Yield potential and factor influencing yield gap in industrial hemp cultivation under nemoral climate conditions

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Graphical abstract

Abstract

Hemp (*Cannabis sativa* L.) is a productive multi-purpose crop that can be cultivated in different climatic conditions including northern latitudes. However, no comprehensive study on the hemp yield potential has been conducted, particularly in high latitude regions. This study investigates hemp development and the suitability of the AgroC model to simulate hemp growth in cool climate. Field experiments were conducted at the Lithuanian Research Centre for Agriculture and Forestry on Endogleyic Endostagnic Endocalcaric Luvisol. The AgroC model was calibrated using data sets from 2019, whereby validation was performed with 2020−2021 data sets. The model provided adequate results when simulating hemp and its individual parts biomass, leaf area index, soil water content, and development stages. The validated model was further used to provide hemp yields and water as well as temperature limited yield gaps for the historical 1990−2021 period. Simulated average hemp biomass potential reached up to 20.1 t ha^{-1}. Average biomass yield losses due to water stress are 8.7 t ha^{-1} (gap 43.3 %), while reduction due to low temperatures may reach 6.4 %, but mean reduction was only 0.4 t ha^{-1} (gap 2.0 %). Simulated results showed water stress as the main factor defining hemp yield losses, while low temperatures are of secondary importance.

Keywords: AgroC, Hemp, Potential yield, Temperature stress, Water stress

1. Introduction

Hemp (*Cannabis sativa L.*) is a highly productive multi-purpose crop, which is beneficial to the environment and can be cultivated in a wide range of agricultural (soil and climatic) conditions (Boulac et al., 2013; Struik et al., 2000). Even if *Cannabis sativa L.* is one of the oldest and in history also an economically important crop, a controversial discussion has been raised about hemp growing over the past 100 years due to its possible use as a drug. Despite continuous controversies, the interest in hemp cultivation steadily increases mainly since all parts of the plant can be commercially used (seeds, stems, and leaves) and because hemp growing also has low environmental impacts. Additionally, the demand for natural biomass, fibers, and oilseeds globally increases therefore, it could replace or reduce the use of petrochemical-based products, thus minimazing negative environmental impacts (e.g., CO_2 footprint).

The European Green Deal strategy is aiming to transform the EU into a fair and prosperous society, with a modern, resource-efficient, and competitive economy with net zero emissions of greenhouse gases by 2050, whereby the economic growth will be decoupled from the use of non-renewable resources (European Commission, 2019). Additionally, the European Green Deal aims to preserve and restore natural resources and biodiversity and to ensure sustainability of economic agricultural systems, resulting in a transfer to sustainable agriculture. These overall goals can be only achieved by implementing sustainable agricultural practices, such as precision agriculture, organic farming, and agroecology. Within the context of a sustainable agricultural management, hemp cultivation can play a major role for the EU has ambitious Green Deal targets.

Hemp growing shows essential environmental benefits, e.g. it has the potential to remediate contaminated soils (Citterio et al., 2003; Angelova et al., 2004). Due to the fast growth of hemp and the large biomass produced, it is also ideal for conversion of high amounts of atmospheric CO_2 to biomass through bio-sequestration. On the other hand, hemp biomass is also a suitable feedstock in the bioenergy sector (Adesina et al., 2020). Secondly, the environmental advantages of hemp cultivation are the low nutrient requirements, leading to low fertilization needs, and it shows high resistance to pathogens (Kok et al., 1993) and weed suppression (Lotz et al.,1991). Therefore, hemp can be an ideal crop in organic agriculture (Stickland, 1995). It is expected that in near future the demand for raw material of industrial hemp will increase (Parvez et al., 2021), which probably will lead to further expansion of hemp cultivation.

In general, hemp can be grown under a wide range of climatic conditions. However, hemp cultivars best grow within the temperate zone approximately from 40 to 60°N (Ehrensing, 1998) and is currently cultivated in at least 47 countries (Schluttenhofer and Yean, 2017), whereby the expected demand of bio-based materials originated from hemp and global warming will likely increase the number of producing countries and areas in future. Main abiotic factors influencing hemp yield potential are air and soil temperature, solar radiation, as well as nutrient and water availability (Amaducci et al., 2015). Currently, hemp is cultivated in areas where the average temperature ranges from 5.6 to 27.5 ^{0}C (Dhondt and Muthu, 2021). However, best growing conditions are at mean daily temperature between 13 to 22 ^{0}C, (Ehrensing et al., 1998). Other authors have stated that the optimal growing temperature is 26.4 ^{0}C (Amaducci et al., 2012). In comparison to these studies, it was shown by Cosentino et al. (2012) that optimal growing temperatures mostly depends on genotype characteristics and may vary between 21.0 to 26.4 ^{0}C. For optimum yield, hemp requires a significant amount of plant available water during its growing season, whereby highest water demand occurs during the vegetative stage, i.e. during the first 6 weeks when plants are extremely sensitive to water stress (Adesina et al., 2020). It was calculated that hemp requires between 500 − 700 mm of water over the entire growing period, whereby approximately half (250−300 mm) of the water should be available during the vegetative growth stage (Bócsa and Karus, 1998). Lisson and Mendham (1998) carried out irrigation trials, based on deficit cumulative rainfall and evaporation measurements. Hereby, treatment plots were irrigated up to the limit of field capacity. The authors concluded, that for clay loam soils, which are susceptible to drought, roots penetrate deep into the profile due to a favourable soil structure. They detected an amount of 535 mm water for hemp growth to be sufficient.

In Baltic States, hemp is usually planted from the end of April until the end of May, whereby rainfall variation is particularly high during this time period, and therefore, water stress, especially during vegetative growth stage, may results in rather significant decrease of potential yield. On the other hand, different climate models of the special report on Emissions scenarios (SRES) demonstrated that by the 2050s and 2080s the potential allocation of hemp growth in Europe is expected to shift northwards with essential increase in northern Europe at latitudes 55−64° N, while hemp cultivation in Southern Europe at latitudes 35−44° N will significantly decrease or even disappear due to climate change (Tuck et al., 2006).

Modelling as an essential tool in agriculture systems science has been developed for more than six decades and many scientists from a wide range of disciplines have contributed to the development of this concept (Jones et al., 2016). Currently, the scientific community offers various types of crop models and the users can choose the most appropriate one in terms of detail, scales, purposes, and representativeness (Di Paola et al., 2015). Although, crop models are available for different plants (cereals, legumes, root and oil crops, vegetables, fiber, forages, sugar, energy), there are not many modelling applications on hemp crop. Models of hemp crops were first implemented in the Agricultural Production System sIMulator (APSIM) approximately 20 years ago (Lisson et al., 2000a, 2000b, 2000c). Later, other hemp modelling applications focused on predicting phenological development that involves the mixed effect of photoperiod and temperature on established flowering time and plant growth (Amaducci et al. 2008a; Cosentino et al., 2012). It was also aimed to parameterize canopy photosynthesis models based on experimental hemp photosynthetic water and nitrogen use efficiency data (Tang et al., 2018). A more recent study combined the approach of experimental trials and modelling and aimed to develop a simple simulation approach to predict hemp growth stages, seed and oil yield, as well as water requirements (Baldini et al., 2020). A recent study on hemp modelling was carried out by Wimalasiri et al., 2021. The Authors analysed options for hemp cultivation in Malaysia in terms of climate suitability, yield and economic potential and with multistage suitability assessment. They determined that more than 95% of the country could be suitable for hemp cultivation.

Cold temperatures and water stress influence hemp growth and development in northern regions and there are still knowledge gaps associated with hemp potential yields and adaptation to climate change. More research, combining different methods of field experiments and modelling approaches is therefore urgently needed to provide data to policy makers and farmers. Although, modelling approaches were used in a few hemp studies, there are no assessments of the model capability to simulate potential yield and yield gaps. Finally, the actual temperature and water stress levels for hemp potential yield in northern climates remain unknow.

In this study, we used the mechanistic AgroC model because of its physical representation for soil water and heat transport, as well as the ability to parameterize any crop to be investigated. The AgroC model was already applied to several field crops like winter wheat (Klosterhalfen et al., 2017), maize (Žydelis et al., 2018; Žydelis et al., 2021a), sugar beet (Herbst et al., 2021), or oat and barley (Groh et al., 2020, Groh et al., 2022). However, so far the AgroC model has not been parameterised for hemp. Therefore, the objectives of this this study are (i) to parameterize and test the AgroC model to simulate the growth and development of industrial hemp crop in nemoral climate conditions (ii) to estimate current yield potential of industrial hemp and its individual parts, and (iii) to unravel and quantify the effect of cold and water stress on hemp growth using historical weather data from the same site.

2. Materials and methods

2.1. Study site

According to the environmental stratification of Europe, Lithuania is in the Nemoral climate zone characterized by a continental and cool climate with a relatively short vegetation period (Metzger et al., 2012). The territory of Lithuania shows variations in terms of air and soil temperature, precipitation, but also soils. The average annual air temperature fluctuates between 5.8–7.6 ^{0}C, and annual precipitation between 550–910 mm. The main soils are Luvisols, Cambisols, Gleysols, and Arenosols and cover 28.5, 15.9, 14.6, and 13.2% of the area, respectively.

The input data required for the AgroC model were collected from hemp (*Cannabis sativa L.*) field experiments carried out during the three years between 2019 and 2021 in Akademija (Central Lithuania; 55°40′ N, 23°86′ E, 65 m asl). Field experimental locations fall into the agro-climatic zone IID of central Lithuania, which is warm, relatively dry, and with most fertile soils usually used for intensive cash crop production. The mean annual temperature of the agro-climatic zone IID is 7.5 °C and annual precipitation is 569 mm (mean values over the 30 years period 1991–2020). The soil is *Endogleyic Endostagnic Endocalcaric Luvisol* (Loamic) with a depth of 165 cm (WRB, 2014).

For each experimental season, the soil nutrient status was assessed from composite soil samples taken from 20 different locations within the experiment field. The main soil agrochemical characteristics were determined for the top soil layer (0–20 cm) and nitrate and ammonium concentrations were additionally measured for 0–30 and 30–60 cm soil depths (Table 1).

2.2. *Hemp experiments*

The hemp monoecious cultivar − Felina32 (French national hemp grower association) was grown under rainfed conditions in the years 2019, 2020, and 2021. This cultivar is well adapted to the Atlantic climate and is widely grown in various parts of Europe. This variety was selected due to its suitability to be grown for flowers, seeds and fibre because it reaches full maturity under Northern climate conditions. The vegetative cycle of this variety lasts approximately 135 days. According to producer the grain/seed yield reaches up to 1 t ha^{-1} and total above-ground biomass (TAB) can reach up to 12 t ha^{-1}. Felina 32 cultivar THC and CBD content reaches <0.12% and 2–3%, respectively. The hemp was sown after conventional tillage. Fertilizers were applied manually according to the protocol of the experiment and incorporated into the soil before hemp drilling. The amounts of fertilization are documented in Table 1. Hemp was sown as soon as the soil temperature reached 8–10 °C and available water was sufficient to guarantee prompt germination and a rapid crop establishment. Harvest was carried out manually at the end of seed maturity.

Table 1 Soil and agrochemical characteristics, treatment, and agronomic management of the hemp field experiments conducted under rainfed conditions.

	2019	2020	2021
Soil (FAO classification)	Endogleyic Endostagnic Endocalcaric Luvisol (Loamic)	Endogleyic Endostagnic Endocalcaric Luvisol (Loamic)	Endogleyic Endostagnic Endocalcaric Luvisol (Loamic)
Soil pH_{KCl} (1 N KCl extraction), 0–30 cm	6.6	6.4	5.0
Soil pH_{KCl} (1 N KCl extraction), 30–60 cm	7.5	7.4	6.7
Soil P_20_5, (mg kg^{-1}) (Egner-Riehm-Domingo (A-L)), 0–30 cm	157	207	99
Soil P_20_5, (mg kg^{-1}) (Egner-Riehm-Domingo (A-L)), 30–60 cm	116	172	62
Soil K_20, (mg kg^{-1}) (Egner-Riehm-Domingo (A-L)), 0–30 cm	139	186	159
Soil K_20, (mg kg^{-1}) (Egner-Riehm-Domingo (A-L)), 30–60 cm	116	138	138
NO_3^--N (mg kg^{-1}), 0–30 cm	11.54	22.9	8.33
NO_3^--N (mg kg^{-1}), 30–60 cm	7.31	16.8	5.06
NH_4^+-N (mg kg^{-1}), 0–30 cm	2.18	1.33	0.49

NH_4^+-N (mg kg^{-1}), 30−60 cm	1.23	1.22	0.52
Soil N total, (%) (Kjeldahl), 0−30 cm	0.168	0.144	0.138
SOC (%) (Tjurin), 0−30 cm	1.99	1.38	0.93
Previous crop	Winter rape	Winter rape	Winter wheat
Hemp cultivar	Monoecious cultivar −Felina32	Monoecious cultivar −Felina32	Monoecious cultivar −Felina32
Hemp sowing dates	14 May 2019	14 May 2020	21 May 2021
Hemp density	16 plants m^{-2} (160000 plants ha^{-1})	16 plants m^{-2} (160000 plants ha^{-1})	16 plants m^{-2} (160000 plants ha^{-1})
Plot size	3 × 7 m	3 × 7 m	3 × 7 m
Hemp fertilization	Ammonium nitrate (34.4-0-0) 150 kg N ha^{-1}, superphosphate(0-20-0) 100 kg P_2O_5 ha^{-1}, potassium chloride (0-0-60) 100 kg K_2O ha^{-1}	Ammonium nitrate (34.4-0-0) 150 kg N ha^{-1}, superphosphate(0-20-0) 100 kg P_2O_5 ha^{-1}, potassium chloride (0-0-60) 100 kg K_2O ha^{-1}	Ammonium nitrate (34.4-0-0) 150 kg N ha^{-1}, superphosphate(0-20-0) 100 kg P_2O_5 ha^{-1}, potassium chloride (0-0-60) 100 kg K_2O ha^{-1}
Hemp harvesting	18 September 2019	18 September 2020	21 September 2021

2.3. Experimental layout

The experimental design for the three years included nine treatments combining five different mineral fertilizers levels (N0, $N_{120}P_0K_0$, $N_0P_{100}K_{100}$, $N_{120}P_{100}K_{100}$, and $N_{150}P_{100}K_{100}$) with two plant densities (16 and 32 plants per m^2). Treatments were arranged in four blocks with four replicates. The total size of each experimental plot was 21 m^2 (7 × 3 m). In this study, where the effect of low temperatures and water stress was analysed, we focused on the $N_{150}P_{100}K_{100}$ plots, sown at the density of 16 plants m^{-2} to ensure optimal (no nutrient limited) growth. Nitrogen fertilization was split into two applications, with the first application of 90 kg N ha^{-1} (in form of ammonium nitrate) applied at the beginning of the vegetation period and second application of 30 kg N ha^{-1} before flowering. The phosphorus (in the form of superphosphate) and potassium (in the form of potassium chloride) was applied manually after sowing.

It should be noted that due to pre-planned crop rotation plans and their strict application, we were not able to grow hemp in precisely the same location during all experimental years, therefore, the location of experimental plots slightly changed but the maximum distance between the experiments did not exceed 1 km. However, as it can be seen from Table 1, in 2019−2021, the soils were rather comparable at the three sites. Nevertheless, soil hydraulic properties (Table 2) had to be estimated each year in order to match SWC observations as small scale heterogeneity is quite pronounced at the site.

2.4. Plant measurements

During the hemp vegetation period, the crop development stages were recorded weekly. A decimal code for hemp was used, where the life-cycle is divided into four principal stages: i) germination and emergence, ii) vegetation, iii) flowering and seed formation, and iv) senescence (Mediavilla et al. 1998). Hemp development stages were assigned given that 50 % or more of the plants in the entire treatment when were at a particular development stage.

In 2019 −2021 hemp total above-ground biomass (TAB) was sampled periodically over the entire growing season. In total, five measurements were carried out in 2019, one measurement was carried out during vegetative stages (stage code − 1012) and four measurements were carried out during flowering and seed formation stage (stage codes – 2000, 2300, 2305 and 2307). In 2020, in total six TAB measurements were carried out, 2 measurements were performed during the vegetative stage (stage code −1012, 1014) and four measurements were performed during the flowering and seed formation stage (stage codes – 2300, 2303, 2305, 2307). In 2021, in total four TAB measurements were carried out, one measurement during the vegetative stage (1014) and three measurements during flowering and seed formation (2301, 2304 and 2307). For the TAB measurements, samples were cut at the soil surface from an area of $3 \times 0.5 = 1.5$ m^2. The individual plants were counted and weighed in order to determine their fresh weights. After, 12 plants were randomly selected from each treatment (3 per replicate) and separated into the main organs (if present at the sampling date) leaf, stem, while flowers and seed were not separated due to the complicated separation of these parts. Therefore, only the combined weight of flowers and seeds was used. Samples were oven-dried at 65 ± 5 °C until weight constant to receive dry weights.

In 2019, several days before hemp harvest, the hemp rooting depth was determined. Therefore, a soil profile was dug approximately 50-70 cm away from the plants and after every soil layer was carefully washed using a high-pressure device. We found that the maximum of individual hemp roots extended to ~120 cm. This hemp root data was used for AgroC modelling and an overview of all parameters used for AgroC modelling is given in Table S1.

Leaf area was measured periodically using a HP printer scanner and the scanned leaves were analysed using the WinFOLIA (Regent Instruments Canada Inc.) image analysis tool to calculate the leaf area index (LAI). In total, five LAI measurements were carried out in 2019, six in 2020, and three in 2021.

2.5. Soil measurements

2.5.1. Measured soil physical and hydraulic properties

In May 2019, 16 undisturbed soil samples of 250 cm^3 were taken from major soil horizons at 15−20, 25−30, 40−45, 60−65, 70−75, 90−95, 120−125, 150−155 cm depth (Supplementary 1 figure) and transferred to the Forschungszentrum Jülich GmbH, Germany for analysis. Soil hydraulic properties were determined using the HYPROP® (Meter, München, Germany) method as described by Schindler et al. (2010) in combination with the WP4® Dewpoint Potentiometer (Decagon Devices, WA, USA). Saturated hydraulic conductivity, K_{sat}, was measured using the KSAT system (Meter, München, Germany). Soil texture was analysed according to DIN ISO 11277 method (Müller et al., 2009) by wet sieving and the pipette method.

Table 2. Soil horizons, texture and soil hydraulic properties for the period of 2019−2021 of the experimental plots.

Horizon description	PWP	θ_r	θ_s	α	n	K_s
		(cm^3 cm^{-3})		(cm^{-1})	(-)	(cm day^{-1})
			2019			
Ahp (0−25 cm)	0.111	1.0e-5	0.240	0.0492	1.115	24.3
Ahm (25−30 cm)	0.084	1.0e-5	0.274	0.0205	1.204	8.8
E (30−50 cm)	0.121	6.0e-5	0.357	0.0189	1.189	29.1
E/Btk (50−80 cm)	0.129	1.0e-5	0.469	0.0294	1.210	72.3
BC (80−90 cm)	0.112	6.0e-5	0.261	0.0287	1.138	23.7
Cg/Cl (> 90 cm)	0.052	1.0e-5	0.240	0.0318	1.245	18.45
			2020			
Ahp (0−25 cm)	0.166	1.0e-5	0.299	0.0299	1.095	35.0
Ahm (25−30 cm)	0.134	1.0e-5	0.267	0.0214	1.117	28.5
E (30−50 cm)	0.160	6.0e-5	0.269	0.0204	1.090	33.4
E/Btk (50-80 cm)	0.123	1.0e-5	0.296	0.0288	1.143	61.6
BC (70−90 cm)	0.083	6.0e-5	0.341	0.0314	1.227	26.1
Cg/Cl (>90 cm)	0.051	1.0e-5	0.272	0.0303	1.272	39.0
			2021			
Ahp (0−25 cm)	0.137	1.0e-5	0.265	0.0298	1.107	36.2
Ahm (25−30 cm)	0.135	1.0e-5	0.245	0.0229	1.101	30.3
E (30−50 cm)	0.156	6.0e-5	0.294	0.0200	1.110	32.8

E/Btk (50−70 cm)	0.129	1.0e-5	0.300	0.0312	1.135	62.8
BC (70−90 cm)	0.077	6.0e-5	0.344	0.0310	1.240	26.9
Cg/Cl (>90 cm)	0.026	1.0e-5	0.256	0.0301	1.368	40.2

The soil hydraulic parameters according to Mualem/van Genuchten (van Genuchten, 1980) are: θ_r = residual water content; θ_s = saturated water content; a = inverse air entry pressure; n = shape parameter; K_s = saturated hydraulic conductivity; *PWP* = permanent wilting point; **horizon description**: *Ahp* = Accumulative humic plaggic horizon in which decomposed organic material is being accumulated; *Ahm* = Accumulative humic compacted horizon in which decomposed organic material is being accumulated; E = Elluvial horizon from which chemically not disaggregated clay particles are leached; *E/Btk*= Intermediate horizon between elluvial and illuvial horizon in which illuviated clay particles and pedogenic calcium carbonates are being accumulated; *BC* = Intermediate horizon, from witch primary calcium carbonates are started to be leached ; Cg/Cl layer consist of: *Cg1* + *Cg2* = Initial carbonate horizons complex which has stagnic properties ; *C1* = Initial carbonate horizon in which gleyic properties can be seen. It has to be noted, that θ_r values were taken from laboratory data.

2.5.2. Inverse determination of soil hydraulic properties

Using soil hydraulic properties measured in 2019, we could not simulate water content with acceptable error, so we had to estimate soil hydraulic properties for each field site (Table 2). Soil texture was analysed according to DIN ISO 11277 method (Müller et al., 2009) by wet sieving and the pipette method.

The soil hydraulic parameters according to Mualem/van Genuchten (van Genuchten, 1980) were not estimated for each pedogenetic soil layer identified in the field, as no information was available by the SWC measurements for the relatively small subhorizon Ebt. Therefore, the E and the E/btk horizons were combined to one 'hydrological' horizon. For the remaining horizons, the soil hydraulic parameters were estimated. To do so, the Shuffled Complex Evolution (SCE-UA) algorithm (Duan et al., 1992 and 1993) was used to estimate water content at saturation (θ_s), inverse of the air entry pressure (α), shape parameter n and saturated hydraulic conductivity K_s. The soil water capacity $d\theta/dh$ and the unsaturated hydraulic conductivity function $K(h)$ are calculated according to Mualem-van Genuchten (van Genuchten, 1980). Hereby, the soil water retention is given by:

$$S_e = \frac{\theta-\theta_r}{\theta_s-\theta_r}\begin{cases}1 & h \geq 0 \\ (1+|\alpha h|^n)^{-m} & h < 0, \alpha, n,\ m > 0\end{cases} \quad [1]$$

where S_e is the effective saturation (-), θ, θ_s, and θ_r are the actual, saturated, and residual volumetric water content (cm^3 cm^{-3}), respectively, h is the pressure head (cm), α is the inverse of the air entry pressure (cm^{-1}), and n and m are a shape parameters (-), whereby m is related to n by 1-1/n. The unsaturated hydraulic conductivity is computed by scaling the saturated hydraulic conductivity K_s (cm d^{-1}) with relative conductivity K_r (-) given as:

$$Kr(h) = \left[\frac{[1-(\alpha h)^{mn}[1+(\alpha h)^n]^{-m}]^2}{[1+(\alpha h)^n]^{m\lambda}}\right] \quad [2]$$

where the tortuosity λ (-) is set to the standard value of 0.5 as recommended by van Genuchten, (1980).

The laboratory-measured soil hydraulic properties were used as start parameters for the inversion procedure, The residual water content (θ_r) was not fitted and the laboratory determined values were used instead, which minimized the number of parameters to estimate. Please note that the soil hydraulic parameters for each of the three locations in the test field had to be estimated because the high small-scale variability, typically found in soils developed in glacial sediments, did not allow acceptable water content simulations using a single set of parameters.

In order to emulate the annual course of groundwater table fluctuations at the lower boundary of the simulation domain a time variable Dirichlet pressure head boundary condition was used. In the form of a sine wave with a mean of -800 cm and an amplitude of 250 cm with the peak at 1st of July in combination with a dip at 31st of December. More information about the model setup and parameters can be found in Supplementary Table 1.

2.5.3. Soil agrochemical properties

Before each individual growing season, the soil nutrient status was assessed. For soil analysis, composite soil samples were taken from the plough layer (0−30 cm) at 20 different locations within the field and soil pH, soil organic carbon (SOC), total nitrogen (N_{total}), plant available phosphorus (P_2O_5), and potassium (K_2O) were analyzed. Additionally, composite soil samples for nitrate (N-NO_3) and ammonium nitrogen (N-NH_4) were taken from the 0−30 and 30−60 cm depths. The pH of soil samples was measured using pH-meter (XS Instruments, Italy) in a 1M KCl solution at a ratio 1:5 (vol/vol). Soil SOC content was determined by the dry combustion method using a Liqui TOC II instrument (Elementar, Germany). Prior SOC analysis the soil samples were pre-treated with HCl to remove the inorganic carbon fraction. Each sample was analysed in triplicate. N_{total} was determined by the Kjeldahl method by means of a semi-automatic Velp ScientificaTM UDK 139 instrument (VELP Scienticica, Italy) and manual sample titration using 0.1M NaOH solution. Soil P_2O_5 was determined using Shimadzu UV 1800 spectrophotometer, while K_2O was measured by means of flame emission spectroscopy using a flame photometer JENWAY PFP7 (Thermo Scientific, UK) at 766 nm wavelength. Both nutrients were determined according to Egner-Riehm-Domingo (A-L) method (Grigg, 2012). Soil mineral nitrogen concentration was determined using a spectrometric analyser Fiastar 5000 (Foss, Denmark). All soil chemical analyses were conducted in the Agrochemical Research Laboratory of the Lithuanian Research Centre for Agriculture and Forestry.

2.5.4. Soil water content

In the years 2019 to 2021, the soil volumetric water content (SWC) was monitored hourly at five different depths (15, 30, 50, 70, and 90 cm) using a wireless sensor network SoilNet (Bogena et al., 2017). For the AgroC model simulations the average daily SWC values recalculated from hourly SWC measurements were used.

2.6. Climatic data

Daily weather data from 2019 to 2021 included maximum ($T_{max,}$ °C) minimum ($T_{min,}$ °C), and average temperature ($T_{avg,}$ °C), precipitation (P, mm), relative humidity (%), wind speed at 2 m height (m s^{-1}), and solar radiation (J cm^2 day^{-1}) were collected from the Dotnuva meteorological station of the Lithuanian Hydrometeorological Service (Ministry of Environment), located approximately 700 m away from the hemp experimental fields. The reference evapotranspiration (ET_0) (mm day^{-1}) was computed based on the FAO Penman-Monteith method according to Allen et al. (1998). Meteorological data of 2019 – 2021 were compared to the climate normal between 1990−2020.

A standardized precipitation index (SPI) was used to assess the conditions in soil water content. SPI calculations require the long-term precipitation data (minimum 30 years), which is fitted to a probability distribution and transformed into standard normal distribution. Therefore, the SPI mean for the location and desired period is zero (McKee et al. 1993). In general, positive SPI values demonstrate greater than median precipitation, while negative values show less than median precipitation. According to SPI wet, normal/optimal, and dry periods can be identified. In this study, we used the SPI index interpretation by Tsakiris and Vandelis (2004), according to which a drought event occurs when SPI ≥ -1, near-optimal soil water content conditions are when SPI ranges between -0.99 to 0.99, and wet periods were identified as SPI ≥ 1. For SPI calculation, the long-term (1990–2021) precipitation data was taken and calculations were performed by the DrinC software (Tigkas et al., 2015).

Dividing years (and individual periods) into warm, normal, and cold periods we defined by a simple method when 25% of the highest values of air temperature from the entire variation were attributed to the warm period, 25% of the lowest values from the entire variation were attributed to the cold period, and the remaining part of the variation was considered as the normal period.

2.7. *AgroC model and parameterisation, calibration and validation procedures*

The AgroC model (Herbst et al., 2008; Klosterhalfen et al., 2017) has a modular structure. Within this study, only the variably saturated water flow module (SoilCO_2, Simunek and Suarez, 1993), which solved the Richards equation (Richards, 1931) and the crop growth module SUCROS (Spitters et al., 1989) were employed. The two modules are mainly linked via root water uptake RWU. The RWU demand is given by distributing the potential transpiration (ET_0) over the profile depth, based on a prescribed relative root density over the profile depth. According to the actual pressure head h (cm) given at that profile depth z (cm), the RWU is eventually reduced. The reduction factor at that depth is computed according to the commonly applied trapezoidal-shape approach of Feddes (1978):

$$\alpha(h) = \begin{cases} \frac{h_0 - h}{h_0 - h_1} & h_0 \le h \le h_1 \\ 1 & h_1 \le h \le h_2 \\ 10^{\frac{h_2 - h}{h_3}} & \text{for } h_2 \le h \le h_3 \end{cases} \qquad [3]$$

where α(*h*) is the dimensionless pressure head-dependent water stress indicator (between 0 and 1) and h_0 to h_3 are the four pressure head threshold values (cm). We further refer to the averaged, root density weighted α(*h*) over the profile as the average water stress indicator or water availability α_{avg}. Subsequently, it is used to scale the potential photosynthesis rate. Threshold values of h_0 and h_3 are defined as pressure heads at saturation (= 0 cm) and at wilting point (= -15849 cm), respectively. Parameter h_1 is rather less important, being the pressure head near saturation below which optimum water uptake is given. In contrast, the pressure head h_2 below which RWU is reduced is very relevant and was set to a value of -14000 cm, indicating a rather water stress-tolerant crop.

To account for the effect of cold stress, photosynthesis is multiplied with a temperature reduction function defined by interpolating between pairs of daily average temperature and respective reduction value given as model input. The temperature stress (Eq. 4) of assimilation is given by:

$$A_l = A_{max}\left(1 - e^{\frac{\varepsilon I_l}{A_{max}}}\right) R_{Tamax} \qquad [4]$$

where A_l is gross photosynthesis rate of a unit leaf area within the canopy (kg CO_2 m^{-2} leaf s^{-1}), A_{max} is the maximum gross photosynthesis rate of a unit leaf area at light saturation (kg CO_2 m^{-2} leaf s^{-1}), ε is the initial light use efficiency (kg CO_2 J^{-1}), I_l is absorbed photosynthetically active radiation (PAR) (W m^{-2} leaf), and R_{Tamax} is the A_{max} reduction factor accounting for temperature (-). Crop-specific tabulated values are provided as pairs of R_{Tamax} against air temperature measured at 2 m height.

The calibration/inversion procedure is described in detail in the Supplement Table 1.

Based on five different crop types, SUCROS offers the opportunity to estimate the development and growth of any crop. To simulate the hemp growth, we started with literature values and manually calibrated the parameters for development stage and senescence progression, root water uptake stress, specific leaf area, and photosynthesis. This calibration was performed using the 2019 data only. The two following years were used as an independent validation period.

2.8. Statistical analyses

The prediction ability of the AgroC model for both calibration and validation was investigated with the coefficient of determination (R^2) (Eq. 5), root mean square error (RMSE) (Eq. 6), mean absolute error (MAE) (Eq. 7), and model efficiency (ME) (Nash and Sutcliffe, 1970) (Eq. 8) and is computed as follows:

$$R^2 = \left[\frac{\sum_{i=1}^{n} (x_o - \overline{x_o})_i (x_s - \overline{x_s})_i}{\sqrt{\sum_{i=1}^{n} (x_o - \overline{x_o})^2{}_i \sum_{i=1}^{n} (x_s - \overline{x_s})^2{}_i}} \right]^2 \qquad [5]$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (X_o - X_s)^2} \qquad [6]$$

$$MAE = \frac{1}{n} \sum_{1=1}^{n} |x_o - x_s| \qquad [7]$$

$$ME = \frac{\sum_{i=1}^{n} (x_o - \overline{x_o})^2{}_i - \sum_{i=1}^{n} (x_o - x_s)^2{}_i}{\sum_{i=1}^{n} (x_o - \overline{x_o})^2{}_i} \qquad [8]$$

where x_o is the observed value at time t, x_s is the simulation result at time t and $\bar{X}_o$ is the arithmetic mean of the observed values. ME and R^2 are dimensionless criteria. ME values range between $-\infty$ and 1, the latter indicating that observation and model are completely in agreement. ME should be higher than 0.5, otherwise the mean of the observations is a better predictor than the model. R^2 values should also be close to 1 to indicate good model to data agreement. The R^2 only indicates agreement over the temporal course, whereas ME is a stricter criterion because it is also sensitive to the agreement of measured and simulated mean values. The RMSE and MAE provide values in the unit of the investigated variable and should be as small as possible. The RMSE is more sensitive to single large deviations between measurement and model.

2.9. AgroC model application

To evaluate the effect of climatic variables on potential hemp yield and yield gap, the previously calibrated and validated AgroC model was used for simulations with historical weather data of the Dotnuva meteorological station for the time period 1990 to 2021. As historical hemp seeding and harvest dates are not available, annual sowing and harvest dates were set to 10th of May and 20th of September in each year, which is almost identical to the hemp growing period during the field experiments performed in 2019−2021.

The effects of water and cold stress on hemp yield were assessed as follows. In the initial stage, the potential yield was estimated by switching off responses to temperature and water (no abiotic stresses) considering that there was no nutrient-limited fertilization. In the next step, only the function responsible for the temperature impact was switched off, allowing to calculate water-limited yields only. In a third step, water stress was switched off and temperature stress was enabled, allowing the analysis of temperature-limited yields only. Finally, actual hemp yields were simulated by enabling both response functions (water and temperature). The difference between potential yields and the yields simulated in the four realizations indicate a measure of the yield gaps caused by cold temperature, water stress, or combined water and temperature stresses.

3. Results and discussion

3.1. Hemp growing conditions

During the three years of the experiment, the hemp growing seasons were quite similar, with 127, 128, and 124 days in 2019, 2020, and 2021, respectively. Despite a similar growing season length during the three experimental years, a significant difference in TAB with 12.08±1.3, 15.53±1.5, and 12.76±1.1 t ha^{-1} for 2019−2021 was measured, indicating essential differences of environmental condition between the seasons. From hemp sowing to harvest, the mean air temperature was 17.8, 16.8, and 17.7°C in 2019, 2020, and 2021, respectively. Thus, the mean air temperature in 2019 and 2021 was 1.2°C and 1.1°C above the 1990−2020 historical average, while in 2020 it was only slightly higher (0.2°C) than the historical average. The minimum daily air temperature over the hemp growing period ranged from 3.7°C to 19.9°C in 2019, from 0.6°C to 17.9°C in 2020, and from

3.6°C to 20.9°C in 2021, while the maximum daily temperature ranged from 10.8°C to 33.7°C in 2019, from 11.7°C to 29.9°C in 2020, and from 8.1°C to 34.8°C in 2021. For comparative purposes, we calculated average air temperature over the long-term records from 1990−2021 (Figure 1) for the full hemp life cycle period (10 May – 20 September), for vegetative (10 May – end of June), and for reproductive growth stage (July – 20 September). Analysing those data in term of air temperature, the experimental years of 2019 and 2021 are referred to as warm, while 2020 was a normal year.

Additionally, the conditions in soil water content during the hemp growing seasons, especially for different growth stages, were contrasting. It seems that over the entire season the sum of precipitation fluctuated only slightly from 238.4 mm in 2019 (87.3% of precipitation compared to the climate normal between 1990−2020) to 254.1 mm in 2021 (93% of precipitation compared to the climate normal between 1990−2020) and 311.7 mm in 2020 (114.2% of precipitation compared to the climate normal between 1990−2020). Variation of the calculated SPI index for full hemp growing season showed that all three experimental years were attributed to optimal rainfall conditions in this region (SPI: 2019 = 0.01, 2020 = 0.78, 2021 = 0.03). In contrast, significant changes between years were observed already at the beginning of the season. For example, in 2020, during the hemp vegetative growth stage, the precipitation sum was 211.8 mm (SPI – 2.25) and is the highest during the period 1990–2021. In 2019 and 2021, the precipitation sum during the vegetative growth stage was very similar with 61.4 mm in 2019 (SPI = -0.84) and 64.8 mm in 2021 (SPI = -0.48). The opposite precipitation distribution was found during the hemp reproductive period. In 2020 the precipitation sum was the lowest with 100 mm (SPI = -0.64), increased in 2019 to 177 mm (SPI = 0.43), and was the highest in 2021 with 189 mm (SPI = 0.35). The number of days with heavy precipitation (above 10 mm) was higher in 2020 (seven days) and 2021 (eight days) compared to 2019 with five days. To sum up the meteorological conditions, the seasons of 2019 and 2021 are further referred as warm with optimal rainfall conditions, while 2020 is characterized as normal in temperature and optimal in rainfall conditions for this region. It is important to mention that even though 2019 and 2021 are classified as optimal for rainfall, 2020 had a significantly higher rainfall, and probably this is reflected in the higher TAB. The frequency percentage of environmental conditions that prevailed during the experimental years 2019 –2021 represents 46.9 % of environmental conditions observed in the long-term records 1990−2021. A detailed classification of the prevailing air temperature and rainfall conditions in the period 1990–2021, i.e. from 10th May to 20th September, is provided in Supplementary Table 2.

Figure 1. Variation of average air temperature, precipitation, and standardized precipitation index calculated for three different hemp growth stages (full growing cycle, vegetative growth, and reproductive growth) during 1990-2021.

3.2. Model calibration and validation

3.2.1. Soil water content

The measured SWC for the five depths and three experimental periods (2019–2021) are presented in Figure 2. Additionally, the statistical measures R^2, RMSE, MAE, and ME are presented in Table 3. Measured SWC fluctuations in the arable Ahp (0-25 cm) and Ahm (25-30 cm) soil layers, as well as in the E soil layer (30-50 cm) was higher than at greater depths such as the E/Btk (50-80 cm) and BC (80-90 cm) soil layers. It can be directly related to the effect of precipitation-evapotranspiration processes that influence soil water dynamics mostly. In general, measured SWC for most of the time remained above the plant wilting point and below saturation, thus no water logging occurred, which might be problematic as hemp is particularly sensitive to water logging.

In general, AgroC matched the SWC dynamics quite well after calibrating the model for each experimental year. Slightly better statistical results were obtained during the 2020–2021 period compared to 2019. For 2019, statistical values have shown that the SWC simulated by AgroC were better matched in deeper soil layers at 70 cm (E/Btk horizon) and 90 cm (BC horizon) compared to the three upper soil layers at 15 cm (Ahp horizon), 30 cm (Ahm horizon), and 50 cm (E horizon). The agreement between simulated and measured SWC at 70 and 90 cm was reasonably good and almost identical when comparing both soil layers together, with R^2 0.67 and 0.72, RMSE 0.016 and 0.020 $cm^3\ cm^{-3}$, MAE 0.014 and 0.014, and ME 0.62 and 0.03, respectively. Despite the fact, that the AgroC model predicts SWC levels similar to the measurements in the upper soil horizons, some peaks of in the soil water content were not well captured and worsened the statistical indices. For example, in the Ahp soil layer, the model well captured the first SWC peaks where high rain events (29/05/2019 – 17.10 mm, 16/07/2019

– 19.6 mm, and 22/07/2019 – 22 mm) were recorded, but during the later hemp growing season (August and the beginning of September) the model overestimated some SWC peaks. A rather different situation was observed in the Ahm and E horizons, although the first SWC peak on 29 May 2019 was well represented, the model did not catch several SWC peaks in July and August. Nevertheless, the overall predictive capacity for SWC of the calibrated model was satisfactory.

Figure 2. Comparison between measured (dot) and simulated (lines) volumentric water content, θ, (cm^3 cm^{-3}) at 15, 30, 50, 70, and 90 cm depths. Grey coloured lines and filled areas show standard deviation values of 2 sensors (except 90 cm depth). θ_s is the saturated water content, *PWP* is the permanent wilting point, and θ_s – PWP is the plant available water (all in cm^3 cm^{-3}).

The statistical indices for the SWC simulation during the 2020–2021 period showed also a good agreement with measurements for all five depths (Table 3). In general, the AgroC model was able to accurately simulate the SWC for the arable soil layers at 15 cm (RMSE = 0.028 cm^3) and 30 cm (RMSE = 0.022 cm^3 cm^{-3}), as well as in a deeper Elluvial E horizon at 50 cm (RMSE = 0.028 cm^3 cm^{-3}), and Illuvial Btk horizon at 70 cm (RMSE = 0.013 cm^3 cm^{-3}), and finally in the deepest BC horizon at 90 cm (RMSE = 0.017 cm^3 cm^{-3}). Overall results of the SWC simulations are depict in Fig 2 and listed in Table 3 show that the AgroC model is an adequate model for SWC predictions under hemp cultivation.

Table 3. Statistical values for the plant parameter calibration (2019) and the plant parameter validation (2020–2021) period for industrial hemp in Akademija.

Parameters	Observed	Simulated	R^2	RMSE	MAE	ME
		2019				
Leaf area index			0.95	0.41	0.37	0.91
TAB (t ha^{-1})	12.08±1.31	14.98	0.95	1.34	0.93	0.91
Leaf (t ha^{-1})	1.38±0.24	1.74	0.98	0.17	0.13	0.97
Stem (t ha^{-1})	8.24±1.05	9.62	0.97	0.67	0.47	0.96
Flower and seeds (t ha^{-1})	2.46±0.42	3.62	0.93	0.55	0.32	0.70
SWC @ 15 cm (cm^3 cm^{-3})			0.19	0.031	0.022	-0.73
SWC @ 30 cm (cm^3 cm^{-3})			0.07	0.029	0.022	-0.23
SWC @ 50 cm (cm^3 cm^{-3})			0.01	0.026	0.210	-0.56
SWC @ 70 cm (cm^3 cm^{-3})			0.67	0.016	0.014	0.62

SWC @ 90 cm (cm^3 cm^{-3})			0.72	0.020	0.014	0.03
2020						
Leaf area index			0.91	0.59	0.43	0.88
TAB (t ha^{-1})	15.53±1.51	13.01	0.91	2.27	1.88	0.86
Leaf (t ha^{-1})	2.13±0.52	1.97	0.92	0.44	0.33	0.88
Stem (t ha^{-1})	10.15±1.22	9.07	0.94	1.03	0.88	0.93
Flower and seeds (t ha^{-1})	3.24±0.34	1.97	0.78	1.07	0.74	0.37
SWC @ 15 cm (cm^3 cm^{-3})			0.76	0.024	0.018	0.76
SWC @ 30 cm (cm^3 cm^{-3})			0.69	0.025	0.021	0.61
SWC @ 50 cm (cm^3 cm^{-3})			0.85	0.014	0.007	0.75
SWC @ 70 cm (cm^3 cm^{-3})			0.74	0.016	0.009	0.72
SWC @ 90 cm (cm^3 cm^{-3})			0.81	0.026	0.017	0.70
2021						
Leaf area index			0.77	0.70	0.57	0.71
TAB (t ha^{-1})	12.76±1.09	11.87	0.98	1.18	1.03	0.93
Leaf (t ha^{-1})	1.66±0.26	1.45	0.87	0.37	0.27	0.92
Stem (t ha^{-1})	7.99±0.70	7.20	0.99	0.79	0.71	0.92
Flower and seeds (t ha^{-1})	3.11±0.23	3.22	0.99	0.11	0.078	0.99
SWC @ 15 cm (cm^3 cm^{-3})			0.50	0.031	0.022	0.34
SWC @ 30 cm (cm^3 cm^{-3})			0.77	0.018	0.011	0.76
SWC @ 50 cm (cm^3 cm^{-3})			0.55	0.042	0.033	0.43
SWC @ 70 cm (cm^3 cm^{-3})			0.75	0.009	0.008	0.22
SWC @ 90 cm (cm^3 cm^{-3})			0.68	0.007	0.006	0.10

Note: In 2019−2021 for all SWC depths calibration/validation procedures we used 135, 167 and 81 observations, respectively.

3.2.2. Leaf area index and hemp development stages

For the plant parameter calibration (2019) and plant parameter validation (2020−2021) period the simulated and measured green leaf area index (LAI) showed a good fit. As shown in Figure 3, the different environmental conditions over three years affected the seasonal LAI dynamic variation, which were well captured by AgroC (see also Table 3).

Figure 3. Measured (dots) and simulated (lines) leaf area index (LAI) and development stages (DVS) for the three hemp growing seasons 2019 (calibrated) and 2020-2021(validation). Error bars for LAI indicate the standard deviation of the mean (*N* = 4).

During the 2019 hemp vegetative growth stages AgroC underestimated the first two LAI measurements by 9.9−11.4% (LAI on 18 June: measured = 0.71±0.01, simulated = 0.64; on 3 July: measured = 1.40±0.47, simulated = 1.24). On the other hand, the remaining three measurements carried out during the hemp flowering and seed formation stage were slightly overestimated by AgroC (LAI on 18: July measured = 1.60±0.45, simulated

= 2.35; LAI on 23 August: measured = 4.76±1.75, simulated = 5.12; and LAI on 18 September: measured = 1.85±0.15, simulated = 2.62). Despite those discrepancies the simulated LAI values always fell within the calculated standard deviations. Here, it has to be noted, that relatively large standard deviations of measured LAI are detectable, which are related to plant heterogeneity in the field experiment, and the maximum number of leaves measured per plant reached up to 180 leaves in August. Overall, AgroC predicted the seasonal trends in LAI reasonably well for the calibration period with a R^2 of 0.95 (ME =0.91, RMSE =0.41, and MAE = 0.37).

The validation results for the year 2020 showed, that the simulated LAI values during the hemp vegetative stage and at the beginning of hemp flowering were slightly overestimated, and during hemp seed formation slightly underestimated by up to 4.4 %. In the second validation year (2021), AgroC did not capture the values of the first measurements at vegetative growth stage well (1 July: measured = 0.36±0.21, simulated = 1.52). However, the remaining two measurements during hemp flowering and seed formation stage were reproduced correctly (LAI on 2 August: measured = 2.57±0.63, simulated = 2.22, LAI on 17 August: measured = 3.46±0.86, simulated = 3.63). For the entire validation period (2020−2021) the calculated statistics R^2, RMSE, MAE, and ME were 0.88, 0.63, 0.48 and 0.84, respectively, indicating slightly higher predictive power for the calibration period compared to the validation years (Table 3).

The comparisons between simulated and measured hemp development stages (DVS) are also presented in Figure 3. During all experimental years, seed germination was suitable due to favourable temperature conditions and lasted 9−11 days until emergence. The measured hemp flowering (DVS = 1), and physiological maturity (DVS = 2) occurred 44−53 and 123−127 days after seeding during the 2019−2021 seasons. The AgroC model simulated the hemp flowering stage after 40−58 days after seeding. Here, it is important to note, that during all experimental years the full senescence stage (DVS = 2) was never reached in the hemp simulation. However, hemp yield in our experiments was harvested at end of fully seed maturity (code – 2307). In the field trials, the hemp was grown for dual-purpose, i.e. for high stem and flowers plus seed yields, and therefore, harvest was performed at end of seed maturity that is before full senescence will be reached. Additionally, leaves and stems will already deteriorate before full senescence will be reach in our climates due to frequently autumn frosts. Therefore, simulated DVS values at harvest did not reach 2 and ranged between 1.73−1.83 for the field trials.

3.2.3. *Partitioning of total above-ground biomass and its individual parts*

The measured individual parts of the dry matter hemp biomass along with the simulated data from the AgroC model are presented in Figure 4 and Table 3. The results show that during the calibration period (2019) the model reproduces the seasonal variation of the individual hemp parts reasonably well with a high R^2 of 0.98 for leaves (RMSE = 0.17 t ha^{-1}). Just slightly poorer results were obtained for the simulated stems yield (R^2 = 0.97, RMSE = 0.67 t ha^{-1}), whereby a relatively large mismatch in the stem simulation occurred at harvest with an overestimation of 16 % (measured = 8.24±1.05, simulated = 9.62 0.17 t ha^{-1}). Simulated flower and seed biomass also showed a good fit to the measured yield with a R^2 of 0.93, RMSE of 0.55 t ha^{-1}. AgroC reproduced the TAB development with acceptable accuracy. However, the TAB yield at harvest was overestimated by 23.6 % but the general statistical measures, R^2 (0.95), RMSE (1.34 t ha^{-1}) showed good agreement between the simulated vs. measured TAB data. Although, hemp root biomass was not measured, the AgroC model predicted that in 2019 maximum roots weight could reach up to 1.93 t ha^{-1}, which is an important information with respect to the return of biomass (above and belowground) into the soil, e.g. for considering soil carbon stock changes.

For the validation period (2020‒2021), the statistical indicators show that the agreement between measured and simulated total hemp and its individual biomass parts was slightly lower compared to the calibration period, but still reaches acceptable accuracy (Table 3). For example, for the years 2020‒2021 the measured leaf biomasses were reproduced with a R^2 of 0.91 (RMSE = 0.41 t ha^{-1}). Similar statistical results were also obtained for stem biomass (R^2 = 0.95, RMSE = 0.95 t ha^{-1}) but again the predictive capacity of the calibrated model was less satisfactory for the flower plus seed yield (R^2 = 0.70, RMSE = 0.86 t ha^{-1}). On the other hand, simulated TAB for the entire validation period was in good agreement with observation (R^2 = 0.93, RMSE of 1.95 t ha^{-1}). Compared to the calibration period, the total below ground biomass (root biomass) was estimated slightly lower for the validation period with 1.36 (2020) and 1.83 t ha^{-1} (2021).

It should be mentioned that for 2019 the simulated 'flowers + seeds' biomass was higher in relation to the measurements, whereas in 2020 the estimated 'flowers + seeds' biomass was lower than measured. Apparently, for end of July/August 2020 too much water stress was estimated, which particularly affected 'flowers + seeds' development, since the biomass increase occurs over a rather short period from mid of July until harvest. However, the soil water content simulation is basically in good agreement to the measurements for that period (see Fig. 2, middle column), except for the 15 cm depth. For this depth, the measurements show higher water contents than the model, which indicates a water content at permanent wilting point. This subsequently leads to a probably unrealistic water stress for the time period end of July/August (Fig. 5). This also affected TAB estimation, being too low for 2020.

Figure 4. Comparison between observed (dots; error bars: standard deviation) and simulated (lines) dry matter biomass of hemp individual parts (leaves, stems, (flowers+seeds), and roots) for the calibration seasons 2019 and the validation period 2020–2021.

3.2.4. Estimated cold and water stress

As hemp growing is sensitive to water shortages and as precipitation is lower in the study area than those reported for optimal hemp growth, the simulated intensity of stress for the three climatically contrasting growing seasons for main hemp growing stages (emergence, vegetative stage, and flowering/seed formation) were analysed and are presented in Figure 5. As an indicator for water stress the water availability α_{avg} (-) was used, which ranges between 1 and 0 and provides information about the average water stress over the entire root zone. α_{avg} values of 1 indicate no water stress, whereas values of 0 indicate full water stress. The soil water availability α_{avg} is computed as the root density weighted average stress indicator α computed according to Eq. 3 from the profile of soil pressure head over depth and the threshold parameters.

Figure. 5. Estimated water stress intensity index (α_{avg}), potential evapotranspiration (ET_p) and precipitation (P) for the three main hemp growth stages (emergence, vegetative stage, and flowering/seed formation) in 2019–2021 growing seasons.

As can be seen from the graphs for the years 2019–2021, the occurrence of water stress and its intensity reflects the precipitation and potential evapotranspiration distribution over the growing seasons. Looking at the data for 2019, it becomes visible that during the vegetative stage (36 days duration), precipitation summed up to

54 mm, and mean water stress intensity during this period was 24.2 %, whereby water stress increased at later times during the intensive growth of leaves and stems and lasted for about ten days in the range of 60−73 %. Precipitation during the hemp flowering/seed formation stage (78 days) was 177 mm while the mean calculated water stress intensity was slightly lower with 21.6 %. It is important to mention, that during the flowering/seed formation stage five high precipitation events occurred (up to 110.9 mm), which affected the water stress pattern and no water stress occurred over several days after each consecutive event. On the other hand, during periods without rainfall, water stress kicked in again and even reached 70 %. As expected, the water stress pattern also follows the SWC pattern shown in Figure 2.

In 2020 during the vegetative stage (lasted for 40 days) the precipitation was sufficient (194.2 mm) for nearly optimal growth, and therefore, only mild water stress occurred with a mean water stress intensity of 1.9 %. Only one day showed larger stress reaching 27.1 %. Opposite results were obtained during the hemp flowering and seed formation (74 days), when relatively small precipitation of 99.9 mm was recorded, leading to higher water stress over a longer time span with an average of 28.3 %, while maximum stresses between 67−77 % were reached in the first half of August. During the vegetative stage 2021, (33 days), only 30.2 mm of precipitation was available leading to constant water stress, only interrupted by a 3 days period after a rainfall event. Average water stress intensity reached 19 % during this period, whereby the maximum values reached 60 %. Finally, during the flowering and seed formation stage (lasted for 79 days), 189.3 mm of precipitation were recorded associated to a mild mean water stress intensity of 25.9 %. Although, the amount of precipitation was relatively high during this period, it should be noted, that four high rainfall events (all of them in August) with a total sum of 80.2 mm were recorded at the beginning of flowering, whereby in July only 17 mm of precipitation were available leading to a relatively high water stress intensity peak of 79.3 %.

In a next step, the simulated TAB and its individual parts for the three growing seasons were compared to potential above-ground biomasses without water stress (Table 4). As can be seen, the impact of water stress in all experimental years on biomass generation was substantial. For example, TAB losses over one of the three years varied in the range of 33.3−45.7 %, and the corresponding gap for leaves, stem, and flower + seeds amounted to 26.9−45.5, 34.6−51.1, and 18.5−31.4 %, respectively. Overall, the impact of water stress on biomass generation was largest in 2021 except for flower and seeds, where the gap was somehow smaller as those simulated for the year 2020, where less stress occurred.

Table 4. Simulated industrial hemp potential total above ground biomasses (TAB) and relative loss for the contrasting growing seasons in 2019−2021.

Simulated yield	TAB	Leaves	Stem	Flower+Seeds
2019				
Potential (t ha^{-1})	24.14	2.23	17.11	4.80
Temperature-limited (t ha^{-1})	22.5 (−6.8%)	2.19 (−1.8%)	15.72 (−8.1%)	4.59 (−4.4%)
Water-limited (t ha^{-1})	15.24 (−36.9%)	1.63 (−26.9%)	9.70 (−43.3%)	3.91 (−18.5%)
Water/temperature limited (t ha^{-1})	14.98 (−37.9%)	1.74 (−22.0%)	9.62 (−43.8%)	3.62 (−24.6%)
2020				
Potential (t ha^{-1})	21.39	2.79	15.45	3.15
Temperature-limited (t ha^{-1})	19.77 (−7.6%)	2.77 (−0.7%)	14.10 (−8.7%)	2.90 (−7.9%)
Water-limited (t ha^{-1})	14.26 (−33.3%)	1.99 (−28.7%)	10.11 (−34.6%)	2.16 (−31.4%)
Water/temperature limited (t ha^{-1})	13.01 (−39.2%)	1.97 (−29.4%)	9.07 (−41.3%)	1.97 (−37.5%)
2021				
Potential (t ha^{-1})	22.83	2.33	15.38	5.12
Temperature-limited (t ha^{-1})	21.18 (−7.2%)	2.27 (−2.6%)	14.30 (−7.0%)	4.61 (−10.0%)
Water-limited (t ha^{-1})	12.39 (−45.7%)	1.27 (−45.5%)	7.52 (−51.1%)	3.60 (29.7%)
Water/temperature limited (t ha^{-1})	11.87 (−48.0%)	1.45 (−37.8%)	7.20 (−53.2%)	3.22 (−37.1%)

In Northern latitude countries, low temperatures can be a critical environmental factor for the growth of certain crops, such as maize (Žydelis et al., 2021b) or soybean (Toleikiene et al., 2021). However, over the study period only a small number of extremely low (lower than 8°C) average air temperatures were recorded during the growing season. In 2019, those days accounted for < 2 % of the days during the vegetative stage and no days were recorded for the period of reproductive stages. The range of slightly higher average air temperature between 8−16°C during vegetative and reproductive stages accounted for 25.5 and 38.5 %, respectively, indicating that the climatic situation was in large parts over the growing season far from being optimal. In the same year, the most favourable temperatures between 16−24°C were recorded during the vegetative and reproductive stages for 66 and

61.5 % of days. High temperatures (24−32°C) were recorded only during the hemp vegetative stage (< 2 %). In 2020, similar temperature conditions were recorded. For example, temperatures below 8°C during the vegetative stage summed up to only 3.8 %, while during the reproductive stage there were no such cold temperatures. Slightly higher temperatures (8−16°C) for the vegetative and reproductive stages occurred for 39.6 and 38.4 % days. The highest corresponding values for the optimal temperatures between 24−32°C occurred as well in 2019 with 56.6 % for the vegetative stage and 61.7 % for the reproductive stage. Compared to 2019 no mean daily temperature exceeding 24°C was recorded. In the last experimental year of 2021 only three days below 8°C were recorded during the reproductive stage (3.8 %) and 33.3% and 33.8 % of the days during the vegetative and reproductive stage showed temperatures between 8−16°C. As well as in all former experimental years, temperatures were most often in the range of 16−24°C during the vegetative stage with 66.7 % and during the reproductive stage with 48.8 %. High temperatures (24−32°C) were recorded only during the reproductive stage totalling 13.8 %.

In the next step, the production gaps caused by low temperatures were analysed and listed in Table 4. The results showed that hemp TAB losses due to low temperatures were not as high as those caused by water stress and were in general lower than 7.6 % compared to the non-limited conditions. The corresponding temperature biomass gap for leaves were even smaller and did not exceed 2.6 % over all years, whereby the gap for stem biomass varied within a narrow range of 7.0− 8.7 %. Similar results as for the stem were obtained for the flower + seed gap ranging between 4.4−10.0 %.

The combined water/temperature stress biomass generation in comparison to potential ones indicate the highest losses compared to individual stresses, but combined stress gaps were smaller as the simple addition of single stresses, indicating that both stresses occurred, at least partially, at the same times. The AgroC predicts highest TAB reduction for the combined stress in 2021 totalling 10.96 t ha^{-1} (or 48.0 %), slightly lower TAB losses in 2020 with 8.38 t ha^{-1} (39.2%), and lowest relative losses in 2019 with 37.9 % (9.16 t ha^{-1}). Based on the data presented it can be concluded that water stress is the dominant factor for potential biomass losses at this location.

3.3. Model application to assess the environmental impact on hemp yields and yield gap

Simulated partitioning of TAB and its individual parts, as well as water-limited and temperature-limited gap during hemp growing season for the historical time period (1990−2021) were divided into nine environmental classes and corresponding results are shown in Figure 6. Large variations in hemp TAB and its individual parts were simulated under different environmental conditions. However, despite a few exceptions, in almost all cases the statistically significant highest hemp yields were obtained in wet years, slightly lower ones under optimal soil water conditions, and lowest yields were obtained in dry years, while the effect of temperature on hemp yields was much less pronounced compared to the impact of changing soil water content conditions. This can be explained by the fact that the variation of the amount of precipitation during the hemp growing season over the time span 1990–2021 was ≈ 4 times higher compared to air temperature variation. For instance, seasonal coefficient of variation (CV) of the precipitation reached 28.1 %, (CV: per vegetative period = 38.5 %, per reproductive period = 37.1 %), whereby the CV for temperature reached only 6.7 % (CV: per vegetative period = 10.1 %, per reproductive period = 7.2 %).

The simulated TAB yield in wet years reached 14.5 t ha^{-1} (range: 11.6 − 16.0 t ha^{-1}), and it was 3.14 t ha^{-1} or 21.7 % higher than the TAB yield under optimal soil water conditions. Hemp TAB yield under dry years averaged only 6.51 t ha^{-1} (range: 5.08−8.05 t ha^{-1}), and it was -7.98 and -3.37 t ha^{-1} lower than under wet and optimal soil water contents, respectively. Rather similar trends were observed for leaves, where significantly highest yield was determined for wet years with an average of 1.96 t ha^{-1} (range: 1.28 − 2.37 t ha^{-1}), medium leave yield was found under optimal (mean – 1.45 t ha^{-1}, range: 0.51 − 2.08 t ha^{-1}), and statistically lowest yield occurred for conditions with low soil water contents (mean – 0.71 t ha^{-1}, range: 0.49 − 1.16 t ha^{-1}). When analyzing the long-term yields of hemp stems, there are three distinct groups: i) highest yield – 9.52 t ha^{-1} (range: 7.51 − 10.40 t ha^{-1}) was found under wet conditions, ii) under optimal soil water conditions stem yield reached 7.51 t ha^{-1} (range: 4,91 − 11.05 t ha^{-1}), while the lowest yield was again obtained under dry conditions and reached 4.52 t ha^{-1} (3.15 − 6.06 t ha^{-1}). Hemp 'flowers + seeds' yield under wet conditions averaged 2.86 t ha^{-1} and was larger than under optimal soil water contents (2.34 t ha^{-1}). However, these differences were not significant. On the other hand, dry conditions resulted in significantly lower 'flowers + seed' yield, which were about twice as low as those found for optimal conditions and reached only 1.24 t ha^{-1}.

The simulated results showed that for the period 1990-2021 predicted potential hemp TAB yield may reach up to a maximum of 24.1 t ha^{-1}, whereby on average it was slightly lower with 20.1 t ha^{-1}.

Hemp water-limited yield was more sensitive to climatic variability compared to air temperature limited yield as shown in Figure 6. Over the 32 years of simulation, average hemp water-limited TAB gap varied from 1.2 to 75.5 %. The range of leave and stem gap was similar from 2.4 to 74.8 % and 1.7 to 78.4 %, respectively, whereby the gap for ‚flowers + seeds' was slightly higher from 5.5 to 90.6 %. The model results reveal the same tendency for all hemp biomass parts, with statistically largest water limited yield gap detected for dry years, while the smallest water limited gap was found for wet years.

Hemp temperature-limited yield gap was much less affected by temperature. Hemp temperature-limited TAB yield varied within a rather narrow range, from 0.4 to 7.6 %, and similarly for the leave and stems gap from 0.2 to 5.7 % and 0.5 to 7.3%, respectively. For ‚flowers + seeds' the temperature-limited yield gap was slightly higher, ranging between 0.9 and 12.5 %.

Regardless of the weather pattern of the historical time period 1990‒2021, our simulation study clearly shows that water limitation was the main hemp biomass limiting factor.

Figure. 6. Simulated hemp biomass, its parts and water and temperature yield gaps for different environmental conditions for the period 1990‒2021. Box boundaries indicate the 25th and 75th percentiles, and whiskers below and above indicate the minimum and maximum values. Lines and rectangles within each box indicate median and mean, respectively.

In order to identify relations between the climatic variables SPI, estimated water stress and simulated hemp yields a linear correlation analysis was established (Table 5). A significant positive correlation was found among precipitation, SPI, estimated water stress and hemp biomass and its individual parts, whereby the R^2 among the above-mentioned variables ranged between 0.52 and 0.81. It should be noted, that when comparing the different parts of the hemp biomass, a slightly stronger correlation was always found between TAB and total precipitation, averaged SPI and estimated water stress, while the correlation between stem, leaves, ‚flowers + seeds' and the above-mentioned climatic variables was slightly lower. Our model study results showed, that there was no significant correlation (except for leaf biomass) between air temperature, solar radiation and hemp biomass and its individual parts. The linear correlation analysis corroborates our finding that soil water conditions are the main climatic factor affecting hemp yield changes in Nemoral climates. On the contrary, the effects of temperature and radiation variability were less pronounced in relation to the variation of precipitation on hemp yield.

Table 5 Coefficient of determination (R^2) between hemp biomass and climatic variables.

	TAB	Leaves	Stem	Flowers + seed
Mean air Temperature	0.04	0.26	0.02	0.04
Solar radiation	0.03	0.13	0.02	0.01
Precipitation	0.78**	0.57**	0.74**	0.53**
SPI	0.81**	0.59**	0.76**	0.56**
Estimated water stress	0.71**	0.65**	0.62**	0.52**

** Correlation is significant at $p = 0.01$

4. *Discussion*

Growing hemp as multi-purpose crop is increasingly attracting attention, especially growing them for high stem and seed yields (Tang et al., 2017). However, very limited information is available on theoretical hemp (and individual parts) yield potential. Our model study provided modelling evidence that maximum hemp TAB yield potential may reach up to 24.14 t ha^{-1} (in dry weight) for the Northern Europe region. This level of yield potential was estimated for the season of 2019 under non-limiting water, temperature, and nutrient conditions. On average quantified hemp TAB potential yield for the historical period of 1990–2021 reached 20.1 ha^{-1}. This year-to-year simulated hemp yield potential variability (CV – 9.9%) is mostly related to the variation in solar radiation.

After running the model for the time period 1990–2021 we have also found that individual hemp parts can produce high biomasses (data not shown), e.g. theoretical maximum (non-limiting) stem yield may reach up to 17.1 t ha^{-1} (CV – 13.2 %), combined flower and seed yield up to 5.7 t ha^{-1} (CV – 18.9 %), and maximum leaves yield approximately up to 2.9 t ha^{-1} (CV – 13.0 %). It should be noted, that leaves potential yield was calculated at harvest (end of seed maturity). However, each year leaves reached their peak before harvest, i.e. approximately in the middle of August (at flowering stage) and potential leaf yield reached ≈5.0 t ha^{-1}, at this point, which was almost twice as much as those simulated at harvest. Hemp individual parts yield reported in several previous studies was equal to, or even higher than the calculated theoretical yield potential in our study (MultiHemp, 2017). Here it has to be noted, that higher yield might also be affected by seeding density, as in this study the plant density was 16 plants m^{-2}, which was lower than in those in the cited studies. Meier and Mediavilla (1998) found that the highest inflorescence yield was obtained using almost identical seeding rates (15 plants m^{-2}), while for optimal seed yield slightly higher planting density (from 30 to 75 plants m^{-2}) is recommended (Amaducci and Gusovius, 2010). Additionally, Tang et al. (2017) reported that by increasing plant density from 30 to 120 plants m^{-2}, the stem yield only increased by 29 %. Therefore, it is likely that growing hemp at higher densities will lead to higher yields of some plant parts (especially stem), and therefore, would be higher than those obtained in our study.

Measured TAB yield at seed full maturity across experimental years (mean – 13.5 t ha^{-1} , range: 12.08 – 15.53 t ha^{-1}), was quite similar to measured hemp TAB yield in the same climate zone in Denmark (mean – 12.7 t ha^{-1}, range: 11.3 – 13.9 t ha^{-1}), Latvia (mean – 13.9 t ha^{-1}, range: 11.6 - 17.1 t ha^{-1}), or Lithuania (mean – 10.8 t ha^{-1}, range: 7.6 – 14.4 t ha^{-1}) (Deleuran and Flengmark, 2006; Tang et al., 2017; Jankauskienė and Gruzdevienė., 2015). However, in the mentioned field trials hemp was grown at different seeding densities and different cultivars and fertilization intensities were also used. Therefore, the reported data should be used carefully for biomass comparisons. Unfortunately, the Lithuanian Department of Statistics did not provide the data on the average hemp TAB from a different farmer, and therefore, it is impossible to relate the calculate the gap between the yield obtained in the experiment and the yields reported by farmers.

Although, hemp can be grown as a sustainable crop over a wide range of climatic and agronomic conditions (Tang, 2018), paying attention to the understanding of cultivar and environmental conditions is substantial to guarantee high and stable yields under local conditions, particularly where soils may add restriction regarding water and nutrients stress. So far, responses of hemp yields to abiotic stresses have not been adequately addressed for hemp growth in the high latitudes. Additionally, it is not feasible to disentangle the effects of abiotic stresses (here, water and cold temperature stress) on yields using field experimental data directly. On the other hand, combining experimental and crop modelling approaches are suitable to disentangle both stressors, whereby water stress appeared to be the most dominant factor in the region. This finding is in agreement with Cosentino et al. (2013), who stated that for hemp growth water deficiency is the main constraint, and if water is not limiting growth, hemp photosynthesis is strongly influenced by air temperature, which is of secondary importance for hemp growth and development. Additionally, Tang et al. (2018) have shown that for hemp growth water stress may be divided into short- and long-term stresses. They found that the effect of short-term water stress was reflected by stomatal regulation, while the long-term stress increased leaf senescence and decreased LAI. During our experiments, both short- and long-term water stresses occurred, whereby both stresses only reduced photosynthesis and did not result in long-term changes in plant performance. AgroC accounts for short-term effects of water stress only, i.e. the instantaneous reduction of assimilation due to stomatal closure. Like most agroecosystem models it does not account for pathological reactions, like premature leaf dieback, which could affect the long-term behavior of the plant. Nevertheless, in 2021 severe water stress occurred during the flowering and seed formation stage, which significantly decreased LAI values.

5. Conclusions

This study is the first attempt to estimate yield potential and factors influencing yield gap in industrial hemp cultivation in the nemoral zone. In this study, a three-year hemp growing field experiment was performed, and its data gathered in the year 2019 were used for model calibration, whereby the validation was carried out on the data sampled in 2020 to 2021. Very good agreement between simulated and measured hemp and its individual parts biomass, leaf area index, soil water content, and development stages indicate that the AgroC model can successfully be used to predict hemp growth and development under nemoral climate. Further, the model results demonstrated a good agreement not only between measured and simulated hemp TAB but also for the individual plant components (stem, leaves, flower and seeds), giving confidence that the AgroC model is suitable for hemp growth prediction.

The simulated data showed that the hemp total above-ground biomass (TAB) was highly variable (range: 5.1−16.1 t ha^{-1}) under historical (1990–2021) climate conditions indicating a large sensitivity of hemp growth on the climatic conditions in this region, whereby the same tendency for all hemp biomass parts including stem, leaves, and flower and seeds was observed with statistically largest yields, as expected, simulated for wetter conditions. Largest average yield was determined for optimal soil water contents. On the other hand, lowest yield was simulated under dry years. Additionally, the AgroC model was used to predict potential yield (without water and cold stress), whereby the average potential yield for the historical period between 1990–2021 was calculated and reached 20.1 ha^{-1}. Looking at the individual stressors separately, showed that for this test site water stress is the dominant stress-reducing potential yield, while cold stress is of secondary importance. Over the course of the simulated 32 years average yield losses due to water stress are 8.7 t ha^{-1} (gap 43.3 %), while average reduction due to low temperatures was only 0.4 t ha^{-1} (gap 2.0 %). The simulation results also indicate that both stresses do not always occur during separate periods but to some extent also occur at the same time. As the climate is expected to increase temperature and increase the growing period in the future in this region (Žydelis et al., 2021a) more favourable growth conditions for hemp are expected but a detailed study is still lacking.

Acknowledgements

The internship (02/11/2019–04/12/2019) at the Agrosphere Institute IBG-3 at the Forschungszentrum Jülich, Germany was funded by EU Structural Funds under Measure No. 09.3.3-LMT-K712 ‘Development of scientific competence researchers, other researchers, students through practical scientific activities’ under a grant agreement with the Research Council of Lithuania (LMTLT).

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Supplementary Table 1 Parameter setting for AgroC simulation of hemp growth at Akademija, Lithuania.

Parameters	Value	Units or symbol meaning	Remarks
Base temperature	4	°C	Literature
Start temperature for plant growth	10.0	Sum of GDD	Calibrated
Specific leaf area of new leaves	0.00075	ha leaf kg^{-1} dry matter	Calibrated
Potential CO_2 assimilation rate of a unit leaf area for light saturation	75	kg CO_2 ha^{-1} leaf h^{-1}	Calibrated
Initial light use efficiency	0.47	(kg CO_2 ha^{-1} leaf h^{-1})(J m^{-2} s^{-1})$^{-1}$	Calibrated
Maximal rooting depth	1.2	m	Calibrated
Number of seedlings per area	16	m^{-2}	Measured
Leaf area of one seedling	0.000669	m^{-2} per seedling	Calibrated
Critical LAI for leaf death due to self-shading	3.25	ha ha^{-1}	Literature
Reduction factor of the maximal light assimilation rate as a function of DVS	0 1.0 1.3 1.0 1.6 1.0 2 0.5	DVS = 1.0: Flowering; DVS = 2.0: end of seed formation Reduction factor of maximal light assimilation is dimensionless	Calibrated
Daily average daytime temperature against reduction factor of the maximal light assimilation rate	-10 0.01 9 0.7 16 0.8 18 0.94 20 1.0 30 1.0	Temperature in °C Reduction factor is dimensionless	Calibrated
DVS against fraction of dry matter allocated to the shoot	0.0 0.4 0.8 0.99 0.9 1.0 1.0 0.98 1.5 0.875 2.5 0.65	dry matter fraction allocated to the shoot is dimensionless	Calibrated
DVS against fraction of dry matter of the above ground biomass allocated to the leaves	0.0 0.5 0.8 0.6 1.5 0.8 2.0 0.01	dry matter fraction allocated to the leaves is dimensionless	Calibrated
DVS against fraction of dry matter of the above ground biomass allocated to the stem	0.0 0.0 0.25 0.0 0.8 1.0 1.5 0.7 2.0 0.0	dry matter fraction allocated to the stem is dimensionless	Calibrated
DVS against fraction of dry matter of the above ground biomass allocated to the flowers	0.0 0.0 0.95 0.0 1.2 0.4 1.4 0.05	dry matter fraction allocated to the flowers is dimensionless	Calibrated

2.0 1.0

LAI = leaf area index, DVS = development stage

Supplementary Table 2. Classification of the period 1990–2021 from 10 May and 20 September into nine different environmental classes.

Classification by Temperature	Classification by SPI index	Selected years	Frequency percentage
Warm	Wet	2010, 2011	6.25
Normal	Wet	2009, 2012, 2017	9.38
Cold	Wet	1993, 1998, 2000	9.38
Warm	Optimal	2013, 2016, 2019, 2021	12.50
Normal	Optimal	1995,1997,1999,2001,2003,2005,2006,2007,2008,2014,2020	34.38
Cold	Optimal	1990, 1996, 2004	9.38
Warm	Dry	2002, 2018	6.25
Normal	Dry	1992, 1994, 2015	9.38
Cold	Dry	1991	3.13

Supplementary 1 figure. Soil horizons, texture and bulk density measured in 2019 before hemp sowing