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Published in:
European Journal of Agronomy

DOI:
10.1016/j.eja.2022.126690

Publication date:
2023

Citation for published version (APA):
Romero-Vergel, A. P. (2023). TURION: A physiological crop model for yield prediction of asparagus using sentinel-1 data. *European Journal of Agronomy*, *143*, [126690]. https://doi.org/10.1016/j.eja.2022.126690

European Journal of Agronomy 143 (2023) 126690

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

TURION: A physiological crop model for yield prediction of asparagus using sentinel-1 data

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ARTICLE INFO

Keywords:
Growth-simulation
LAI
Photosynthesis
Thermal-time
Brix
CHO-storage

ABSTRACT

In Peru, asparagus is an important crop for the export market. Forecasting the yields is key in planning ahead sales to exporters. Farmers currently apply an empirical method by counting the number of mature buds per crown per metre and making linear regressions with the previous harvests. There was no simulation model so far for a continuous cycling crop grown in Peru. Therefore, this research describes TURION, a mechanistic crop model coded in Python which includes 27 physiological parameters, some crop variables based on literature and field data. Growth rate, thermal time per phenological stages, biomass partition, stem diameter variations, spear volume and leaf area index (LAI) across the crop cycle were determined for model parameterisation. TURION includes three sub-models: (1) spears production and its root carbohydrates (CHO) depletion, (2) stems establishment and its root CHO depletion and (3) replenish CHO storage in roots by photosynthesis, LAI and CHO translocation. This model predicted: yield, numbers of spears, biomass of spears/stems, and root CHO changes brix% values. Predictions provided outputs at plant level. This model was validated on crops ranging from 3 to 12 years post-establishment, for 75 commercial harvests reported between July 2018 and May 2020 over 38 different plots. Results showed a relative root mean square error (rRMSE) of 16.72 % for final yield, 13.46 % for CHO at the end of harvest and 9.79 % CHO at the end of the crop cycle.

1. Introduction

Asparagus (*Asparagus officinalis* L.) is a perennial herbaceous C_3 horticultural crop. Its spears can be harvested during 15–20 years under optimal temperature of 26 ˚C (Avilés et al., 1999; Benson et al., 1978; Drost, 1997; Apaza, 2019). This monocotyledon species is dioecious (plants can be male or female depending on the flowers' gender) (Avilés et al., 1999) and it is member of the *Asparagaceae* botanical family native of the Mediterranean region; It is salt and drought tolerant (Avilés et al., 1999; Drost, 1997). However, irrigation is essential to guarantee yield with a long term healthy crop in the arid Sechura coastal desert of Peru (Martel, 2017; Vázquez-Rowe et al., 2016; Vargas, 2015) where drip-irrigation systems are implemented for large and medium scale agro-industrial producers. (Vargas, 2015; Apaza, 2019; Martel, 2017; Shimizu, 2009). Harvest can be conducted two or three times per year by controlling water availability, but harvest time also depends on the international market demand. These multiple harvests can only be obtained in Peru because its constant high solar radiation and temperatures over 16 ˚C.

Peru and Mexico are the primary asparagus exporting countries from Latin America, with 32,365 ha and 26,139 ha cultivated in 2017, respectively (FAO, 2017; Goyal et al., 2003; Shimizu, 2009). Peru produced 11,836.8 kg ha^{-1} (FAO, 2017). In contrast, all the European countries producing asparagus had 5277.8 kg ha^{-1} on 61,929 ha cultivated (twice as big as Peru). Europe produces less than half of yield obtained in Peru and using the double of land (FAOSTAT, 2021) hence fresh asparagus export from Peru is highly competitive (Apaza, 2019; Shimizu, 2009). The greatest yield is produced from November to January (summertime in Peru), which is coincident with the highest demand of asparagus in Europe due to winter season. On the market, the harvested spears are either white or green. That is why, forecasting the green asparagus yield is an important concern for most producers as they can plan the future commercialization.

Asparagus physiology is still not completely understood. Some physiological variables (such as gas interchange) are difficult to measure due to its canopy morphology, which is compound by thin and fine cladodes without a continuous leaf area. Most of cladodes capture diffuse light (Mantovani et al., 2019). The dense cloud of phylloclades (canopy) is the main assimilation site for photosynthesis (Hills, 1986) to recover the brix values in the asparagus roots. That is why, asparagus

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https://doi.org/10.1016/j.eja.2022.126690
Received 23 September 2022; Received in revised form 1 November 2022; Accepted 8 November 2022
Available online 5 December 2022

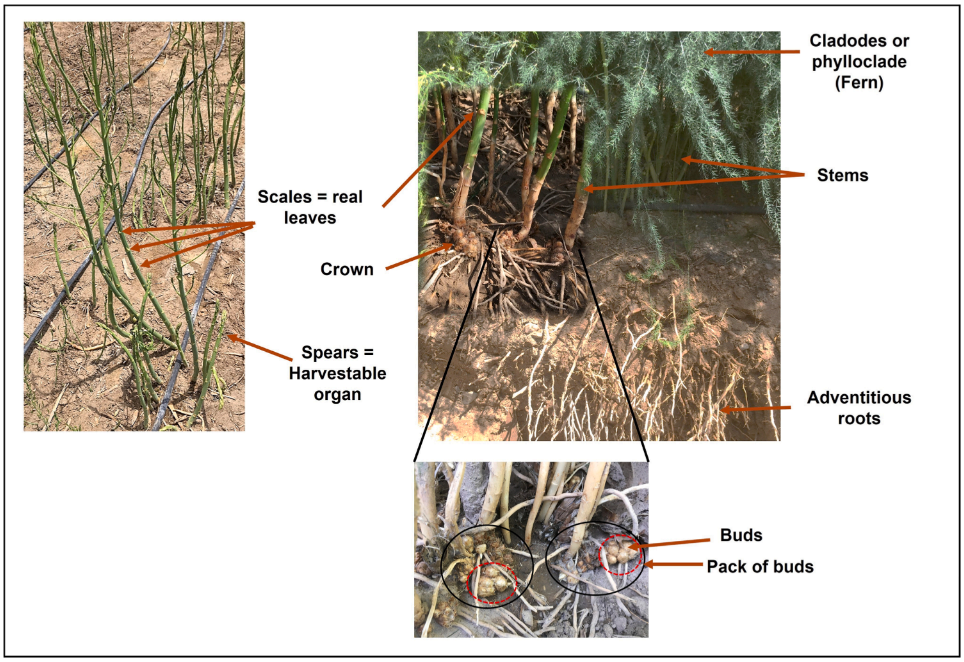

Figure 1. Asparagus UC157 plant morphology. Photos were taken in Nazca and Trujillo farms Dec,2018 and Dec,2019.

plants in Peru manteing a photosynthesis at efficient levels in a large portion of the canopy despite plants are exposed to high solar radiation levels. Moreover, asparagus crop management has focused on canopy growth stages and carbohydrate accumulation. However, new technologies such as remote sensors (RS) and reflectance data should be tried for field measurements on asparagus plantations. Data for non-optical sensor such as Sentinel-1 radar is not easily related with physiological responses of plants. Instead, reflectance data has been applied for characterize physiological responses of crops in Latinoamerica (Romero et al., 2017). For asparagus crop modelling purposes, LAI measurements on ground and solar radiation from a weather station play a crucial role for the validation of RS data (Danner et al., 2015).

The key to understanding crop productivity in asparagus are the dynamics of Water-Soluble Carbohydrates (WSC) reserves in the roots thought phenological stages. Asparagus accumulates WSC as fructans mainly, in the fleshy fasciculate adventitious roots of the rhizome system (Drost, 1997; Wilson and Drost, 2008). Carbon products as WSC are exported from the canopy cells through the phloem to the roots with a time lag of about three hours (Guo et al., 2002); the amount of WSC exported is proportional to the amount of carbon captured (Guo et al., 2002). This rapid translocation means there is little carbohydrate accumulation in cells of the canopy cladodes. Once WSC are in the roots, most of them are stored in vacuoles as fructans and in plastids as starch in a smaller proportion (Drost, 1997). Roots can reach levels in excess of 70 % of dry weight when the crop is ready to be harvested (Vijn and Smeekens, 1999; Wilson et al., 2000). Fructans are more soluble than starch (Vijn and Smeekens, 1999; Wilson et al., 2000), hence they can be easily used in spear production and stem establishment (Shiomi, 1992).

An asparagus crop model for yield prediction requires solar radiation data to calculate the rate of root WSC recharge from the canopy. Moreover, spear growth rate has long been recognized as a temperature dependent process (Culpepper and Moon, 1939; Watanabe et al., 2019). However, neither of the Crop Simulation Models (CSM) have been developed for the continuously cycling crop grown in Peru, where temperatures are much higher than in seasonal production temperate zones.

Although there is a wide range of techniques available for crop modelling and CSM have been built for many species (Dourado-Neto et al., 1998; Soltani and Sinclair, 2012; Oteng-Darko et al., 2013), only two CSM of asparagus have been described in the literature. A stochastic model of Graefe et al. (Graefe et al., 2010) which requires soil temperature; and a mechanistic model for winter dormant asparagus crops grown in temperate climates. The latest called Aspire is a mechanistic model that requires air temperature which is a common record from meteorological stations. It was developed by Wilson, Cloughley and Sinton in the New Zealand Institute for Crop and Research Ltd from 1999 to 2008 based on mathematical and statistical assumptions.

The aim of Aspire model was to predict spear yield during an annual crop cycle understanding the physiological processes of asparagus under temperate climates (Wilson et al., 1999; Wilson et al., 2002; Wilson et al., 2005; Wilson and Drost, 2008) . Comparison between observed and simulated values showed a root mean square deviation (RMSE) of 0.39 cm. There is no code of any programming language available, Although Wilson et al., determined some equations for physiological parameters of asparagus crop to describe spear growth related with CHO usage, temperature, solar radiation and phenological changes under seasonal regions, there is no an open code or or a platform to use the model, structural development on plants can be detected using remote sensors.

Structural development on plants can be detected using remote sensors.such as Sentinel −1 (S1) satellites which have been used in studies made by Silva-Perez et al. (2020) to show that S1 backscatter detected asparagus crop growth in Peru as the canopy volume changes through phenological stages. S1 is a mission of two radar satellites (non-optical sensors) providing continuous all-weather, day-and-night imagery at C-band (Waring et al., 1995). A single satellite can acquire data for the whole Earth every 12 days (Čotar et al., 2016), but during full operation both of the satellites provide a revisit time of six days over Peru. S1 has a Synthetic Aperture Radar (SAR) instrument to acquire backscatter represented as negative values of decibels (db). A complete pulse sent by SAR is equivalent to 1 db. After interacting with crop surface the pulsed signal is dispersed and the portion returned (backscatter) is lower than 1 db. Smoother surfaces return less backscatter towards the satellite. SAR can transmit and receive a signal in either vertical (V) or horizontal (H) polarisation. SAR signals are recorded using two word (e.g., VH) (Zink et al., 2001; Čotar et al., 2016). The order of letters indicates the orientations of the transmitted (first letter) and received signals (second letter) (Zink et al., 2001; Čotar et al., 2016).

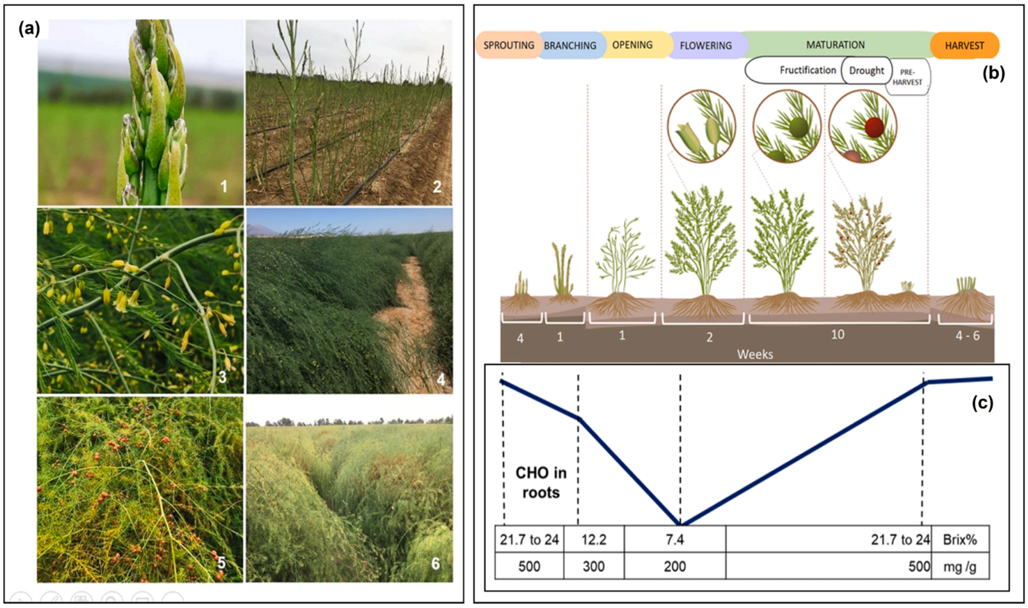

Figure 2. Asparagus campaign, phenology and WSC for crop modelling. a: Asparagus growth phases in field, 1- Branching, 2- Opening, 3-Flowering, 4-Maturation, 5-Fructification, 6- Drought. b: Crop phenology for crop simulation, draw modified from sqm-vitas.com. c: WSC balance basis for crop simulation.

Interferometric Wide swath (IW) is the most used mode for studying topography and agricultural land areas (Cloude and Papathanassiou, 1998; Bamler and Hartl, 1998; Rosen et al., 2000). IW data can be used for crop monitoring (Kussul et al., 2017) phenology changes of asparagus crop in Peru (Silva-Perez et al., 2020).

The aim of this study is to describe the development of an appropriate physiological crop model "TURION" of green asparagus growth, under Peruvian conditions, based on the adaptation and re-parameterisation of some equations used in Aspire model approach and using an open programming language.

2. Materials and methods

2.1. Plant Material

The asparagus variety UC157 was used in this study. It is the main cultivar planted in arid Peruvian coast with a crop density of 30000 plants per hectare. UC15 was developed by the University of California in 1978 (Benson et al., 1978; Cantaluppi and Precheur, 2012). UC157 F1 is free from asparagus latent virus 2 and highly tolerant to infection by *Fusarium oxysporum* and the blight *Puccina asparagi* (Vargas, 2015). This variety is widely accepted by international commercial fresh asparagus markets because of its tight spears tips without purplish colouring (Cantaluppi and Precheur, 2012). UC157 is productive in moderate and hot climates like California, Peru and Mexico (Farías et al., 2004). It is tolerant to high temperatures and plants can be 50 % male and 50 % female (Krarup and Krarup, 2002; Risso et al., 2012). Female plants have a slightly shorter crop cycle, and can produce thicker spears (Risso et al., 2012) than male plants.

The Fig. 1 shows the morphological organs of a typical asparagus UC157 planted in Peru, base on (Avilés et al., 1999). The asparagus *crown* is located underground . It is composed of the rhizome and adventitious root system. The *fasciculate adventitious* roots are the storage organs of carbohydrates. The *rhizome* is a plant structure that joins the aerial part with the roots. Crown also contain a structure named *bud*. They are grouped at the base of the steams. A group of buds is called *pack*. The optimal number of buds per stem is 4.5 differentiated. Commercial plantation asparagus producers use an empirical prediction of yield is made counting buds per pack, counting packs per a meter of the crop furrow and checking the yield of previous harvest. Over the soil asparagus plants have the edible stem is called *spear*. *scales* wich are modified leaves on the stem at branching points and *stems wich* are the organs forming the *canopy* structured by *cladodes or cladophylls*. These are needle structures with 1 mm of diameter and 6–20 mm long arranged in spiral on branches; Cladodes are also the main photosynthetic organs of aspragus plants (Downton and Torokfalvy, 1975; Inagaki et al., 1989; Drost, 1997; Nakayama et al., 2012).

2.2. Growth cycle and CHO balance

The asparagus agronomic cycle is called *Campaign* in Peru. Fig. 2a shows the crop stages in field. Usually, one campaign lasts around five months. There is no dormant phase, hence the canopy is cut before harvest when WSC in roots are between 20 and 24˚Brix; (in Spanish the activity to cut the canopy is called *chapodo*). The campaign starts just after the end of harvest (stage 33 BBCH (Feller et al., 2012)). However, for the purposes of this research *a campaign starts when the canopy is cut in the BBCH stage 92 or 93 and ends when asparagus canopy is cut again (from chapodo to chapodo)*. Spears can be harvested twice per year. The crop grows continuously from one harvest to another, through a canopy formation phase with no dormancy, as there are no cold temperatures in Peru. Instead, senescence and the translocation of WSC are stimulated by reducing the irrigation amount. This agronomical event is named *Agoste* and induced drought responses before canopy is ready to cut. The campaign has five main stages: Branching (one week, 11 BBCH), Opening (one week, 55 BBCH), Flowering (two weeks, 60–69 BBCH), Maturation (ten weeks, 69–92 BBCH) and Harvest (three to six weeks, 33 BBCH). The duration of each phenological phase can vary depending on weather conditions and agronomical management (Fig. 2B).

In Peru WSC content in roots are monitored weekly measuring degrees Brix degrees (˚Bx) to monitor the *depletion and recharge* during a crop cycle. Figure 2c shows the optimal values of˚Brix per each crop stage. At the beginning of the crop cycle when canopy is ready to cut WSC values must be between 20 and 24˚Brix (maximum values). At this stage a low˚Brix value indicates a small yield production of spears, hence the canopy cut must be delay. During the harvest, WSC are depleted in roots caring about not going below 12˚Brix. This is important to ensure enough WSC resources are left to support the stem establishment until opening phase from 39 to 55 BCCH (Feller et al., 2012); otherwise a small canopy will have low photosynthesis, reducing reserves available

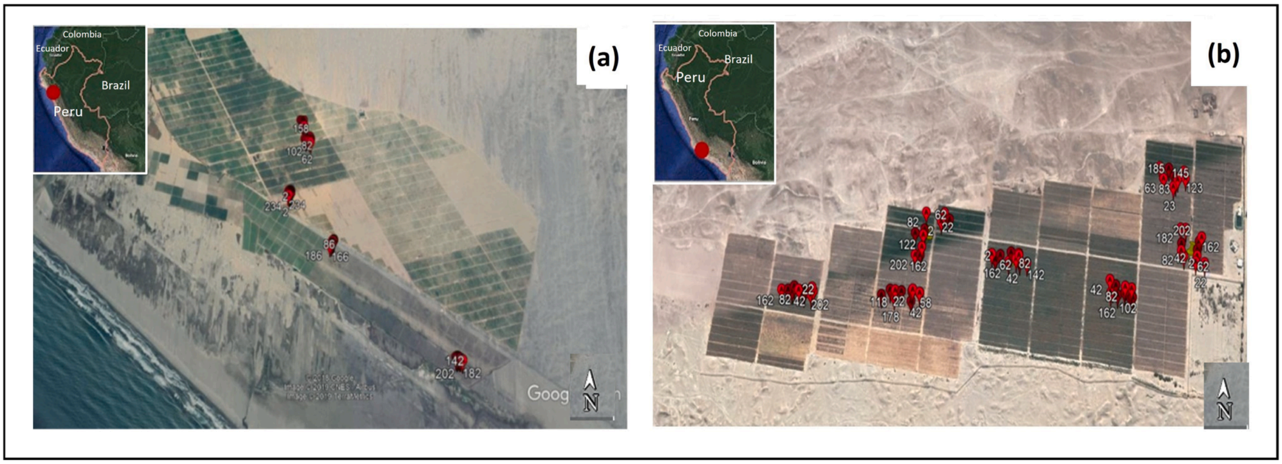

Figure 3. Test sites in Peru. (a): Trujillo, northern. (b): Nazca, southern. Red points show some LAI measurements location.
Source: Google earth, images acquired in 16/10/2019.

to the next crop cycle. Once the stem is established, WSC stored reaches its minimum value of around 7˚Brix. However, the new canopy doing photosynthesis will recharge WSC reserves until the root system is fully replenished to 20–24˚Brix again at the end of crop cycle (Wilson et al., 2000, Wilson et al., 2005).

2.3. Data acquisition

- Two field trips in two regions of Peru: Trujillo (northern) and Nazca (southern) (Fig. 3) were conducted to the commercial partners sites in Peru from October 30 to November 09, 2018 and from November 05 to December 13, 2019. A farm in Nazca was visited during the first field trip. Both regions were visited during the second field trip. Crop measurements were taken to complemented the data provided by the commercial partners. Field measurements included biomass per organ, LAI, and WSC in roots.
- LAI measurements were recorded using a LAI-2200C Plant Canopy Analyzer (LI-COR Inc, USA) following the protocol for row crops without the cap over the sensor Anon (Anon, 2020). Each LAI value is composed of 5 readings: one A-readings and four B-readings. A = Above canopy, B = Below canopy. A-readings are the reference of total solar radiation for B-readings. The B-reading measures diffuse radiation in the blue spectral range (320–490 nm) (Leske, 2011; Danner et al., 2015) at five zenith angles.
- WSC in roots was determined sampling 400 gr of fresh adventitious roots from each plot during field works at the same time when LAI was taken. Plots size vary from 3.5 to 12 hectares. Root samples were cleaned with tube water and macerated using clean stones to extract the soluble fraction of WSC in field. The root epidermis was not removed. Drops of this extraction were put in the portable Sucrose Brix Refractometer with ATC RF15 (Extech, USA). Producers already used to measure brix regularly from canopy cut to end of harvest, WSC content was reported every week on farms data sets by producers for this research after field works time.
- Farm data sets: Farmers from Nazca and Trujillo provided weather data and soil analysis and reports of crop cycle dates and quantities

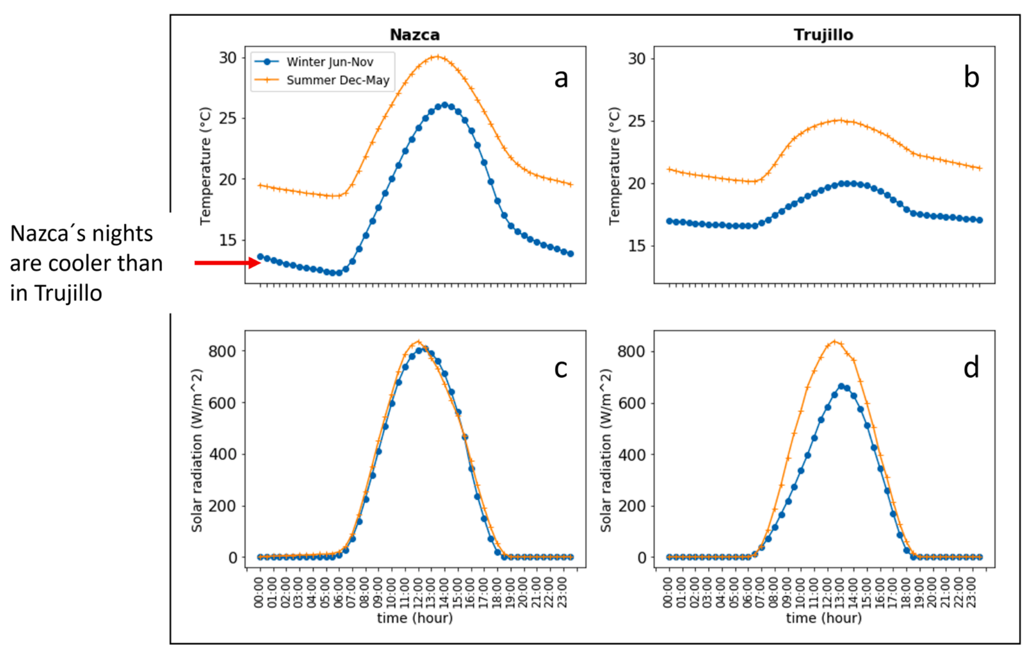

Figure 4. Hourly average of temperature and solar radiation to compare the two sites across the seasons. Trujillo is cooler than Nazca during day and has less radiation in winter (c and d). Data were collected using a weather station (Davis Pro2 Weather Station, Hayward, USA) in each farm in Peru from Jan-2018 to Mar-2020 (Nazca) May-2022 (Trujillo).

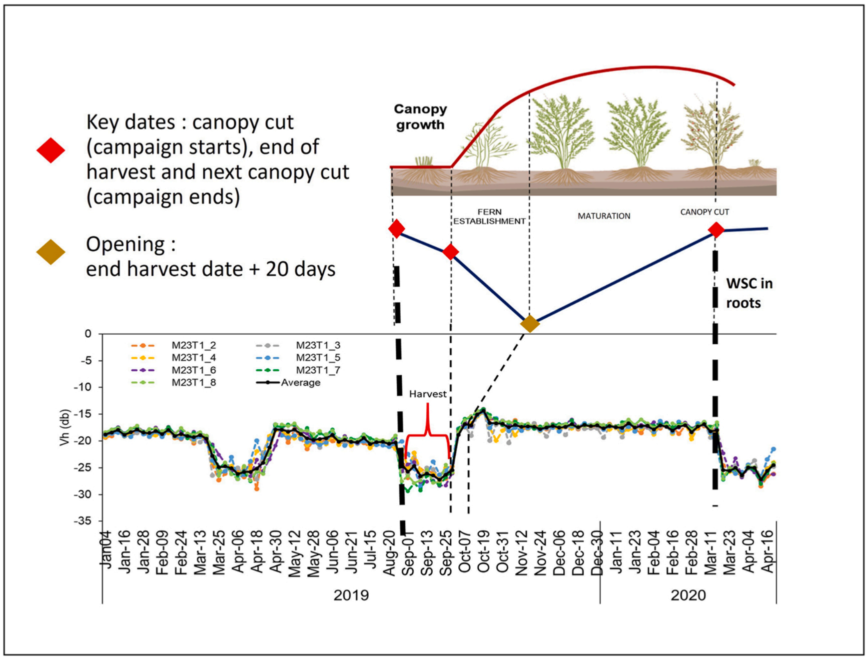

Figure 5. Sentinel-1 backscattering to identify crop key dates for asparagus modelling. db = decibels. Low db values= bare soil when farmers harvest asparagus. High db values= canopy with branches making photosynthesis. Opening is the phenological phase when stem grows after harvest, it takes 20 days before branches and cladodes begin to develop. Each colour of line represents a plot of asparagus crop with plants of the same age.

of spears harvested. Reports included some brix values and yield per plot during campaigns (crop cycles) from 2016 to 2021. Data sets have up to 61296 rows.

2.4. Environmental conditions

Temperature and solar radiation data were collected using a weather station in each farm (Davis Pro2 Weather Station, Hayward, USA). Farmers from commercial partners shared available reports since the weather stations started to record data since 2017 in Nazca and 2018 in Trujillo. These records were used to compare the two sites across the season.

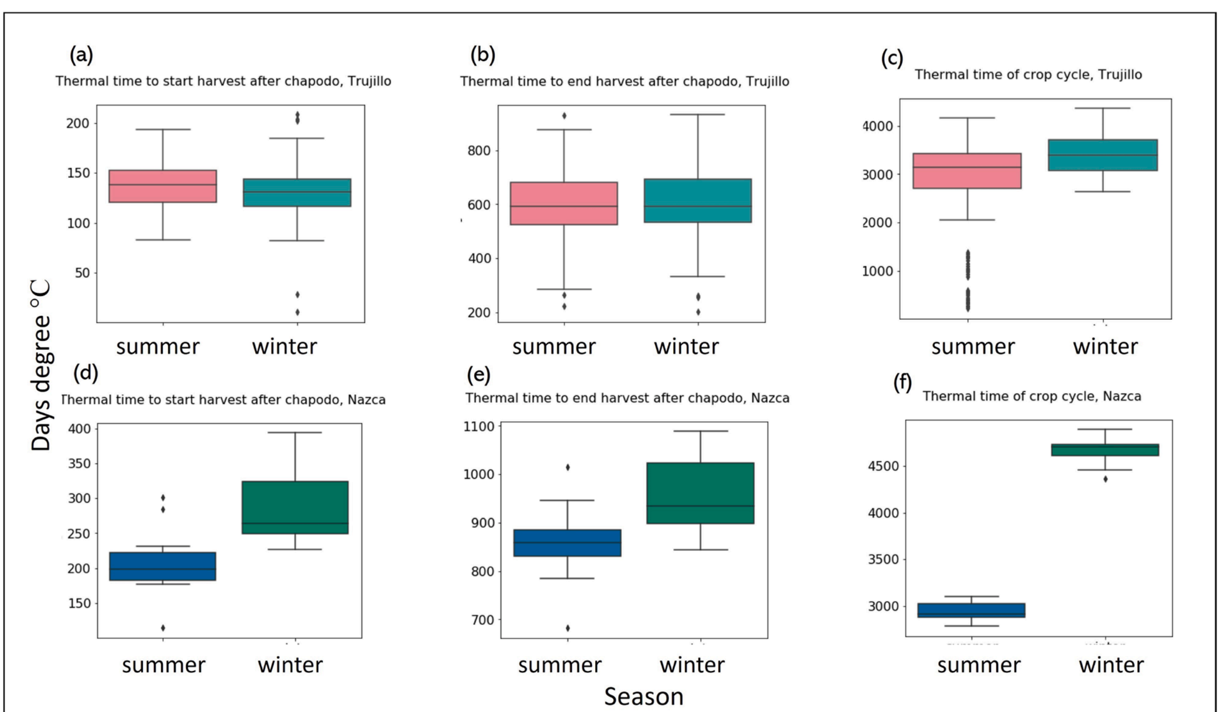

Figure 6. Data analysis of thermal time at three crop cycle dates per region. Asparagus campaigns from Nazca and Trujillo were studied considering three key dates after canopy cut (a) and (d) to start harvest, (b) and (e) at the end harvest and (c) and (f) at the end of entire asparagus crop cycle (end of the campaign). T_b of 7.1°C was considered in calculations.

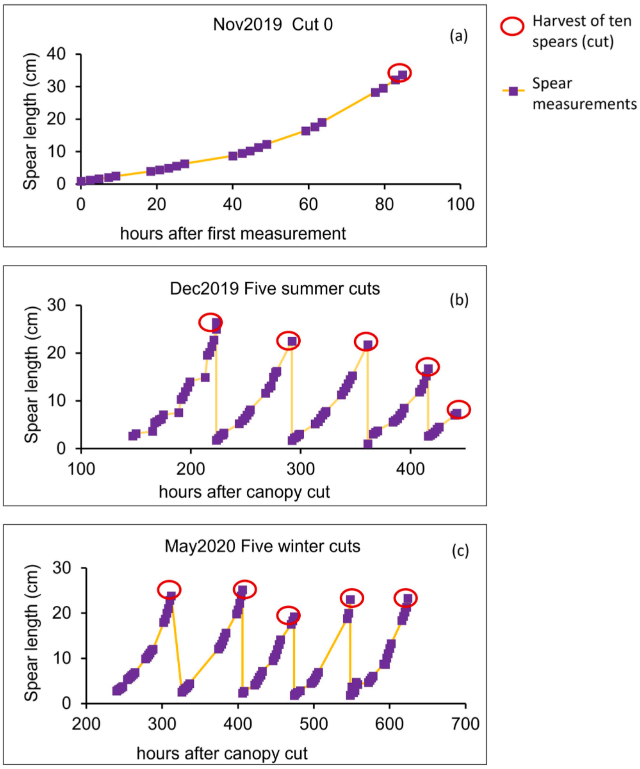

Figure 7. Spears growth measurements from Trujillo field (a) Only one cut growing in Peru Nov2019 summer time. (b) Five cuts spears growing in summer time December 2019, (c) Five cuts pears growing in summer in May 2020. x axis shows cumulative hours starting since the first spear length record in (a) or since canopy was chopped in (b) and (c). A cut = ten spearsgrowing at the same time from various crowns. The harvest (red circles) is the end of each cut, immediately after a new cut started to growth.

$$MJm^2day^{-1} = \frac{\sum_{i=1}^{24} R_i \times Pt}{10^6} \quad (1)$$

Equation (1) shows how the solar radiation values in Watts m^{-2} were transformed into integral values in MJ m^{2}day^{-1}, where R is the solar radiation in (watts) W m^{-2}, Pt is the Period of time in seconds during which a given reading was recorded. For example, if the station recorded climate data every 30 min, then W m^{-2} * 1800 s = J m^2 30 min^{-1}, divided by 10^6 to obtain the integral solar radiation in MJ m^{2}day^{-1}.

Figure 4 shows that in Nazca the daily difference of temperature (ΔT) between day and night is around 10˚C in summer and 15˚C in winter (Fig. 4a) and the maximum solar radiation at midday does not vary between summer and winter (Fig. 4c). Thus, the summer season in Trujillo have similar features to winter seasons in Nazca. In Trujillo ΔT is around 5 ˚C in summer and 11 ˚C in winter (Fig. 4b). The maximum solar radiation at midday varies around 100 Watts m^{-2} between summer and winter (Fig. 4d).

2.5. Sentinel-1 for key dates identification

The Sentinel-1 data was collected using the Google Earth Engine (GEE) platform (Gorelick et al., 2017) following the specifications of Silva-Perez et al. (2020) to detect three key dates of the campaign: canopy cut (start of campaign), end of harvest and next canopy cut (end os campaign). The SAR datasets were downloaded from Interferometric Wide swath (IW) with spatial resolution of 20 m (one pixel), swaths of 250 km, temporal resolution of 12 days using ascending angle with VV and VH polarisation channels. The code required to download data from GEE was provided by Silva-Perez et al. (2020) and is available at GitHub https://github.com/crisjosil/Sentinel_Earth_Engine/tree/master/Earth_Engine_scripts. The SAR signal from Sentinel-1 was characterized for asparagus plots in Nazca and Trujillo as shown in Fig. 5. The relationship of SAR backscatter with phenology phases was identified in Peruvian asparagus crops as VH backscatter is sensitive to asparagus development rate and crop height (Silva-Perez et al., 2020).

2.6. Model parameterisation

2.6.1. Thermal time characterisation for harvest asparagus

Asparagus is a perennial crop, hence, the thermal time was calculated from canopy cut date as point 0 for campaigns between 2018 and 2020. Thermal time calculation was conducted to predict the date when the harvest starts once the canopy is cut (Fig. 6a, d) and to characterize the duration of harvest (Fig. 6b, e) and the length of the crop cycle (Fig. 6c, f) in Trujillo and Nazca respectively for summer and winter time. In general, Figure 6 shows that the emergence of first spears after the canopy is cut and the harvest period takes longer in Nazca-winter.

Resulting in those the longest crop cycles (campaigns) are in Nazca during summer with 4469.5 days˚C in 211 days. The emergence of first spears after the canopy cut and the harvest period takes longer in Nazca-winter than in Nazca-summer and Trujillo. However, crop cycles of Nazca-winter and Trujillo-summer are similar with 3000 days˚C. These results indicate that spears started to emerge at 140 days˚C after canopy cut in Trujillo and at 200 and 260 days˚C for summer and winter respectively in Nazca (Fig. 6b and e).

2.6.2. Growth rate

In the crop model, growth rate defines the “speed” of spear elongation on field under specific conditions of temperature and solar radiation. In Peru spears grow so fast that they can be harvested one to three times a day. Therefore, spear extension was reported as a function of time at approximately 2 h intervals during working hours by fixing a ruler alongside each spear. There were two sets of measurements, in summer (November - December 2019) and in winter (May 2020).

Figure 7a shows the first preliminary trial in summer November 2019, tracking the growth of ten spears (Cut-0) and it stopped when they

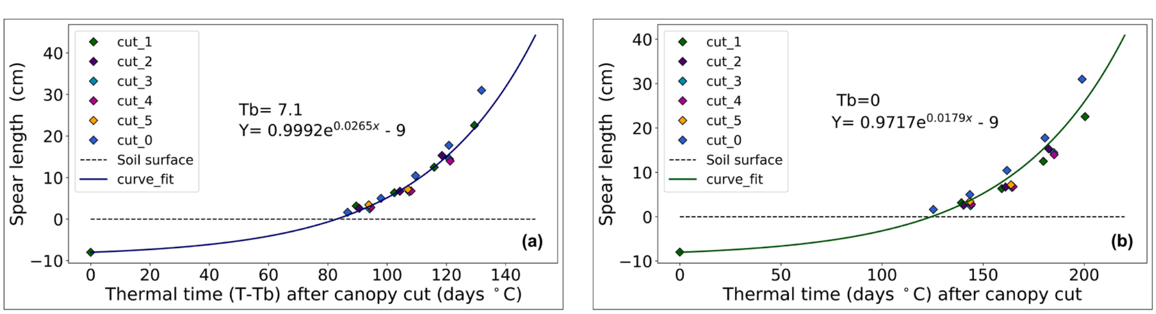

Figure 8. Growth rate: Spear-length vs thermal time. (a) Tb = 7.1˚C as reported by Wilson et al. (1999), Wilson et al. (2002). (b) T_b = 0˚C Fitting relationship between modified accumulated thermal time after canopy cut and spears length. Data was collected in the same plot M12T3 from Trujillo in December 2019.

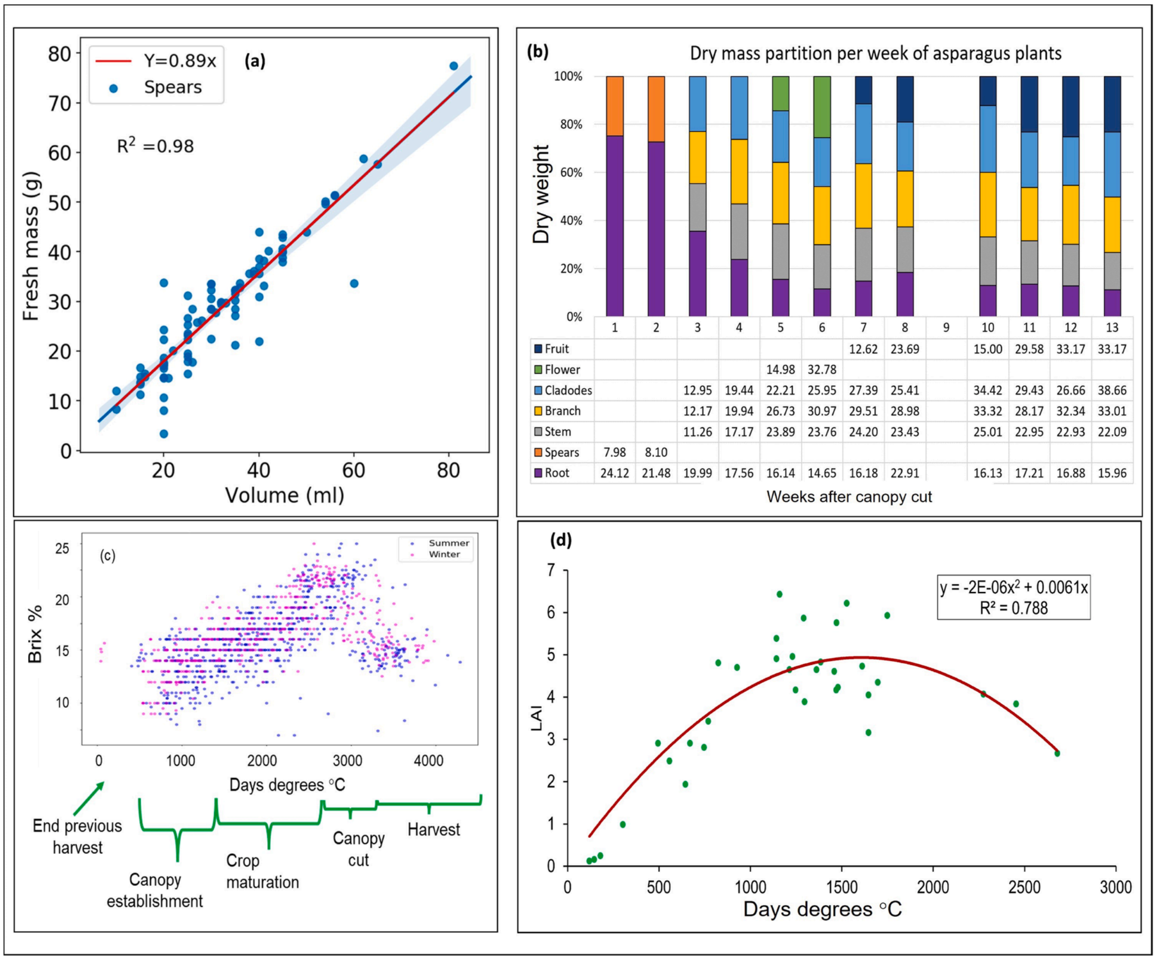

Figure 9. Asparagus crop characterization under Peruvian conditions. (a) Relation spear volume vs fresh used in TURION. (b) Dry mass distribution per organ: values in the table are g of dry mass. (c) Relation of WSC and thermal time of asparagus phenology phases from Trujillo. (d) LAI and thermal time of Peruvian asparagus campaigns of 2018 and 2019. Thermal time calculation with $T_b = 0$°C. Green points: LAI measurements. Red line: polynomial line.

measured 35 cm without considering the date of when canopy was cut. Spears in summer take about 80 h to be ready for harvest after emergence. Fig. 7b shows spears growing in summer December 2019. These summer spears begin to grow about 150 h after the canopy is cut. Fig. 7c shows spears growing in winter May 2019, when a new harvest started in the same plot. These winter spears begin to grow about 230 h after the canopy is cut. In general, spears in winter grow slower that spears in summer as is shown in Fig. 7.

2.6.3. *Fitting spears growth rate: Bring the model closer to field reality*

To copy the reality in this fitting process, the date when the canopy is cut and the depth of crown have to be included. In Peru fields d*epth of crown is* $-$ *9cm (*D_c*)* below soil. The harvest periodo starts when spears length is 1 cm (L_0.) over the soil surface. The spears growth rate was studied as a function of the thermal time. Thus, the exponential curve started when the canopy was cut assuming a D_c below soil.

D_c are negative values respect to the soil surface which do not fit in the exponential model. Therefore. in order to have only positive values $-(D_e) + L_0 = 10\ cm$ were added to each spear length value reported in the field. Only the first cut is related with the canopy cut date. Thus, using the spears length data from field starting at 1 cm length, canopy cut date and D_c, an exponential curve was fitted using the equation (2):

$$length = A \times e^{cx} \quad (2)$$

Here, *length* is in cm, *x* can be cumulative hours or accumulated thermal time in˚C days (tt). This tt was calculated with $T_b = 7.1$ or 0˚C , *e* is Euler number (2.71828), A and c are the contants controlling the curve shape depending on T_b.

Thus, figure 8 shows the spear growth rate using Tb = 7.1˚C as reported by Wilson et al. (1999), Wilson et al. (2002) and $T_b = 0$˚C as Peru has permanent temperatures over 7 ˚C. Therefore, Fig. 8(b) shows the equation (3) from summer cuts used by TURION model to simulate spear growth. where, length is the spear length (cm) over the soil surface, A = 0.9717 and *c = 0.0179* (Fig. 8)(b), *e* is Euler number (2.71828),$_{tt}$ is thermal time, the depth crown D_c is 9 cm below the soil. The number of spears per plant in the code is determined by counting the number of times the length reaches 22cm for harvest spears.

$$length = 0.9717e^{c(tt)} - D_c \quad (3)$$

2.6.4. *Spear volume and quality*

Commercial asparagus spears are classified according to base diameter and tip quality for market standards (Risso et al., 2012). Therefore, spear volume (Fig. 9a) is an important variable for asparagus crop model (TURION) because it indicates the space that will be occupied by carbohydrates from root storage. In this way, TURION quantifies the amount of carbohydrates destined for fresh spear formation. Therefore, the volume of each fresh spear from Trujillo was identified using the Archimedes method (Hughes, 2005). Thus, TURION calculates spear fresh weight with an efficiency of 0.89 g per ml.

2.6.5. *Biomass partition*

Asparagus as a perennial crop play a significat role on CO_2

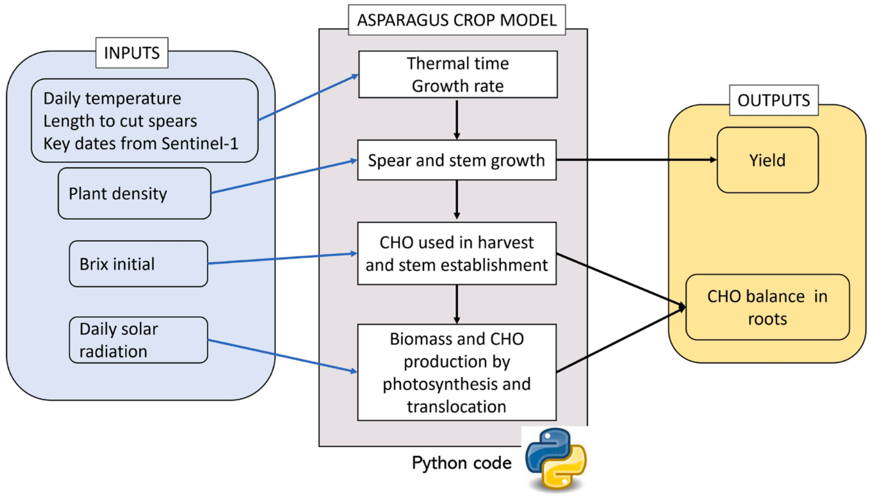

Figure 10. Representation of TURION crop model and its sub-processes.

sequestration to storage CHO in roots and build plant structure. However, biomass distribution of asparagus cultivated in Peru was not identified completely. Studying biomass partitioning of asparagus plants in Trujillo fields allowed to know how structural CHO are distributed across the plant organs. Fresh weight also includes the amount of water each organ contains. Therefore, biomass weight per organ was reported from 06/12/2019 when the harvest started until 10 weeks later as is shown in Fig. 9b. Root dry weight was stable since week 10 while fruits increased their dry weight values. 20 % of dry mass was used by fruits after the week 10. The stem was established at the opening stage. Canopy storage 80 % of carbon forming the asparagus plant, hence the dry weight of stems, branches and cladodes showed the highest values after harvest. However, CHO composing canopy organs can be translocated to roots at the end of the maturation stage (agoste) when senescent and dorught is induced by irrigation reductions to reach the optimal 24 brix % in roots.

2.6.6. WSC balance in roots

In Peru there are optimal values of˚Bx per each crop stage (Fig. 2). The relationship of WSC content in roots and thermal time across the crop cycle was defined analysing reports of 93 plots from January to August of 2019 (Fig. 9c). There were no major differences of WSC content between summer and winter seasons in both regions. Producers in both Nazca and Trujillo started the harvest when WSC content was around 22˚Bx. The harvest stopped around 14˚Bx without reaching the minimum WSC content allowed 12˚Bx. TURION uses (Brixini)˚Bx at start of harvest when the canopy is cut to simulated three˚Brix values: (1) at the end of harvest, (2) at stem establishment and (3) at the end of campaign (when canopy is cut again).

2.6.7. LAI measurements

LAI are interpreted as foliage area index (m^2 foliage per ground area m^2 ground), or as foliage area density (foliage area m^2 per canopy volume m^3) (LI-CORBiosciences, 2020). In this research, LAI was considered as foliage density due to the canopy morphology of the asparagus. So far these are the first known LAI values for asparagus in Peru. Therefore, a second degree polynomial equation was fitted (Fig. 9d) to simulate the relation between leaf area index (LAI) and thermal time across the crop cycle.

2.7. Model description

The Asparagus Crop Model for Peru (TURION) is a physiological crop growth model that simulates the daily time courses of: **1**. spear and stem growth for yield calculation and **2**. depletion and accumulation of CHO stored in roots. Daily thermal time for growth calculations is based on mean of air temperature during harvest and stem development. TURION also uses daily integral solar radiation in MJ $m^2 day^{-1}$ to estimate carbon sequestration by the canopy once stems are developed. The model is designed for commercial production in Peru but can be used for regions without long and cold winters. It mainly considers asparagus mature crops, older than 2 years. TURION is largely based on Wilson et al. (1999), Wilson et al. (2002), Wilson et al. (2005); Wilson and Drost (2008). Fig. 10 shows the TURION crop model flow and its sub-processes:

Table 1
Input used in TURION model.

Input	Variables	Unit
Carbohydrate root content	Initial value when canopy is cut (Brixini)	Brix%
Weather	Daily mean temperature (T)	˚C
	Daily solar radiation (SRAD)	MJ m^2 day^{-1}
Key dates (Sentinel-1)	Canopy cut (chapodo)	y-m-d
	End of harvest	y-m-d
	End of campaign when canopy is cut again	y-m-d
Crop characteristics	Length for harvest spears (L)	cm
	Approximate percentage of loses expected	%
	Plant population	plants ha^{-1}

2.7.1. Inputs

Input variables required to run the TURION model include WSC content in roots when the canopy is initially cut before harvest, daily temperature and solar radiation, key dates of crop cycle and crop features (Table 1). In total, TURION uses 27 parameters of plant morphology and plant physiology. The values for these parameters (See appendix A) were obtained from my own field work evaluations (parameterisation) and some assumptions were also taken from and literature sources Wilson et al. (1999), Wilson et al. (2002), Wilson et al. (2005); Wilson and Drost (2008). Losses of spear production were reported by farmers and can vary per plot and region.

2.7.2. Temperature for spear elongation

TURION uses cumulative daily mean temperature T_c to simulate phenological stages of spear production and stem elongation. The thermal time calculation included T_b of 7.1 and 0˚C using the equation (4), where$\boldsymbol{T}$ is the daily mean temperature in˚C, $\boldsymbol{T}_b$ is the temperature

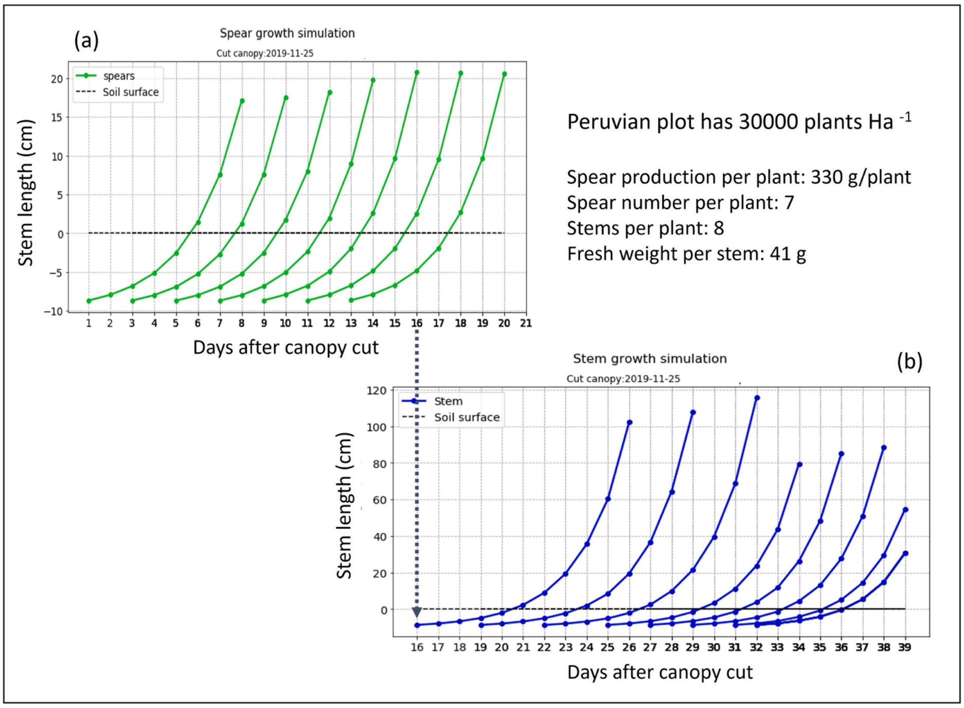

Figure 11. Simulation of spears and stems per crown growing from below the soil. (a) spear growth during harvest time. (b) Stems growth after harvest until opening phase. Spears and stems growth with same growth rate dependent on temperature changes. Stems are the continuation of spears that are not cut after harvests stops. Longer lines mean that temperature was higher those days accelerating the growth rate.

base. T_c is the cumulative T from i = 1 when the canopy is cut until i = n when the harvest ends.

$$Thermal\ time\ T_c = \left\{ \begin{array}{ll} & \sum_{i=1}^{n} T_i - T_b \\ 0, & Day\ when\ canopy\ is\ cut \end{array} \right\} \quad (4)$$

2.7.3. Spear production

Spear growth extension is expressed by an exponential equation (Equ. 3) assuming no limitation by nutrients, water or any affectation by pests and diseases. The number of spears or stems per plant (***NumberS***) in the code is determined by counting the number of times the length reaches the maximum value of 22 cm and 120 cm respectively. Spear growth is also affected by the depth of the crown below the soil. Depth of crown (D_c) was determined from monthly reports of northern Peru for 81 plots having 633 field readings in total. The model assumes that elongation of green spears under and above soil behaves in a similar way (Wilson et al., 1999).

Emergence of the first group of spears from below the soil does not happen simultaneously. Therefore, the model simulates the growth of the first new spear, computing the thermal time from canopy cut until harvest according to Sentinel-1 signals. Subsequent spears are initiated every other day according to the model parameterisation. Spears per plant are growing sequentially during the harvest period (Wilson et al., 1999, Wilson et al., 2002). In Peru, spears from the same linear meter where there are three crowns are cut once or twice per day depending on the temperature. Commercially, spears are cut on the day when their above-ground length becomes higher than 22 cm. However, length of harvest can easily be modified in the model depending on crop and market requirements. Thus, TURION simulations mimic the reality as is shown in Fig. 11a.

2.7.4. Spear volume

Volume identification of spears is important to quantified how many CHO are needed to form a spear. A linear equation expresses the relationship between spear volume and biomass as shown in Fig. 9a. TURION simulations uses a calculation of spear volume in eq. (5), where *NumberS* is the numbers of spear previously calculated from growth rate and thermal time, Average of spears volume is 45 ml of which 15 ml is the volume of spear base This base is cut during post-harvest classification.

$$Spear\ volume = (45ml - 15ml) \times NumberS \quad (5)$$

2.7.5. Spear biomass

Spear fresh mass is proportional to length and hence to volume. The factor to convert volume to fresh mass (**fwm**) is 0.89 g per ml (Fig. 9a.) Therefore, TURION model calculates spear fresh weight (***freshW***) in eq. (6), using *vol (spear volume)* resulted from eq. (5) and *lossesR* = 30 % is the biomass lost by physiological processes such as respiration.

$$freshW\ (g) = vol \times fwm \times (100 - lossesR\ \%/100) \quad (6)$$

Finally, spear dry weight (***dryW***) is calculated, in equation (7), with *fdw =0.0829* as fresh harvestable spears contained 8.29 % g of dry biomass as shown in week 2 of figure (Fig. 9b) and *freshW* is spear fresh weight resulting from equation (6).

$$dryW\ (g) = freshW \times fdw \quad (7)$$

2.7.6. Yield prediction

There are two types of yield in field: **total yield** accounts all spears harvested where quality is not relevant, and **commercial yield** which include only the exportable spears with good quality for market standards (Krarup and Krarup, 2002). TURION simulates both of them; total yield simulated is the *potential yield.* The commercial yield (Yi_{ok}) is calculated in equation (8): where Yi_{ok} is smaller than potential yield (Yi_{to}); $losses_{plot}$ is an input reported by farmers as percentage of spears wasted, these losses vary for each plot and are proportional to the temperature and $freshW_{spear}$ is the spear fresh weight resulting from equation (6).

$$Commercial\ yield^* = \left\{ \begin{array}{l} Yi_{to} = (freshW_{spear} \times plant\ density)/1000 \\ Yi_{ok} = Yi_{to} \times (100 - losses_{plot}\ \%) \end{array} \right\} \quad (8)$$

*Commercial yield = Yi_{ok} kg ha^{-1}. Potential yield = Yi_{to} kg ha^{-1}.

2.7.7. Stem development

When the harvest ends, the new asparagus stems are left to develop and grow to form a new canopy. Fig. 11b shows how TURION model simulates the stems growth by computing equation (3) for growth simulation, from the end of harvest until opening phenological stage (20 days after the end of the harvest) according to Sentinel-1 signals and farm reports. Steam growth simulation stops whent the stems reach approximately 120 cm over soil surface. The number of stems per plant (*NumberS*) in the code is determined by counting the number of stems of length ≥ 120 cm.

2.7.8. Stem volume and biomass

Stem volume is assumed as a conical shape with a constant diameter of 12 mm (r = 6 mm). Stem fresh weight calculation uses the equation (6). However, this calculation does not take into account any losses because stems are not harvestable and will gain biomass thought crop cycle. Given that dry mass of 18 % was determined in the opening stage for Peruvian asparagus crops (Fig. 9b, week 4), the factor of conversion to calculate dry mass in Eq. (7) is fdw = 0.18. Stem development uses WSC from root reserves hence the maximum level of carbohydrates depletion in the root system is achieved at this stage with the lowest brix values.

2.7.9. Water soluble carbohydrate balance in roots

Potential yield (Yi_{to}) of an asparagus crop depends on the availability of CHO in its storage root system. Therefore, to start a harvest, an optimal WSC content (22–24 brix%) is needed to fuel spear growth (Wilson et al., 2005). Two phenological phases need from stored WSC in adventitious roots: spear production and stem establishment, decreasing WSC content until 12 and 7 brix% respectively. That is why, asparagus farmers monitor WSC in brix% to decide when it is the best time for harvest.

TURION model only requires as input the **initial brix%** (***brix*** $_{ini}$) value recorded at canopy cut date. Simulations of CHO dinamics in roots result in three brix% values: at the end of harvest, end of stem establishment and when canopy is finally cut again which is the end of the campaign. Sentinel-1 signals provided timing between these phenological phases. The following equations were used for calculating the amount of WSC depleted during spear production and stem growth, and the amount of WSC recovered simulating canopy light interception for photosynthesis.

First, $brix_{ini}$ must be converted to $CHO\ mg\ g^{-1}$ of dry mass ($\mathbf{CHO}_c$) using the equation (9) described in Wilson et al. (2005) for asparagus crops in California, USA:

$$CHOc = 21.3 \times brix_{ini} + 16.8 \tag{9}$$

*CHO_c = CHO mg g^{-1} of dry mass; small “c” refers to “California”.

Then, in equation (10), the model integrates the root size to define the actual CHO value to start simulations ($\mathbf{CHO}_{start}$). Here root biomass is assumed for medium age crops as 750 g dry mass = 300 g WSC storage plus 450 g of structural CHO forming roots (Wilson et al., 2002). Both, WSC storage and structural CHO can be sources for spear and stems formation.

$$CHO_{start}(g) = (CHO_c/1000) \times 750(g) \tag{10}$$

Secondly, the amount of $\mathbf{CHO}_{used}$ is calculated from fresh spears and stems simulated considering a biosynthetic efficiency of 0.7 g dry mass per g of WSC (Penning De Vries et al., 1974), using eq. (11), where, ***dryW*** is the result from equation (7). Two CHO values are obtained from eq. (11): grams (g) of CHO at the end of harvest (CHO_{endH}) and g of CHO at the end of stem establishment (CHO_{min}).

$$CHOused(g) = dryW/0.7 \tag{11}$$

WSC depletion in roots after harvest ends (CHO_{endH}) is calculated in eq. (12) which uses CHO_{used}-spears value (obtained when harvest ends) from eq. (11) and it is subtracted from the initial value (CHO_{start}) from eq. (10). Then, after stems are established WSC storage keep decreasing so CHO_{used}-steam is subtracted from the CHO_{endH} value to obtain the CHO_{min}, which is the minimum CHO content in roots during crop cycle.

$$WSC\ depletion = \left\{ \begin{array}{l} CHO_{endH}(g) = CHO_{start} - CHOused_{spear} \\ CHO_{min}(g) = CHO_{endH} - CHOused_{stem} \end{array} \right\} \tag{12}$$

WSC are recovered by translocation of CHO produced from light interception photosynthesis processes (CHO_{pho}) simulattion. Equation (13) predicts WSC at the end of the campaign (CHO_{endC}) when the fern is ready to be cut once again. CHO_{endC} will be the $Brix_{ini}$ for next campaign simulation. The process to simulated LAI, CHO_{pho} and translocation are explained on next subsections.

$$WSC\ recover = \{CHOendC(g) = CHOmin + CHO_{pho}\} \tag{13}$$

Finally, CHO_{endH}, CHO_{min} and CHO_{endC} values in g of dry mass are transformed into brix% clearing the equation (9) to obtain the three birx values predicted by TURION crop model .

2.7.10. Light interception for recovering roots storage

LAI of asparagus canopy progressively increases from the end of harvest to flowering. Then, LAI decreases from maturation stage (Figure 9d) until canopy cut, prior to the next harvest. LAI in relation with thermal time for asparagus crops in Peru is described in equation (14) from Figure 9d). This polynomial equation uses T_c which is the accumulative temperature or thermal time.

$$LAI = (-2E-6)(T_c)^2 + 0.0072(T_c) - 0.7098 \tag{14}$$

Beer’s law is a relationship between the attenuation of light through a substance and the properties of that substance, which in this case is asparagus canopy. Light interception was assumed to occur following Beer’s law in eq. (15), where *F* is fractional light interception, *e* is Euler’s number (approximately 2.718), LAI was calculated from equation (14) and Figure 9d) and $\sigma = 0.6$ (Monteith and Moss, 1977) is the extinction coefficient of total solar radiation, which was also used in the Aspire model (Wilson et al., 2002 , Wilson et al., 2005).

$$F = 1 - e^{-\sigma LAI} \tag{15}$$

The *F* is fractional light interception and the input daily solar radiation (MJ m^2 day^{-1}) (SRAD) from the end of the harvest ($\boldsymbol{i}_0$) to the next canopy cut. *F* is used in order to calculate photosynthates accumulated per day per plant, which is produced by photosynthesis in equation (16). Here 1.5 g per MJ intercepted is the Radiation Use Efficiency (RUE) (Wilson et al., 2005). *i* is the day changing 1 by 1 from (i_0) until end of campaign to simulate fresh mass is produced by photosynthesis. Finally, to obtain biomass per plant, plants per m^2 divide the result because LAI values on field were taken per m^2.

$$photosynthates\{Biomass_{acum(i+1)} = (F \times SRAD \times 1.5MJ)/plantsm^2\} \tag{16}$$

i is the day changing 1 by 1 from (i_0) until end of campaign. This fresh mass is produced by photosynthesis process.

Translocation of CHO in asparagus is the 90 % of photosynthates from photosynthesis. These are stored as dry weight in roots considering losses by respiration of 25 % (Wilson et al., 2002 , Wilson et al., 2005) in eq. (17):

$$translocation = Biomass - acum_{(max)} \times 0.9 \times [(100-25)/100] \tag{17}$$

During maturation canopy phase about the 35 % of photosynthesis are driven into fruits and fern maintenance according to the biomass partition of asparagus plants in Peru (week 7 in Fig. 9b). Thus, the final CHO_{pho} value re-storage in roots is calculated in eq. (18):

$$CHO_{pho}(g) = Drymass \times [(100-35)/100] \tag{18}$$

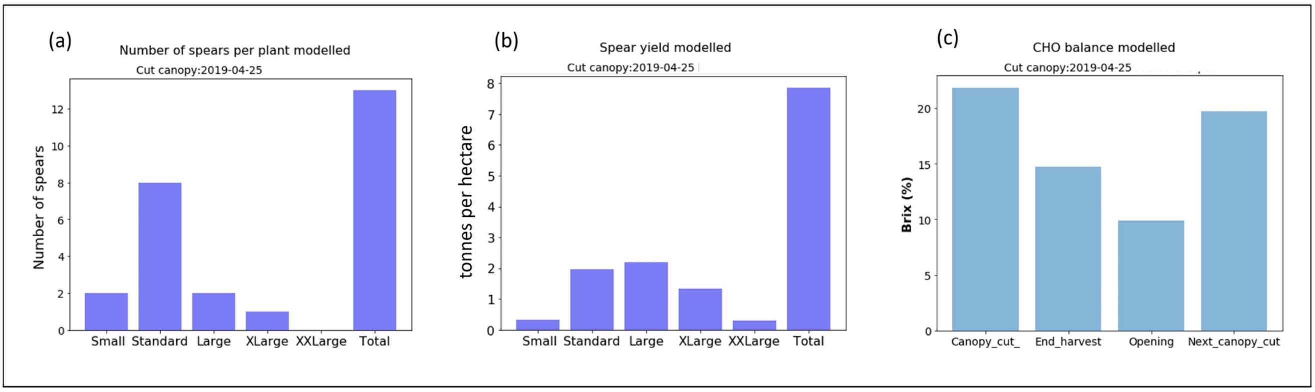

Figure 12. Simulation outputs: CHO balance, number of spears and yield. Python visualization after simulated an asparagus plot. (a) Number of spears. (b) Yield per plant. (c) spear classification per quality (small, standard, large, Xlarge and XXlarge).

2.7.11. Simulations

The simulation produces 10 stems per plant with 40.26 gr of fresh mass per stem. If there are three plants per linear meter the results are 30 stems per meter, which are coincident with field reports and Silva-Perez et al. (2020) study.

The python code was programmed to show visualizations from simulations of spear (Fig. 11a) and stem (Fig. 11b). These initial visualization helps farmers to see their harvest dynamics in advance and predict and approximate number of spears and stems per plant. Moreover, the asparagus export market pays farmers according to the quality of spears. That is why, it is important to quantify number of spears (Fig. 12a), yield per plant in tonnes per hectare (Fig. 12b) and their classification per quality (Fig. 12c) (small, standard, large, Xlarge and XXlarge).

2.8. Model simulations

Simulations in TURION were conducted for mature crops (between 3 and 12 years old) for 75 campaigns reported from July 2018 to May 2020 in 24 plots in Trujillo and 14 plots in Nazca. Simulations predicted yield and CHO changes in roots.These quantitative results of campaigns simulated are register in an excel file for posterior data analysis and model validation.

2.9. Model validation and accuracy metrics

Data sets used for validation of the model were yield and CHO values reported in farm data sets (observed data) versus predicted yield (t ha^{-1}) and WSC as brix values from TURION model after simulations (simulated data). Therefore, model validation compared TURION outputs of commercial yield and the time course of WSC with observed field data. Model accuracy was evaluated using statistical indices of root mean square error (RMSE) (Silva-Perez et al., 2020; Bai et al., 2020; Camargo Rodriguez and Ober, 2019; Göçken et al., 2016) and relative-RMSE (rRMSE) (Saldana-Villota and Cotes-Torres, 2021; Jing et al., 2007; Zhao et al., 2019; Raymundo et al., 2017; Confalonieri et al., 2016). Their values were calculated by eqs. (19) and (20), where Y_i is the predicted value from the model, X_i corresponds to observed value from field and $\overline{X}$ represents the mean of the observed data:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - X_i)^2} \quad (19)$$

$$rRMSE = \frac{RMSE}{\overline{X}} \times 100\% \quad (20)$$

Table 2
Statistical indices for the evaluation of asparagus crop model performance.

Region / Season	Error	Yield	WSC-h[1]	WSC-c[2]
Trujillo-Summer	RMSE	0.94	1.1	2.01
	rRMSE (%)	14.47	7.50	9.15
Trujillo-Winter	RMSE	1.39	1.65	1.99
	rRMSE (%)	17.22	10.71	8.87
Nazca-Summer	RMSE	0.98	2.79	1.93
	rRMSE (%)	11.19	20.09	8.41
Nazca-Winter	RMSE	0.64	2.73	2.96
	rRMSE (%)	23.14	16.71	13.02
Overall	RMSE	1.27	2.04	2.20
	rRMSE (%)	16.72	13.46	9.79

[1]Water soluble CHO at the end of the harvest. [2]Water soluble CHO at the end of the campaign. This table shows a summary of root mean square error (RMSE) and relative-RMSE (rRMSE) for the predicted asparagus commercial yield and WSC for two Peruvian regions using TURION crop model.

3. Results

3.1. Validation of TURION outputs

Table 2 shows the model validation per region in summer and winter seasons. Although. TURION model is accurately performing yield and WSC in roots predictions, it is not producing values exactly like the field data nor predicting extreme outlier events. Overall outputs of asparagus commercial yield, WSC at the end of harvest and WSC at the end of campaign achieved satisfactory predictive accuracy with overall rRMSE of 16.72 %, 13.46 % and 9.79 % respectively.

3.1.1. Yield prediction

Figure 13(a) summarises the TURION model performance for asparagus yield prediction. The values for observed yields varied from 4 to 13 t ha^{-1}, while those for the simulated yields varied from 5 to 11 t ha^{-1}. Campaigns from Trujillo-summer showed the lowest yield values with a rRMSE of 14.47 %. Harvest in Nazca-winter had the highest rRMSE 23.14 % showing less accuracy. The overall accuracy achieved a rRMSE of 16.72 % for asparagus yield predictions (See Table 2). In general, winter campaigns showed more dispersed predictions. It could be caused by the lack of field data as the physiological evaluation were made during summer campaigns. The simulation of the number of spears produced by plant and their weight followed the same tendency of the reported data. Number of spears per plant vary from 10 to 20 with 200–400 g. Campaigns from Nazca-summer had the highest spears production with 30–60 spears per linear meter during a completed harvest time. Asparagus plants are affected by environmental conditions such as the air temperature, hence these results confirm the differences between regions and seasons for spear production.

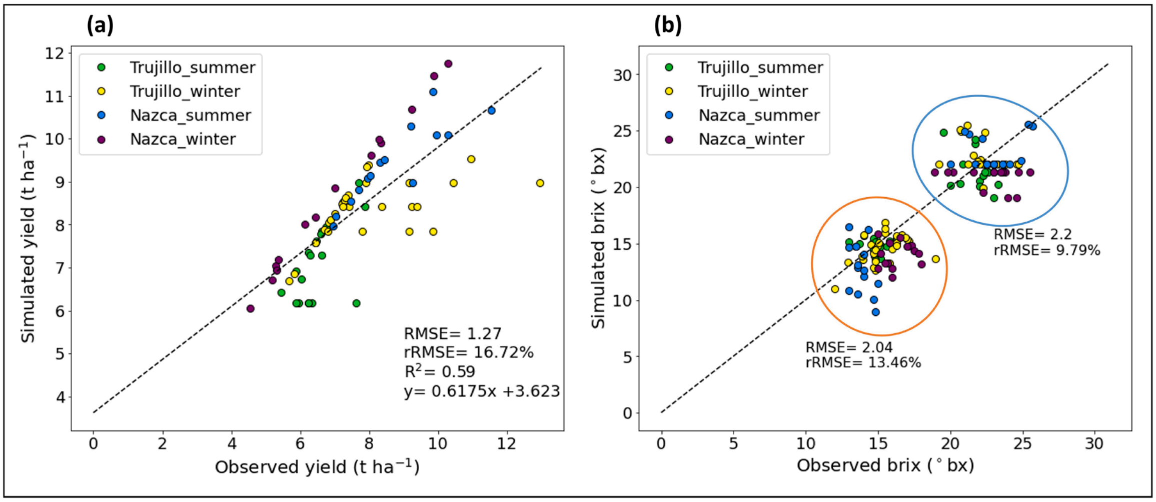

Figure 13. Results simulated versus observed data after parameterisation of TURION crop model. (a) Yield comparison: Dotted line represents perfect linear prediction; Some Trujillo plots were under predicted and some Nazca plots were over predicted. (b) CHO prediction in root storage and the of harvest (orange circle) and at the end of the campaign (blue circle).

3.1.2. WSC prediction

Simulated brix values at the end of harvest (CHOendH) from Fig. 13 (b) ranged from 8.97˚Bx to 17.25˚Bx and observed CHOendH values ranged from 12˚Bx to 19˚Bx. CHOendH simulations of campaigns from Nazca-summer presented mayor variability and hence the biggest rRMSE with 20.09 %. However, campaigns from Trujillo-summer (such as for yield predictions) had the best fit with the lowest RMSE of 1.1 and rRMSE of 7.50 %, resulting in an overall accuracy with a rRMSE of 1.92 % for CHOendH predictions. Simulated brix values at the end of campaign (CHOendC) ranged from 19.4˚Bx to 24.78˚Bx and observed CHOendH values ranged from 18.9˚Bx to 25.7˚Bx. It can be seen in this case that simulations of campaigns from Nazca-winter presented mayor variability and the biggest rRMSE with 13.02 %. However, campaigns from Trujillo-winter had the best fit with the lowest rRMSE of 1.76%. The overall accuracy achieved a rRMSE of 9.79 % for CHOendC predictions, giving an appropriate value to initiate the next harvest. In general, the predicted values follow the optimal range at the end of the campaign (> 20˚Bx), end of the harvest (> 12˚Bx) and stem established (> 7˚Bx). However, predicted and field values are not the same, indicating that although the TURION model is accurately making predictions, it is not over-fitting to produce identical values as the field data can be affected by agronomical decisions which were not considered in this physiological model.

4. Discussion

4.1. Yield prediction

TURION is a simple mechanistic model based on physiological parameters. Although, the previous and the only one asparagus crop model (ASPIRE) (Wilson et al., 1999) presented a RMSE of 0.39 cm there was not a direct comparison among TURION and ASPIRE to predict asparagus yield using the Peruvian data as there was not a ASPIRE code available. However, TURION rRMSE 16.72% was similar to STICS model 16.89 % and AquaCrop 17.84 %, higher than SIMPLE-cacao 7.2 % (Romero Vergel et al., 2022) and lower than those presented in others CSM such as SIMPLE 24.4 % (Zhao et al., 2019), SUBSTOR-potato 21.4 % (Raymundo et al., 2017), DSSAT 29.29 %, CropSyst 19.27 % and WOFOST 25.85 % (Confalonieri et al., 2016). Simulation results presented in this research are coincident with the number of spears produced by plant in field. Data frarm reported 50 spears per linear meter (three plants per m) during the harvest stage. Even though there was a not a proper experiment to know how many spears growth per plant during harvest.

4.2. Thermal time and growth rate

This study defined the temperature-dependent growth rate of asparagus, using two values of T_b following the studies of (Wilson et al., 1999, Wilson et al., 2002). The optimum temperature for asparagus growth is 20 ˚C (Yen et al., 1996) and its growth rate increase up 35 ˚C (Hills, 1986; Watanabe et al., 2019). The growth rate found in Peru showed 3–4 cm day^{-1} the first day after emergence and 10 cm day^{-1} at second day after emergence of spears over the soil surface. Similar values of asparagus growth were reported by Krarup et al. (1997) where spears presented elongation rates of 5.6, 7.4, and 7.7 cm day^{-1}, in shoots longer than 10 cm, with associated temperatures average of 15.5, 16.6, and 19.8 ˚C, respectively. These temperatures are found in Peru during "winter" periods. Growth rates of daily elongation of asparagus shoots increase between minimum temperatures 7–10˚C to maximum of 25–30˚C and when the shoot is longer (Castagnino et al., 2006). Spear growth rates over 34 ˚C was significantly low (Watanabe et al., 2019). Moreover, traditional knowledge of producers from Peru stated that when Tmin values were under 12 ˚C the spear production is significant less compare days with higher Tmin. However, there are no field data or experiments to determine the T_b for asparagus growing in Peru, where there is no winter dormancy and low temperatures are usually above the thresholds of thermal time (7.1 ˚C) (Wilson et al., 1999, Wilson et al., 2002) used for the winter dormant crop in New Zeland and Europe. That is why, these relationships needed to be reconsidered for modelling spear and stems growth in TURION model.

4.3. LAI for WSC balance in roots

This study determined LAI across the Peruvian asparagus crop cycle. TURION uses LAI values for CHO production by photosynthesis. These results are coincident with Guo et al. (2002), showing the current photosynthesis will directly provide CHO to spear yield during a campaign. Results determined LAI values will decrease after flowering. Faville et al. (1999) hence that CHO production decreases over time trough canopy maturation. This crop timing was clearly identified using S1 data which is coincident with (Silva-Perez et al., 2020). However LAI values identification by S1 was not possible with the field data available in this research. Instead, LAI can be identified with optical sensors and reflectance data (Romero et al., 2017). LAI should ideally be measured multiple times during the course of a campaign. Asparagus LAI measurement are not only related with sun light intercepted but also to the canopy morphology, where only a limited number of cladodes are exposed to full sun conditions at any time during the day to from CHO (Drost, 1997). A wide range of complex carbohydrates can be stored in the vacuoles (Cairns, 1992). CHO composition may vary depending on the time of the year and features of roots sampled (Cairns, 1992). Thus, seasonally, the formed assimilates are mainly translocated into storage vacuoles of roots (Downton and Torokfalvy, 1975), where can be utilized for spear growth during the harvest.

5. Conclusion

This research developed the TURION crop model for asparagus growth simulation, yield prediction and carbohydrate changes in roots under Latin American conditions. This research showed an option to link CSM with information available from Sentinel-1, to improve prediction of asparagus crop performance. Based on parametrisation and validation results, it is possible to conclude that asparagus production in Peru can be simulated with accuracy using crop modelling techniques and sentinel-1 data for yield predictions. The way to parameterise TURION crop model successfully depended on the clear understanding of Aspire model equations for annual crop cycles and plant physiology processes characterisation in field. The results identified two main differences between TURION and Aspire: crown depth In Peru is 9 –10cm instead 15 cm as Apire stated; thermal time to grow spears starts counting from the first day of the crop cycle because the daily mean temperatures in Peru are always higher than 7 ˚C whereas Aspire needs seven consecutive days with temperatures higher than 7.1˚C before for spears to start growing. Therefore, physiological parameters such as growth rate, thermal time per phenological stages, biomass partition and LAI across the crop cycle were determined in this study for the first time for asparagus planted in two regions of Peru. Further studies are needed to improve the physiology description of asparagus plants and to find better links between Sentinel-1 data and LAI values. Field data availability, cooperation of the producers and field works were extremely important to understand the crop development and agronomical management under Peruvian conditions.

Data availability and source code

Complementary data can be found in the Docotral thesis "Crop modelling and remote sensing for yield predictions of asparagus cultivated in Peru". It can be consulted at Abersytwtyh University repositories. The final code version of TURION model was written in Python using Pandas (McKinney, 2010), Python Math (Van Rossum, 2017) and NumPy (Oliphant, 2006). A copy of TURION model is deposited at https://github.com/angeromerov/asparagusPeru_crop_model.git. Software will be provided under user request. The data used in this study can be found in the research data repository as follow:

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- Project name: asparagusPeru_crop_model.
- Project home page: https://github.com/angeromerov/asparagusPeru_crop_model.git.
- Operating system(s): Platform independent.
- Programming language: Python.
- Other requirements: Microsoft word, python libraries (pandas, numpy, math, matplotlib).
- License: GNU

Author contributions

A.P.R.V. was primarily responsible for writing this manuscript, data collection, python code development, parameterisation and model validation.

Table 3
Parameter values and variables used in TURION crop model.

No	Symbol	Name	Value	Unit
1	fdw	Conversion factor of spear freshW to dryW	0.0829	g
2	fdw	Conversion factor of stem freshW to dryW	0.18	g
3 *		Biosynthetic efficiency for spear dry mass	0.7	g gCHO^{-1}
4	fwm	Factor to convert volume to fresh mass	0.89	g per ml
5	L0	Initial spear length	1.0	cm
6	c	constant for growth rate equation	0.0179	no units
7	e	Euler number	2.7183	no units
8 *	RUE	Biosynthetic efficiency of solar radiation	1.5	g MJ-1
9	De	Effective depth of crown	8.0	cm
10	Dc	Actual depth of crown	9	cm
11 *		CHO to grow new structural roots	10	%
12	losesY	Losses of spear production	15	%
13	losesR	Losses by respiration processes	25	%
14 *		CHO translocated	90	%
15 *		Root biomass	750	g plant^{-1}
16	tt	Thermal time	variable	˚C day
17	NumberS	Number of spears or stem plant	variable	shoots plant^{-1}
18	vol	Volume	variable	ml
19	dryW	Dry mass	variable	g
20	Yprod	Potential yield	variable	kg ha^{-1}
21	YprodOK	Yield after losses	variable	kg ha^{-1}
22	CHOstart	Carbohydrate content initial	variable	g
23	CHOused	Carbohydrate used form roots storage	variable	g
24	CHOendH	Carbohydrates at the end of harvest	variable	˚Bx
25	CHOmin	Carbohydrates at stem establishment	variable	˚Bx
26	CHOendC	Carbohydrates at the end of campaign	variable	˚Bx
27	LAI	Leaf area index	variable	no units

Values for asparagus cultivar UC157. freshW = fresh weight. dryW = dry weight. *Parameters No 3, 8, 11, 14 and 15 were taken from Penning De Vries et al. (Penning De Vries et al., 1974), Wilson et al. (Wilson et al., 2002), (Wilson et al., 2005)

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

A very special thank you to the founder of this Ph.D. research the UK Space Agency (UKSA) from United Kingdom (ID grant: EO4cultivar), and Environment Systems Ltd for creating links with key partners in Peru and led the EO4cultivar project under the International Partnership Programme (IPP). Special dose of gratitude to the supervisors of this research Prof. John Doonan and Mr Alan Gay from the National Plant Phenomics Centre in Abersytwyth University. Thanks to Cristian Silva from Stirling University for his guidance in downloading S1 signals. I extend my special thanks to the asparagus growers Ing. Maria Suarez from Ginobeto farm, Liliana Guiop from Barfoots in Nazca, Ing. Luis Jose Diaz Lopez and Raul Saldaña from Danper in Trujillo and all engineers, staff and agronomists in Peru for their kind cooperation, patience and availability during the data collection.

Appendix A. Parameters of TURION crop model

Table 3.

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