors for the French production. Considering all the constraints and by balancing the factors, it would be possible to carry out a prospective mapping of flax fiber cultivation. This type of mapping has already been carried out in Switzerland for grain maize over the period from 1983 to 2010 and soft wheat over the period from 1984 to 2010 (Holzkämper et al. 2015).

5 Conclusion

The rising temperatures at the end of the century would lead to a reduction in the cycle time of spring flax fiber. As a result, the plant maturity would occur before the end of summer, thus protecting the crop against water shortage. After a dry and warm spring, flax would not accumulate a greater water deficit during its cycle than it does today. However, the cycle would proceed in a generally warmer context and could therefore encounter heat waves, even though the alternation of coolness and heat is conducive to the retting stage. Normandy would then lose one of the characteristics that make the region favorable to the culture of flax. However, caution may be appropriate at this stage of development, since there still remains significant uncertainties with regard to rainfall, for example, heavy rainfall could decrease while very heavy rainfall would increase slightly (increased risk of lodging).

Based on the more realistic scenario of RCP 8.5, the time of seeding must be advanced by about 3 weeks to maintain the temperatures equivalent to the reference period throughout the whole cycle. Nevertheless, in this case, it will be necessary to check that the climatic and agronomic conditions at the beginning of the cycle are favorable (days available for sowing, modification of the agricultural calendar, soil waterlogging at the end of winter, risk of late frosts, etc.). Other levers exist, i.e., the search for new flax ideo-types that would be adapted to the identified climatic stresses, which could be achieved through varietal selection. If spring flax is not adapted to this new climatic situation, winter flax could guarantee the current outlets and its cultivation — although still confidential — is spreading more and more to reach the geographical areas that are most exposed to water stress in spring. It is being tested in areas where the effects of climate change have already been felt, particularly in inland areas. The cultivation of winter varieties should be subject to the same analysis such as that carried out in this investigation. It seems that these investigations are necessary at a time when the agro-industrial sector is relocating secondary processing plants (weaving) close to the production basin.

This study, at the interface between climatology, agronomy, and geography, which can be transposed to other crops or other regions, demonstrates the relevance of bioclimatic simulations based on regional model projections to help the agro-industrial sector anticipate the consequences of climate change.

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Author contribution FB performed the study and led the writing. OC and PM led the research. PLG supervised and participated in the sampling protocol for the field soil data. SB-M controlled the phenology simulation. HG and M-PB conducted the laboratory analyses. AS took part in the soil sampling and negotiated with the farmer for the instrumentation. TP took part in the rural geography reflections and the SAFRAN observation data were transmitted by MM. All authors participated in the writing and proofreading and agree with the content of the article.

Data availability No new data were created or analyzed in this study. The model simulation outputs that support the findings of this study are available from the corresponding author upon reasonable request. The original data are available free of charge on the website http://www.drias-climat.fr/.

Code availability This study does not use a specific calculation code.

Declarations

Ethics approval The authors certify that this study meets the requirements of scientific ethics.

Consent to participate All authors consent to participate.

Consent to publish All authors consent to publish.

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References

Allen R. G, Pereira L. S, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56, FAO Rome, 300 p. http://www.fao.org/3/X0490E/X0490E00.htm

Arvalis L'Institut du végétal (2015) Le Lin : critères de choix des variétés et stratégies de protection. Journées agriculteurs Basse-Normandie 8 décembre 2015, 37 diapositives. https://www.evenements-arvalis.fr/reunion-agriculteurs-le-8-decembre-2015-saint-pierre-sur-dives-14--@/_plugins/WMS_BO_Gallery/page/getElementStream.html?id=36524&prop=file

Baize D (2000) Guide des analyses en pédologie : choix, expression, présentation, interprétation. INRA, Paris, p 254

Beauvais F, Cantat O, Madeline P (2019a). Changement climatique et céréaliculture en Normandie : quelles perspectives pour 2100 ? Actes du 32ème colloque de l'Association Internationale de Climatologie, Thessalonique, pp 71–76. http://www.climato.be/aic/colloques/actes/Thessaloniki2019_actes.pdf

Beauvais F, Cantat O, Madeline P, Le Gouee P, Brunel-Muguet S, Medjkane M (2019b) Quelles conséquences du Changement climatique sur le blé tendre en Normandie aux horizons 2050 et 2100 ? Etude d'impact prospective à partir du modèle ALADIN-Climat. Climatologie 16:129–158

Beauvais F, Cantat O, Le Gouee P, Brunel-Muguet S, Madeline P, Gaillard H, Bataille M-P, Sallent A, Preux T, Medjkane M (2020) Conséquences du changement climatique sur le lin fibre en Normandie à l'horizon 2100: simulation bioclimatique prospective à partir des données CNRM-2014 et IPSL-2014. *Actes du 33ème colloque de l'Association Internationale de Climatologie*, Rennes, pp 97–102. http://www.climato.be/aic/colloques/actes/Rennes2020_actes.pdf

Beauvais F (2016). Changement climatique et agriculture : quelles vulnérabilités et représentations d'un élément de forçage des agrosystèmes ? L'exemple de la Plaine de Caen dans ses dimensions écologiques et anthropiques. Mémoire de Master 1, Université de Caen Normandie, 253 p.

Bert F (2011) Changement climatique : quelles conséquences pour le lin ? Colloque Changement climatique : quelles conséquences et stratégies d'adaptation pour les grandes cultures. https://www.youtube.com/watch?v=tAPJ0sCCCT8.

Biard C.H (2017) Le lin, l'azote et les intercultures. Réunion technique SIAEPA de la Région de Criquetot l'Esneval et le SMBV Pointe de Caux Etretat. Arvalis. 116 diapositives. http://www.smbv-pointedecaux.fr/upload/editeur/presentation_lin-azote_210217_COMPIL.pdf

Bonhomme R (2000) Bases and limits to using "degree.day" units. Eur J Agron 13:1–10. https://doi.org/10.1016/S1161-0301(00)00058-7

Bonnefoy C, Quenol H, Planchon O, Barbeau G (2010) Températures et indices bioclimatiques dans le vignoble du Val de Loire dans un contexte de changement climatique. *EchoGéo*, 14 p. https://doi.org/10.4000/echogeo.12146

Bouma J (1989). Land qualities in space and time. In Bouma J, Bregt A.K (ed.) On land qualities in space and time, International Society Soil Science Sym. Wageningen, the Netherlands, 22–26 Aug. 1989, Pudoc, Wageningen, pp 3–13.

Briche E, Madelin M, Beltrando G, Kergomard C (2010), Analyse comparative des températures extrêmes de 1950 à 2100 issues des modèles ARPEGE-Climat et LMD: intérêt pour l'activité viticole champenoise, Climatologie, Vol.123, N°2, 214–254

Cantat O, Le Gouée P, Bensaid A (2009) Le rôle de la topographie et des sols dans la modélisation spatiale d'échelles fines et des bilans hydriques en Normandie. Actes des journées de climatologie du CNFG de la commission Climat et Société, pp 81–100. https://www6.rennes.inra.fr/climaster/content/download/3243/32894/version/1/file/CANTAT-et-al_CNFG-2009_ARTICLE.pdf

Cantat O, Le Gouée P, Bensaid A, Savouret E (2010) Une méthode originale de spatialisation d'échelle fine des bilans hydriques. Actes du 23ème colloque de l'Association Internationale de Climatologie, Rennes, pp 101–106. http://www.climato.be/aic/colloques/actes/rennes2010_actes.pdf

Cantat O (2005) Dynamique spatio-temporelle d'un événement météo-climatique extrême : La canicule de l'été 2003 en Europe de l'Ouest. Climatologie 2 : 99–136. ⟨hal-00545083⟩. https://doi.org/10.4267/climatologie.908

Cantat O (2006). Les "caprices" du climat en Normandie. La variabilité des températures et ses conséquences dans une région " tempérée " non dénuée d'excès. "Les apports du géographe-climatologue". France. 83–104. ⟨hal-00532845⟩.

Caubel J, Garcia De Cortazar-Atauri I, Launay M, De Noblet-Ducoudré N, Huard F, Bertuzzi P, Graux AI (2015) Broadening the scope for ecoclimatic indicators to assess crop climate suistability according to ecophysiological, technical and quality criteria. Agric Forest Meteorology 207:94–106

Caubel J, Launay M, Ripoche D, Gouache D, Buis S, Huard F, Laurent H, Brun F, Bancal MO (2017) Climate change effects on leaf rust of wheat: Implementing a coupled crop disease model in a French regional application. Europ J Agronomy 90:53–66

CCE (2008) Rapport de la commission au parlement européen et au conseil sur le secteur du lin et chanvre, Bruxelles le 25 mai 2008, 11 p. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0307:FIN:FR:PDF

CELC (2012) European flax: the creative and innovative green fiber on the future, 20 p https://www.mastersoflinen.com/img/outilsPdfs/argu_dp_ITEN_A3_PRINT_email-1.pdf

Charlet K (2008) Contribution à l'étude de composites unidirectionnels renforcés par des fibers de lin: relation entre la microstructure de la fiber et ses propriétés mécaniques. Université de Caen, Thèse de doctorat, p 182

Déqué M (2007) Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. Global Planet

Change 57:16–26. https://doi.org/10.1016/j.gloplacha.2006.11.030
Déqué M, Dreveton C, Braun A, Cariolle D (1994) The ARPEGE-IFS atmosphere model: a contribution to the French community climate modelling. *Climate Dynamics* 10 :249–266. https://link.springer.com/article/10.1007%2FBF00208992
Doorenbos J, Pruitt W. O (1975) Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24, FAO, Rome, 154 p. http://www.fao.org/3/a-f2430e.pdf
DREAL (2014) Profil Environnemental de Basse Normandie. Partie climat, 80 p. http://webissimo.developpementdurable.gouv.fr/IMG/pdf/PartieClimat_v45_Web_200dpi_cle2c31a9.pdf-
DREAL Normandie (2020) Le climat en Normandie. Profil environnemental, Caen, 94 p
Dubreuil V, Même K, Bonnardot V, Aubert J.-F, Verger A. C, Melec D (2019) Changement climatique et date de floraison des pommiers dans le Val de Rance (Bretagne). *Actes du 32ème colloque de l'Association Internationale de Climatologie*, Thessalonique, pp 83–88. http://www.climato.be/aic/colloques/actes/Thessaloniki2019_actes.pdf
Dufresne JL (2013) Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. Clim Dyn 40:2123–2165. https://doi.org/10.1007/s00382-012-1636-1
Durand R (1969) Signification et portée des sommes de températures. Bulletin Technique D'information - Ministère De L'agriculture 238:185–190
Gate P, Blondot A, Gouache D, Deudon O, Vignier L (2008) Impacts du changement climatique sur la croissance et le développement du blé en France. Quelles solutions et quelles actions à développer ? Oilseeds fats Crops Lipids J 15(5):332–336. https://doi.org/10.1684/ocl.2008.0221
Gate P, Deudon O (2018) Flax crop production and climate change: from diagnosis to solutions for the future, Paris, conference, october 18, 2018
Gouache D, Le Bris X, Bogard M, Deudon O, Pagé C, Gate P (2012) Evaluating agronomic adaptation options to increasing heat stress under climate change during wheat grain filling in France. Europ J Agronomy 39:62–70. https://doi.org/10.1016/j.eja.2012.01.009
Goudenhooft C, Bourmaud A, Baley C (2019) Flax (Linum usitatissimum L.) Fibers for composite reinforcement: exploring the link between plant growth, cell walls development, and fiber properties. Front Plant Sci 10:1–23. https://doi.org/10.3389/fpls.2019.00411
Holzkämper A, Calanca P, Fuhrer J (2011) Analyzing climate effects on agriculture in time and space. Procedia Environ Sci 3:58–62. https://doi.org/10.1016/j.proenv.2011.02.011
Holzkämper A, Calanca P, Fuhrer J (2013) Identifying climatic limitations to grain maize yield potentials using a suitability evaluation approach. Agric for Meteorol 168:149–159. https://doi.org/10.1016/j.agrformet.2012.09.004
Holzkämper A, Fossati D, Hiltbrunner J, Fuhrer J (2015) Spatial and temporal trends in agro-climatic limitations to production potentials for grain maize and winter wheat in Switzerland. Reg Environ Change 15:109–122. https://doi.org/10.1007/s10113-014-0627-7
IPCC (2014) *Synthesis Report*. Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri R. K, Meyer L. A. (eds.)], Genève, IPCC, 151 p. https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf
JaJamagneckson RB, Le Quéré C, Andrew RM, Canadell J.-G, Korsbakken J.-I , Liu Z, Peters G.-P, Zheng B, Friedlingstein P (2019) Global energy growth is outpacing decarbonization. A special report for the United Nations Climate Action Summit September 2019. Global Carbon Project, International Project Office, Canberra Australia, 12 p.
Jamagne M, Betremieux R, Begon J-C, Mori A (1977) Quelques données sur la variabilité dans le milieu naturel de la réserve en eau des sols. Bulletin Technique D'information 324–325:627–664
Jolivet C, Aalmeida Falcon J.-L, Berche P, Boulonne L, Fontaine M, Gouny L, Lehmann S, Maitre B, Ratié C, Schellenberger E, Soler-Dominguez N (2018) *Manuel du Réseau de Mesures de la Qualité des Sols (RMQS). RMQS2 : deuxième campagne métropolitaine 2016–2027,* INRA, 150 p.
Joly D, Brossard T, Cardot H, Cavailhes J, Hilal M, Wavresky P (2010) Les types de climatsen France, une construction spatiale. *Cybergéo*, article 501 https://doi.org/10.4000/cybergeo.23155
Lamy C, Cantat O, Le Gouée P, Dubreuil V, Bensaid A, Lemercier B, Savouret E (2012) Sécheresse et réserve en eau des sols. In: Mérot P, Dubreuil V, Delahaye D, Desnos P (eds) Changement climatique dans l'Ouest : évaluation, impacts, perceptions. Presses Universitaires de Rennes, Rennes, pp 195–215
Lecarpentier C (1975) L'évapotranspiration potentielle et ses implications géographiques. Annales De Géographie 463:257–274. https://doi.org/10.3406/geo.1975.19812
Le Gouée P, Marie M, Cantat O, Bensaid A (2010b) *Quand le géographe fait du sol une interface essentielle entre agriculture durable, société et environnement. Exemple de deux études de cas traitées en Basse-Normandie (France)*. ISDA, 28–30 juin 2010, 10 p. https://hal.archives-ouvertes.fr/hal-00521286/document
Le Gouée P, Cantat O, Bensaid A, Savouret E (2010a) La sensibilité des systèmes de production agricole en Normandie face au changement climatique. *Actes du 23ème colloque de l'Association Internationale de Climatologie*, Rennes, pp 333–336. http://www.climato.be/aic/colloques/actes/rennes2010_actes.pdf
Le Gouée P, Delahaye D (2008). Modélisation et cartographie de l'aléa érosion des sols et des espaces de ruissellement dans le Calvados. Université de Caen, p 240
Madelin M, Bois B, Chabin J-P (2010) Modification des conditions de maturation du raisin en Bourgogne viticole liée au réchauffement climatique. EchoGéo 14:13. https://doi.org/10.4000/echogeo.12176
Ouzeau G, Déqué M, Jouini M, Planton S, Vautard R, [Dir : Jouzel J.] (2014) Le climat de la France au XXIe siècle - Volume 4 - Scénarios régionalisés : édition 2014 pour la métropole et les régions d'outre-mer. Ministère de l'écologie, du développement durable et de l'énergie, 64 p. https://www.ecologique-solidaire.gouv.fr/sites/default/files/ONERC_Climat_France_XXI_Volume_4_VF.pdf
Pédelaborde P, 1958. Le climat du Bassin parisien : essai d'une méthode rationnelle de climatologie physique. Paris, Génin, 539 + 232.
Pettitt AN (1979) A non-parametric approach to the change-point problem. Appl Stat 28:126–135. https://doi.org/10.2307/2346729
Planchon O (1997) Les climats maritimes dans le Monde. Thèse de Doctorat, Presses Universitaires du Septentrion, Villeneuve d'Ascq, p 233
Preux T, Beauvais F, Pauchard L (2020) Le système agro-alimentaire des grandes cultures en Plaine de Caen : une déconnexion entre production, transformation et consommation ? *Atlas Social de Caen*. https://atlas-social-de-caen.fr/index.php?id=390.
Preisner M, Kulma A, Wojtasik W, Zuk M, (2014) Flax Fiber in Danny E. Akin, ECT, 5th ed., vol. 11, Russell Research Center, ARS-USDA, pp. 588–623
Quintana-Segui P, Le Moigne P, Durand Y, Martin E, Habets E, Baillon M, Canellas C, Franchisteguy L, Morel S (2008) Analysis of near-nurface atmospheric variables: validation of the SAFRAN analysis over France. J Appl Meteor Climatol 47:92–107. https://doi.org/10.1175/2007JAMC1636.1
Rezaei EE, Siebert S, Huging H, Ewert F (2018) Climate change effect on wheat phenology depends on cultivar change. Scientific Reports 4891:8. https://doi.org/10.1038/s41598-018-23101-2
Skamarock W. C, Klemp J. B, Dudhia J, Gill D. O, Barker D, Duda M. G, … Powers, J. G (2008) A description of the advanced research WRF version 3 (No. NCAR/TN-475+STR). *University Corporation for Atmospheric Research*. https://doi.org/10.5065/D68S4MVH

Spiridonov V, Somot S, Déqué M (2005) ALADIN-Climate: from the origins to present date. *ALADIN Newsletter*, 4 p. http://www.umr-cnrm.fr/aladin-old/newsletters/news29/N29WEB/SPIRIDONOV.pdf
Sultana C (1992) Growing and harvesting of flax in the biology and processing of flax, eds H. Sharma and C. van sumere (Belfast: M Publications), 83–109
Sultana C (1983). The cultivation of fiber flax. Outlook Agric 12:104–110. https://doi.org/10.1177/003072708301200301
Thorntwaite C, Mather J (1955) The water balance. Centerton, Climatology, 104 p.
Trzpit J.-P (1970) Atlas de Normandie. Article de présentation du climat normand, Caen, Association pour l'Atlas de Normandie, 3 planches (texte et cartes sur le climat).
Van Vuuren D, Edmonds J, Kainuma M, Riahi K, ThomsonHibbard-HurttKramKreyLamarqueMasuiMeinshausenNakicenovicSmith-Rose AKGCTVJ-FTMNSJSK (2011) The representative concentration pathways: an overview. Clim Change 109:5–31
Vidal J-P, Martin E, Franchisteguy L, Baillon M, Soubeyroux J-M (2010) A 50-year high-resolution atmospheric reanalysis over France with the Safran system. Int J Climatol 30:1627–1644. https://doi.org/10.1002/joc.2003
Vigneau J.-P, (1997) Le climat océanisé de la façade atlantique médiane de l'Europe. In Le climat, l'Eau et les Hommes, ouvrage en l'honneur de Jean Mounier, Presses Universitaires de Rennes, 227–244.
Voldoire A, Sanchez-Gomez E, Melia D. S. Y, Decharme B, Cassou C, Senesi S, Valcke S, Beau I, Alias A, Chevallier M, Deque M, Deshayes J, Douville H, Fernandez E, Madec G, Maisonnave E, Moine M. P, Planton S, Saint-Martin D, Szopa S, Tyteca S, Alkama R, Belamari S, Braun A, Coquart L, Chauvin F (2013) The CNRM-CM5.1 global climate model: description and basic evaluation. In presentation and analysis of the IPSL and CNRM climate models used in CMIP5. Climate Dynamics, 40 (9–10) : 2091–2121 https://doi.org/10.1007/s00382-011-1259-y
WMO (2019) Greenhouse gas bulletin, 25 novembre 2015, n°15, 8 p.

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