Identifying Key Crop Traits for Improving Wheat–Faba Bean Intercropping Productivity Using Growth Models

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[3]Apollo Hospitals, Hyderabad, IndiaSupplementary materialSupplementary text S1: Determination of the fraction of intercepted radiation in homogeneously mixed monocrops, monocrops sown in rows, and intercrops in strips

Introduction

The aim of this appendix is to derive the fraction of radiation interception at time t, $f_{\mathrm{int,i}}(t)$, appearing in equations 4 and 7 in the main text. The model that was used in this study largely follows that of Gou *et al.* (2017a) for radiation interception of strip intercrops. The only difference between the model from Gou *et al.* (2017a) and the radiation interception model in M^3 is that the latter one does not consider light interception by storage organs. A strip is defined as one or more consecutive rows of one species that is not interrupted by rows of another species. The aim of this section is to describe the derivation of this model.

The model from Gou *et al.* (2017a) was developed for monocrops and for intercrops of two species and implicitly assumes that the canopy of both species can be described by linear leaf area density functions. M^3 adopts the same assumption. If one wants to change this assumption in M^3, new terms for $f_{\mathrm{int,i}}(t)$ should be derived and implemented in the source code. Given this assumption, the fraction of radiation interception of a crop species i in a homogeneously sown monocrop can be calculated by applying Beer's law. It assumes that the intensity of transmitted radiation within a canopy decreases linearly with leaf area index (Monsi & Saeki, 1953). The fraction of intercepted radiation at time t can be then calculated as:

$$f_{\mathrm{h}}(t) = \mathrm{e}^{-k_{\mathrm{i}} \cdot L(t)} \qquad \text{(S1.1)}$$

where k_{i} is the extinction coefficient of species i.

Mathematical description of the spatial structure of the strip intercrop

M^3 describes the strip intercrop as a mixture of two species, 1 and 2, of width ℓ_1 and ℓ_2 (m) respectively. The heights of the strips at a certain time t are $H_1(t)$ and $H_2(t)$. At each time t, the model checks which of the two species is the highest. The height of the tallest species is $H_{\mathrm{t}}(t)$ and the height of the shortest species is $H_{\mathrm{s}}(t)$. If both species have the same height, $H_{\mathrm{t}}(t)$ is the height of species 1 and $H_{\mathrm{s}}(t)$ is the height of species 2:

$$H_{\mathrm{t}}(t) = \begin{cases} H_1(t) & | \quad H_1(t) \geq H_2(t) \\ H_2(t) & | \quad H_1(t) < H_2(t) \end{cases} \tag{S1.2}$$

$$H_{\mathrm{s}}(t) = \begin{cases} H_1(t) & | \quad H_1(t) < H_2(t) \\ H_2(t) & | \quad H_1(t) \geq H_2(t) \end{cases} \tag{S1.3}$$

Similarly, M^3 defines the width of the strip that contains the tallest crop species $\ell_{\mathrm{t}}(t)$ and the width of the strip that contains shortest crop species $\ell_{\mathrm{t}}(t)$.

$$\ell_{\mathrm{t}}(t) = \begin{cases} \ell_1 & | \quad H_1(t) \geq H_2(t) \\ \ell_2 & | \quad H_1(t) < H_2(t) \end{cases} \tag{S1.4}$$

$$\ell_{\mathrm{s}}(t) = \begin{cases} \ell_1 & | \quad H_1(t) < H_2(t) \\ \ell_2 & | \quad H_1(t) \geq H_2(t) \end{cases} \tag{S1.5}$$

Note that $\ell_{\mathrm{t}}(t)$ and $\ell_{\mathrm{s}}(t)$ are, unlike ℓ_1 and ℓ_2, time dependent, because the identity of the tallest species can change during the growing season. M^3 subdivides the canopy of the taller species in two parts. The lower part has the height of the shorter species. The depth of the upper part of the canopy of the tallest species, $H_{\mathrm{t,u}}(t)$, is calculated as:

$$H_{\mathrm{t,u}}(t) = H_{\mathrm{t}}(t) - H_{\mathrm{s}}(t) \tag{S1.6}$$

Finally, the leaf area index of the tallest crop species is also subdivided into the part of the leaf area index that occupies the upper part of the canopy $L_{\mathrm{t,u}}(t)$ and the part that occupies the lower part of the canopy $L_{\mathrm{t,l}}(t)$:

$$L_{\mathrm{t,u}}(t) = \begin{cases} \dfrac{H_{\mathrm{t,u}}(t)}{H_{\mathrm{t}}(t)} \cdot L_1(t) & | \quad H_1(t) \geq H_2(t) \\ \dfrac{H_{\mathrm{t,u}}(t)}{H_{\mathrm{t}}(t)} \cdot L_2(t) & | \quad H_1(t) < H_2(t) \end{cases} \tag{S1.7}$$

$$L_{\mathrm{t,l}}(t) = \begin{cases} \dfrac{H_{\mathrm{s}}(t)}{H_{\mathrm{t}}(t)} \cdot L_1(t) & | \quad H_1(t) \geq H_2(t) \\ \dfrac{H_{\mathrm{t}}(t)}{H_{\mathrm{s}}(t)} \cdot L_2(t) & | \quad H_1(t) < H_2(t) \end{cases} \tag{S1.8}$$

The leaf area index of the shorter crop is:

$$L_{\mathrm{s}}(t) = \begin{cases} L_1(t) & | \quad H_1(t) < H_2(t) \\ L_2(t) & | \quad H_1(t) \geq H_2(t) \end{cases} \tag{S1.9}$$

The extinction coefficients of the shortest crop $k_{\mathrm{s}}(t)$ and the tallest crop $k_{\mathrm{t}}(t)$ are

$$k_{\mathrm{t}}(t) = \begin{cases} k_1 & | \quad H_1(t) \geq H_2(t) \\ k_2 & | \quad H_1(t) < H_2(t) \end{cases} \tag{S1.10}$$

$$k_{\mathrm{s}}(t) = \begin{cases} k_1 & | \quad H_1(t) < H_2(t) \\ k_2 & | \quad H_1(t) \geq H_2(t) \end{cases} \tag{S1.11}$$

Calculation of the fraction of global radiation intercepted by different parts of the canopy

The length and the width of the field are assumed to be much larger than both the height of the crops and the width of the strip and is assumed to be homogeneous. This assumption allows M^3 to ignore effects at the edges of the field. M^3 assumes that the strips can be modelled as cuboids with heights $H_{\mathrm{s}}(t)$ and $H_{\mathrm{t}}(t)$ with the corresponding strip widths $\ell_{\mathrm{s}}(t)$ and $\ell_{\mathrm{t}}(t)$. It first calculates the fraction $f_{\mathrm{t,u}}(t)$ of the radiation that is intercepted by the upper part of the canopy of the taller crop. Subsequently, it calculates what the fraction $f_{\mathrm{t,l}}(t)$ of radiation is that is intercepted by the lower part of the canopy of the taller crop and the fraction $f_{\mathrm{s}}(t)$ that is intercepted by canopy of the shorter crop. We follow the reasoning from Pronk *et al.* (2003) and Gou *et al.* (2017a) that $f_{\mathrm{t,u}}(t)$ can be calculated as the weighted average between two fractions of light interception by the upper part of canopy of the tallest species in the intercrop in two extreme cases. The first extreme case assumes that the intercrop is homogeneously mixed. The second extreme case is that the intercrop of both species consists of a very wide, single strip; i.e. the canopies of both species are fully compressed. Mathematically, this is formulated as:

$$f_{\mathrm{t,u}}(t) = \big(1 - w(t)\big) \cdot f_{\mathrm{t,u,h}}(t) + w(t) \cdot f_{\mathrm{t,u,c}}(t) \tag{S1.12}$$

where $w(t)$ is a weighing factor between 0 and 1 that quantifies to what extent the intercrop is similar to a compressed intercrop. $f_{\mathrm{t,u,c}}(t)$ is the fraction of radiation that would have been intercepted by a fully compressed upper part of the canopy of the taller crop. $f_{\mathrm{t,u,h}}(t)$ is the fraction of radiation that would have been intercepted by a homogeneously mixed upper part of the canopy of the taller crop. In the next subsections, the derivation of each unknown term in equation S1.12 is explained.

Calculation of the fraction of radiation intercepted by a homogeneous upper canopy of the taller species

The fraction of radiation intercepted by a homogeneous upper canopy of the taller species is calculated as:

$$f_{\mathrm{t,u,h}}(t) = 1 - \mathrm{e}^{-k_{\mathrm{t}}(t)\cdot L_{\mathrm{t,u}}(t)} \tag{S1.13}$$

Calculation of the fraction of radiation intercepted by a fully compressed upper canopy of the taller species

In order to calculate $f_{\mathrm{t,u,c}}(t)$, the compressed leaf area $L_{\mathrm{c,t}}(t)$ has to be determined. This is the leaf area per unit of land covered by the compressed canopy of the taller crop:

$$L_{\mathrm{c,t}} = \frac{\ell_{\mathrm{s}}(t) + \ell_{\mathrm{t}}(t)}{\ell_{\mathrm{t}}(t)} \cdot L_{\mathrm{t}}(t) \tag{S1.14}$$

The part of the leaf area index that is a part of the upper part of the canopy of the taller species, $L_{\mathrm{t,u,c}}(t)$, is calculated as:

$$L_{\mathrm{t,u,c}} = \frac{H_{\mathrm{t,u}}}{H_{\mathrm{t}}(t)} \cdot L_{\mathrm{t,c}} \tag{S1.15}$$

M^3 calculates $f_{\mathrm{t,u,c}}(t)$ as

$$f_{\mathrm{t,u,c}}(t) = \left(1 - \mathrm{e}^{-k_{\mathrm{t}}(t)\cdot L_{\mathrm{c,t}}}\right) \cdot \frac{\ell_{\mathrm{t}}(t)}{\ell_{\mathrm{s}}(t) + \ell_{\mathrm{t}}(t)} \tag{S1.16}$$

Calculation of the weighing factor

M^3 follows the reasoning of Pronk *et al.* (2003) and Gou *et al.* (2017a) that $w(t)$ represents the degree of heterogeneity of the upper part of the canopy of the taller crop. They quantified this degree as the difference between the radiation that is transmitted to the top of the canopy of the shorter crop $f_{\mathrm{trans,s}}(t)$ and the fraction of the radiation that is transmitted to the lower part of the canopy of the taller crop $f_{\mathrm{trans,t}}(t)$. The more similar to a compressed canopy the upper part of the canopy of the taller crop is, the larger the difference $f_{\mathrm{trans,s}}(t) - f_{\mathrm{trans,t}}(t)$ becomes. Therefore, the weight factor $w(t)$ is defined as a function of the difference between $f_{\mathrm{trans,s}}(t)$ and $f_{\mathrm{trans,t}}(t)$. The expression of $w(t)$ must satisfy two conditions. First, $w(t)$ should be equal to 1 in a fully compressed upper part of the canopy of the taller crop. Second, $w(t)$ should be equal to 0 if the upper canopy of the taller crop is homogenous. In order to derive this function, $w(t)$ is rewritten:

$$w(t) = \frac{f_{\mathrm{trans,s}}(t) - f_{\mathrm{trans,t}}(t)}{u_1(t) - u_2(t)} \quad \text{(S1.17)}$$

where $u_1(t)$ and $u_2(t)$ are arbitrary functions. The condition that $w(t) = 0$ in a homogeneous upper part of the canopy of the taller crop is always met, regardless the expressions of $u_1(t)$ and $u_2(t)$, because then $f_{\mathrm{trans,s}}(t) = f_{\mathrm{trans,t}}$ and, consequently, $w(t) = 0$. The condition that $w(t) = 1$, in case of a compressed upper part of the taller canopy, is met if $u_1(t) = f_{\mathrm{trans,s}}(t)$ and $u_2(t) = f_{\mathrm{trans,t}}(t)$. In a compressed canopy, the radiation that reaches the top of the canopy of the shorter crop equals the global radiation. Therefore, $u_1(t) = f_{\mathrm{trans,s}}(t) = 1$ in a fully compressed upper part of the canopy of the tallest crop. Furthermore, the radiation that reaches the top of the canopy of the lower part of the tallest crop is $f_{\mathrm{trans,t}}(t) = \mathrm{e}^{-k_{\mathrm{t}}(t) \cdot L_{\mathrm{t,u,c}}(t)}$. Therefore, $u_2(t) = \mathrm{e}^{-k_{\mathrm{t}}(t) \cdot L_{\mathrm{t,u,c}}(t)}$. Consequently, $w(t)$ can be rewritten as:

$$w(t) = \frac{f_{\mathrm{trans,s}}(t) - f_{\mathrm{trans,t}}(t)}{1 - \mathrm{e}^{-k_{\mathrm{t}}(t) \cdot L_{\mathrm{t,u,c}}(t)}} \quad \text{(S1.18)}$$

Quantification of fractions of radiation transmitted to the top of the canopy of the shortest crop

In order to apply (S1.18), $f_{\mathrm{trans,s}}$ and $f_{\mathrm{trans,t}}(t)$ have to be quantified. M^3 follows Goudriaan (1977), Pronk *et al.* (2003), and Gou *et al.* (2017a), in the calculation of $f_{\mathrm{trans,s}}(t)$. As a first approximation for $f_{\mathrm{trans,s}}(t)$, the view factor of the sky $V_{\mathrm{s}}(t)$ is used. This is $f_{\mathrm{trans,s}}(t)$ in the special case of a black upper part of the canopy of the tallest crop. In this special case, $L_{\mathrm{t,u,c}} = \infty$. This view factor is expressed as (Goudriaan, 1977; Gou *et al.*, 2017a):

$$V_{\mathrm{s}}(t) = \frac{\sqrt{\ell_{\mathrm{s}}(t)^2 + H_{\mathrm{t,u}}(t)^2} - H_{\mathrm{t,u}}(t)}{\ell_{\mathrm{s}}(t)} \tag{S1.19}$$

However, $V_{\mathrm{s}}(t)$ would underestimate $f_{\mathrm{trans,s}}(t)$, because $L_{\mathrm{t,u,c}}$ is in reality finite. It does therefore not include the fraction of the global radiation that i transmitted through canopy of the tallest crop, but is nonetheless reaches to the top of the canopy of the shortest crop. In order to compensate for this, we adopt an important assumption that has neither been mentioned by Pronk *et al.* (2003), nor by Gou *et al.* (2017a), and Gou *et al.* (2017b), but is nevertheless implicit in their models. This is the assumption that the fraction of radiation that passes the strips of the upper part of the canopy of the taller crop and is transmitted to the top of the canopy of the shorter crop equals $f_{\mathrm{trans,u,h}}(t)$ (Goudriaan, 2016). This is the fraction that would have been transmitted by a homogeneous upper part of the canopy of the taller crop. $f_{\mathrm{trans,s}}$ is the sum of two distinct fractions of the global radiations. The first one is the fraction of the global radiation that is directly transmitted to the top of the canopy of the shorter crop ($V_{\mathrm{s}}(t)$) without passing the upper part of canopy the tallest crop. The second one is the fraction that is transmitted through the upper part of the canopy of the tallest crop ($1 - V_{\mathrm{s}}(t)$) and ends at the top of the shorter crop ($\mathrm{e}^{-k_{\mathrm{t}}(t) \cdot L_{\mathrm{t,u}}(t)}$):

$$f_{\mathrm{trans,s}}(t) = V_{\mathrm{s}}(t) + \left(1 - V_{\mathrm{s}}(t)\right) \cdot \mathrm{e}^{-k_{\mathrm{t}} \cdot L_{\mathrm{t,u}}(t)} \tag{S1.20}$$

Quantification of fractions of radiation transmitted to the lower part of the canopy of the taller crop

Similarly, a view factor of the sky is defined for the top of the lower part of the canopy of the tallest species, $V_{\mathrm{t}}(t)$:

$$V_{\mathrm{t}}(t) = \frac{\sqrt{\ell_{\mathrm{t}}(t)^2 + H_{\mathrm{t,u}}(t)^2} - H_{\mathrm{t,u}}(t)}{\ell_{\mathrm{t}}(t)} \tag{S1.21}$$

Only the fraction of the radiation that enters the top of the upper canopy of the taller crop ($V_{\mathrm{t}}(t)$ is assumed to reach the top of the lower canopy of the taller crop. Therefore, $f_{\mathrm{trans,t}}(t)$ is calculated as:

$$f_{\mathrm{trans,t}}(t) = V_{\mathrm{t}} \cdot \mathrm{e}^{-k_{\mathrm{t}}(t) \cdot L_{\mathrm{t,u,c}}(t)} \tag{S1.22}$$

Quantification of fractions of radiation intercepted to the lower part of the canopy of the taller crop

It is assumed that only the radiation that enters the top of the lower part of the canopy of the taller crop $f_{\mathrm{trans,t}}$ can be intercepted by the lower canopy tallest species. Therefore, the fraction of light that is intercepted by the lower part of the canopy of the tallest species is:

$$f_{\mathrm{t,l}}(t) = f_{\mathrm{trans,t}} \cdot \left(1 - \mathrm{e}^{-k_{\mathrm{t}}(t) \cdot L_{\mathrm{t,l,c}}(t)}\right) \cdot \frac{\ell_{\mathrm{t}}(t)}{\ell_{\mathrm{s}}(t) + \ell_{\mathrm{t}}(t)} \tag{S1.23}$$

Quantification of fractions of radiation intercepted by the upper part of the canopy of the taller crop

Since all terms in equation S1.18 have been derived, equation S1.12 can be applied to calculate the fraction of global radiation that is intercepted by the upper part of the tallest crop $f_{\mathrm{t,u}}(t)$.

Derivation fraction of the global radiation that is intercepted by each species

Quantification of the fraction of radiation intercepted by the tallest crop

The fraction of radiation that is intercepted by the tallest crop is the sum of the fractions of the global radiation that is intercepted by the upper part and the lower part of its canopy:

$$f_{\mathrm{t}}(t) = f_{\mathrm{t,u}}(t) + f_{\mathrm{t,l}}(t) \tag{S1.25}$$

Quantification of fractions of radiation intercepted by the shortest crop

It is assumed that only radiation that enters the top of the canopy of the shortest crop, $f_{\mathrm{trans,s}}(t)$, can be intercepted by the shortest species. Therefore, the fraction of radiation that is intercepted by the shorter species is:

$$f_{\mathrm{s}}(t) = f_{\mathrm{trans,s}}(t) \cdot (1 - \mathrm{e}^{-k_{\mathrm{s}}(t) \cdot L_{\mathrm{s,c}}(t)}) \cdot \frac{\ell_{\mathrm{s}}(t)}{\ell_{\mathrm{s}}(t) + \ell_{\mathrm{t}}(t)} \tag{S1.25}$$

Light interception per species in a strip intercrop

Finally, the model determines for species 1 and 2 what their fraction of light interception is:

$$f_{\mathrm{int,1}}(t) = \begin{cases} f_{\mathrm{s}}(t) & | \quad H_1(t) \geq H_2(t) \\ f_{\mathrm{t}}(t) & | \quad H_1(t) < H_2(t) \end{cases} \tag{S1.26}$$

$$f_{\mathrm{int,2}}(t) = \begin{cases} f_{\mathrm{s}}(t) & | \quad H_1(t) < H_2(t) \\ f_{\mathrm{t}}(t) & | \quad H_1(t) \geq H_2(t) \end{cases} \tag{S1.27}$$

Light interception per species in homogeneously mixed intercrop

Although this model is defined for strip intercrops, it can be applied in homogeneously mixed intercrops too. This can be done by assuming strip widths close to zero.

Supplementary tables

Table S1: Management data and phenological observations in faba bean monocrops in experiment 1

	Growing season			
	1985		1986	
Sowing date	[1]		[1]	
Emergence date	April 16		May 1	
Anthesis date	June 13		June 17	
Harvest date	July 29		July 21	
Cultivar	Monica		Monica	
Sowing density	40[2]		40[2]	
	Date	Amount (kg N ha^{-1})	Date	Amount (kg N ha^{-1})
Fertilization	[1]	20	[1]	20

[1] Sowing date was not mentioned by neither Kropff (1989) nor by Boons-Prins *et al.* (1993).

[2] Although the sowing density is unknown, plant density after 100% emergence was reported by Kropff (1989). We assumed that the sowing density equaled this plant density.

[3] Fertilizer was applied at the sowing date, but the sowing date was unknown.

Table S2: Management data and phenological observations in wheat monocrops in experiment 2

	Growing season			
	2013		2014	
Sowing date	March 21		March 13	
Emergence date	April 16		March 29	
Anthesis date	June 26		June 12	
Maturity date	August 5		July 21	
Harvest date	August 20		August 4	
Cultivar	Tybalt		Tybalt	
Initial soil mineral nitrogen (kg N ha^{-1})	18		7	
Sowing density (m^{-2})	250		250	
	Date	Amount (kg N ha^{-1})	Date	Amount (kg N ha^{-1})
Fertilization	April 19	57	April 9	70
	May 30	75	May 9	76
	June 18	27	June 6	26

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Table S3: Management data and phenological observations in wheat monocrops and in wheat-faba bean strip intercrops in experiment 3

	Wheat		Faba bean	
Sowing date	April 1		April 1	
Date first nitrogen fertilization	April 1		April 1	
Emergence date	April 11		April 17	
Anthesis date	June 30		June 3	
Maturity date	August 8		August 14	
Harvest date	August 8		August 14	
Cultivar	Nobless		Fanfare	
	Monocrop	Intercrop	Monocrop	Intercrop
Sowing density	360	360	44	44
Initial soil mineral nitrogen (kg N ha^{-1} land occupied by this species)	18	18	18	18
Amount of N applied in first fertilization (kg N ha^{-1} land occupied by this species)	80	80	20	20
Amount of N applied in second fertilization (kg N ha^{-1} land occupied by this species)	45	45	0	0

Supplementary figures

1985

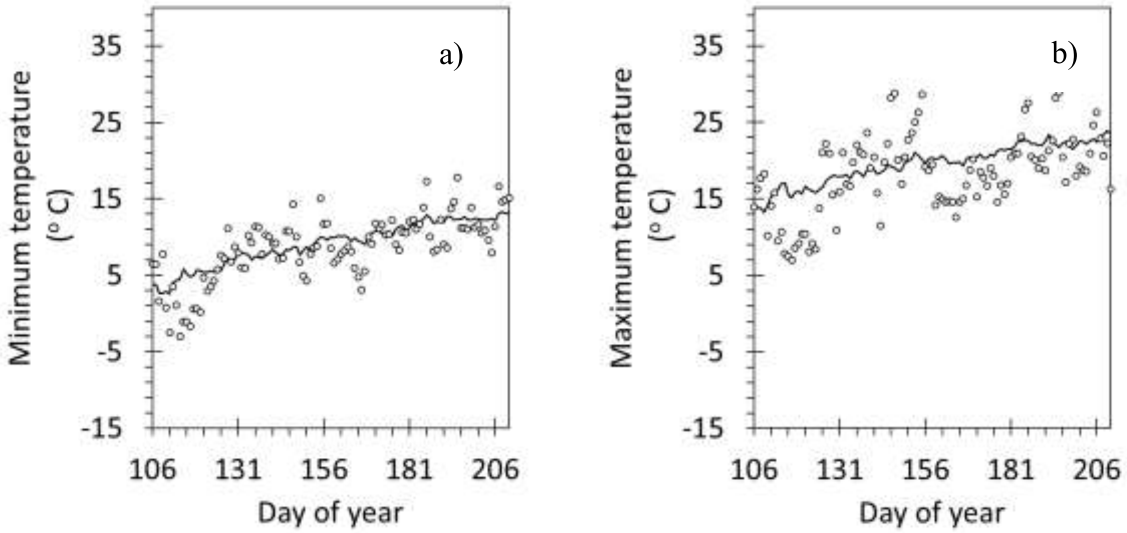


Fig S1: Minimum temperature (a) and maximum temperatures during the field trials of experiment 1 in 1985 in Wageningen, represented by dots. The line represents the average daily minimum (a) and maximum temperature (b) calculated over the period 1978 and 2018 in the same location.

1986

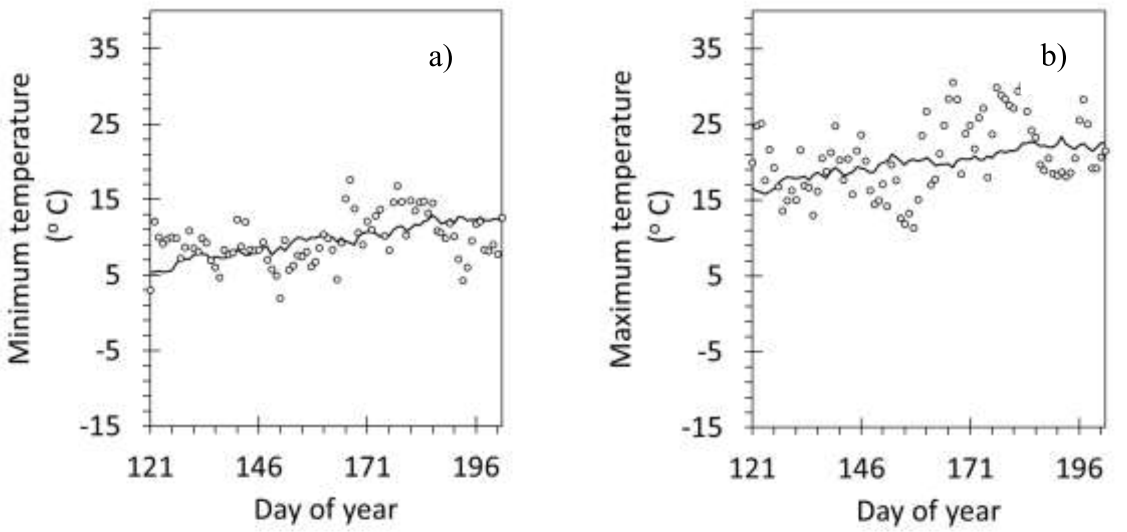


Fig S2: Minimum temperature (a) and maximum temperatures during the field trials of experiment 1 in 1986 in Wageningen, represented by dots. The line represents the average daily minimum (a) and maximum temperature (b) over the period 1978-2018 in the same location.

2013

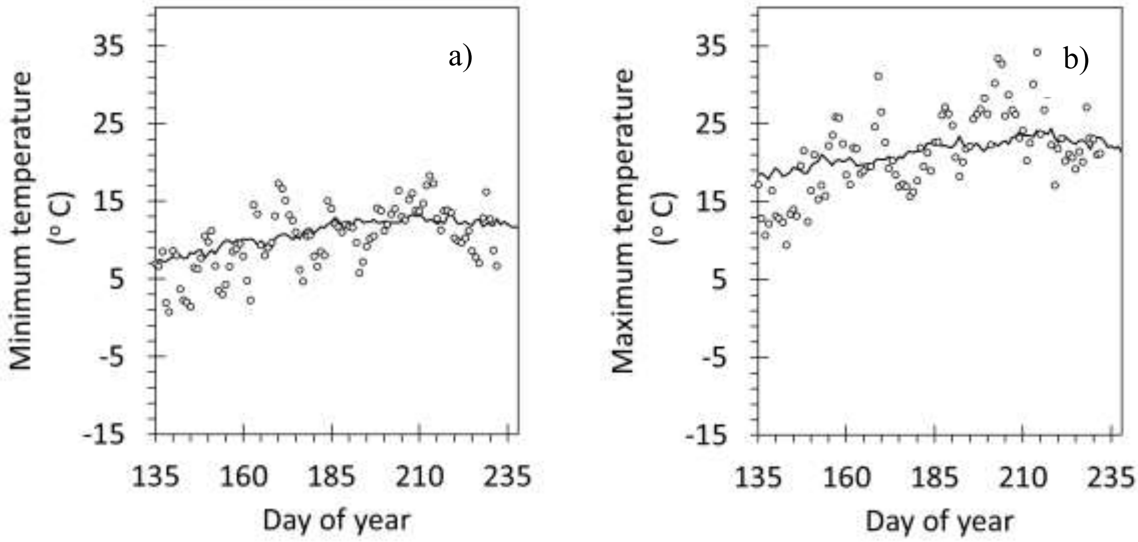


Fig S3: Minimum temperature (a) and maximum temperatures during the field trials of experiment 2 in 2013 in Wageningen, represented by dots. The line represents the average daily minimum (a) and maximum temperature (b) over the period 1978-2018 in the same location.

2014

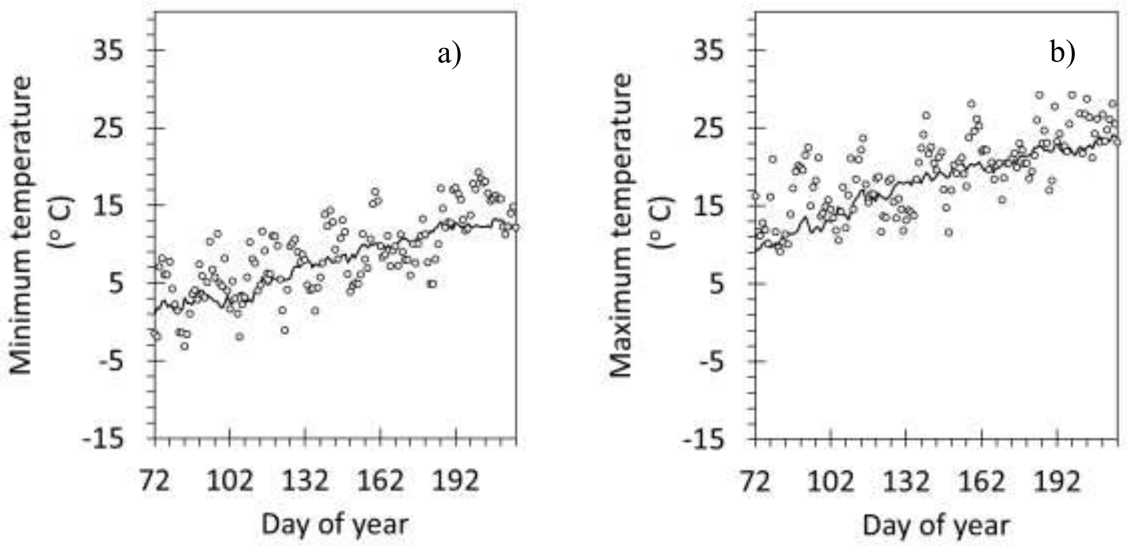


Fig S4: Minimum temperature (a) and maximum temperatures during the field trials of experiment 2 in 2014 in Wageningen, represented by dots. The line represents the average daily minimum (a) and maximum temperature (b) over the period 1978-2018 in the same location.

2019

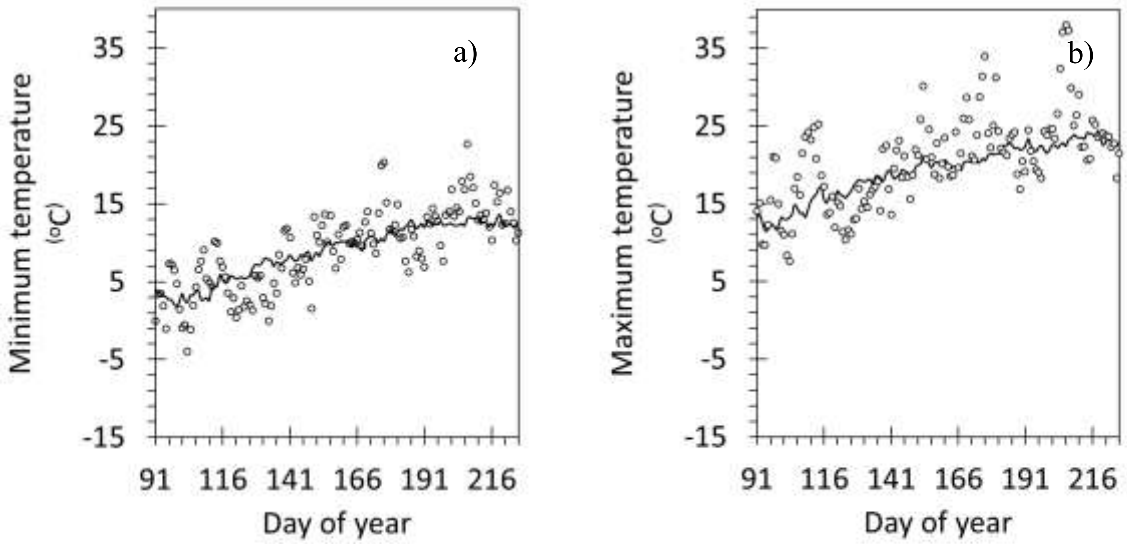
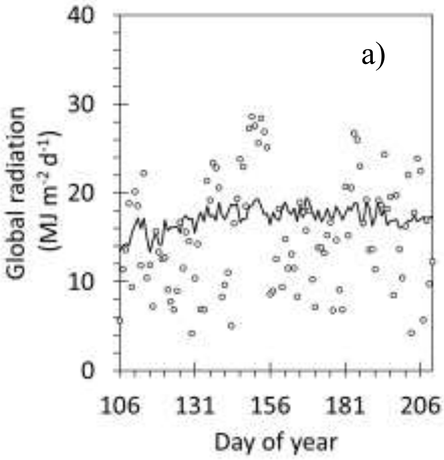
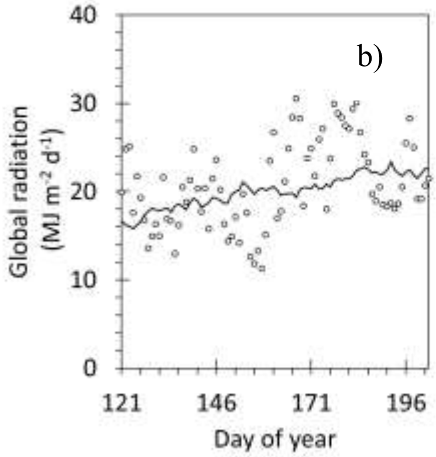


Fig S5: Minimum temperature (a) and maximum temperatures during the field trials of experiment 3 in 2019 in Wageningen, represented by dots. The line represents the average daily minimum (a) and maximum temperature (b) over the period 1978-2018 in the same location.

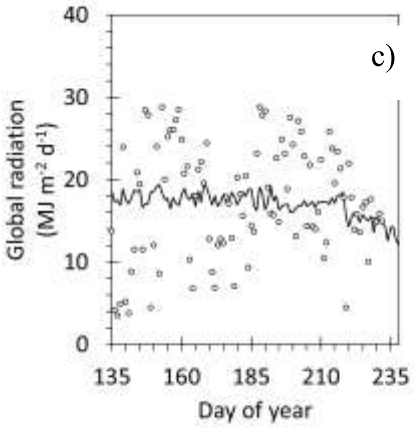
1985



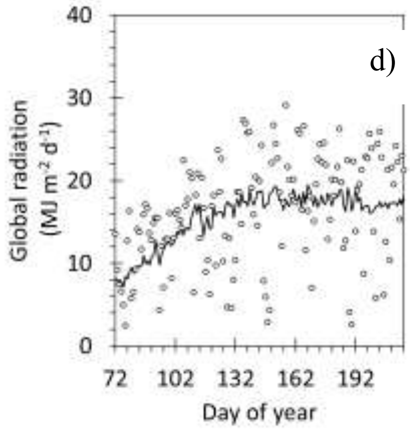
1986



2013



2014



2019

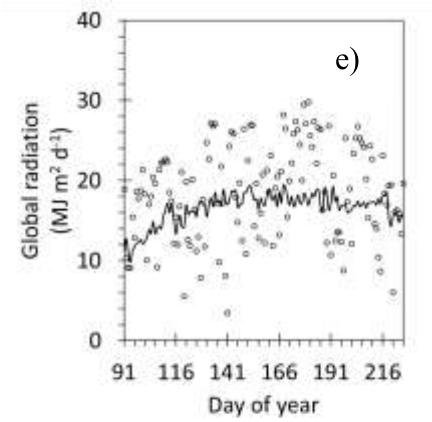


Fig S7: Global radiation during the field trials of experiment 1 in 1985 (a), 1986 (b), of experiment 2 in 2013 (c) and 2014 (d), and of experiment 3 in 2019 (e). The line represents the daily average over the period 1978-2018 in the same location.