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The potential of strip cropping to suppress potato late blight

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ABSTRACT

Context: Crop diversification through intercropping is known to suppress disease severity and incidence. Strip cropping is an adaptation of intercropping in which strips are made wide enough e.g. 3 m or wider to allow management with tractor-pulled equipment. There is, however, little evidence of the efficacy of disease suppression in strip cropping. Furthermore, it is unclear how and to which extent the choice of companion crop species affects the suppression of diseases.

Objective and Methods: Here we determine how potato late blight, caused by *Phytophthora infestans*, is affected by strip cropping potatoes with three different companion crops: grass, maize or faba bean. Potato late blight severity and tuber yield were determined in field experiments in the Netherlands during three years that differed in both weather conditions and timing of the onset of the epidemic.

Results: Strip cropping with grass or maize lowered disease severity compared with potatoes grown in monoculture. Across the three years, the average severity over the observation period was significantly lower in the strip-crop with grass (0.040) or in the strip-crop with maize (0.053) than in the potato monoculture (0.105). Strip-cropping with faba bean did not significantly reduce the average severity. In 2021 and 2022, strip cropping with grass resulted in the highest potato yields (per m^2 potato area) (25.9 and 38.9 t ha^{-1} potato area in 2021 and 2022, respectively), which was 31–33 % higher than the monoculture (19.8 and 29.2 t ha^{-1}). Despite the observed reduction in disease in potato strip-cropped with maize, it resulted in similar yield per unit area of potato as the monoculture, presumably due to competition for light with the taller maize plants.

Conclusion: Together these results show that strip cropping, when integrated with other control measures, can be used to reduce late blight severity. A short non-competitive companion crop species, grass, was effective in simultaneously reducing late blight and enhancing tuber yield.

1. Introduction

Potato is notorious for its high reliance on fungicides for the control of late blight, caused by *Phytophthora infestans* (Goffart et al., 2022; Yuen, 2021). *P. infestans* is considered the most devastating pathogen in potato (Campos and Ortiz, 2020; Majeed et al., 2017). Leaves, stems and tubers are all susceptible and the disease can spread quickly under suitable conditions (Fry, 2008). In northwestern Europe, where conditions for late blight are often suitable, a suite of measures is taken to combat late blight, including the use of healthy seed, resistant cultivars, and the reduction of primary sources of inoculum (Cooke et al., 2011; Kessel et al., 2018). Despite these measures, potato late blight remains a big stressor for potato production, particularly in organic agriculture (Pacilly et al., 2016; Tamm et al., 2004). The use of resistant cultivars as a control measure remains limited, due to the strong market demand for already established (but susceptible) cultivars (Kessel et al., 2018; Pacilly et al., 2016) and the ability of *P. infestans* to quickly overcome host resistance, which limits the usefulness and reliability of resistance (Fry, 2008; Haas et al., 2009). Therefore, in conventional agriculture, fungicide applications remain an indispensable ingredient of the integrated control toolbox.

Although conventional growers heavily rely on fungicides to prevent and control potato late blight, there are concerns about their use. Challenges are arising concerning fungicide resistance (Brylińska et al., 2016; Fones et al., 2020), environmental sustainability (De Jong and De Snoo, 2002; Nicholson et al., 2024; Sánchez-Bayo, 2011), and human health (Tsalidis, 2022). Reducing the use and risk of chemical pesticides is essential for more sustainable food production and is a key point of

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discussion in agricultural and environmental policies (Finger et al., 2024; Möhring et al., 2020). Furthermore, pesticides have a high economic cost (Guenthner et al., 2001; Haverkort et al., 2008). For instance, for the Netherlands, the economic costs of chemicals to control potato late blight and their application are estimated at €115 million per year, approximately 15 % of the total production value (Haverkort et al., 2008). In organic agriculture, where the use of pesticides is not allowed, diseases can reduce crop yields. For example, in Ireland, unsprayed potatoes had a 23 % (10.1 t/ha) average loss in marketable yield over a 25-year period due to late blight compared to fungicide-treated crops, with yield reductions exceeding 50 % in years in which the disease arrived early in the season (Dowley et al., 2008). Thus, exploring additional methods for the integrated control of *P. infestans* is necessary for both conventional and organic growers.

Farmers are implementing multiple control measures against late blight (such as the ones described above: use of healthy seed, resistant cultivars, and the reduction of primary sources of inoculum), a strategy commonly known as integrated pest management (IPM). An additional component of an IPM approach may be strip cropping. Strip cropping is a form of intercropping (Li et al., 2020b; Vandermeer, 1992), in which multiple crop species are grown in a single field at the same time in alternate, multi-row strips wide enough to be operable using equipment that is currently available on modern mechanized farms (Ditzler et al., 2021; van Oort et al., 2020). In practice, a strip width of 3 m or more is used due to limitations set by available equipment (Ditzler et al., 2021). Some advantages of intercropping, such as overyielding, caused by niche complementarity for resource capture (Li et al., 2020a; Vandermeer, 1992; Yu et al., 2016), are lost when strip width is increased, because the species complementarities that drive some of these advantages depend on the proximity of the different species (van Oort et al., 2020). However, for pathogens that spread over larger distances, some of the key mechanisms that lead to disease suppression by species mixture, such as host dilution and barrier effects (Boudreau, 2013), could still play a role in strip crop systems with wider strips. There is, however, little information on the effectiveness of disease control in strip cropping systems.

The effect of crop diversification, including various forms of intercropping and strip cropping, for the control of potato late blight has been investigated by various researchers, all using different companion crop species and spatial configurations of potato and the companion crop species (Bouws and Finckh, 2008; Ditzler et al., 2021; Garrett et al., 2001; Kassa and Sommartya, 2006; Singh et al., 2015; Traugott et al., 2000; Xiahong et al., 2010). The majority of these studies tested either fully mixed or row intercropping systems, and only two studies were done on strip cropping (Bouws and Finckh, 2008; Ditzler et al., 2021). Xiahong et al. (2010) intercropped 2 rows of potato with 2 rows of maize and found that the average severity of potato late blight decreased by 44 % compared with monocrop controls (from ~36 % in the monocrop across two years to ~18 % severity in the intercrop). Bouws and Finckh (2008), who examined a strip cropping system, found that cropping potato in six meter wide strips with either cereals or a grass-clover mix reduced the disease between 4 % and 20 % compared with potatoes grown in monoculture. They reported an area under the disease progress curve (AUDPC, a quantitative measure of the cumulative disease severity over time) of ~1470 percent-days in the strip-crop and ~1568 percent-days in the potato monoculture, across three years. The two different companion crop species had contrasting results; in one year the lowest disease levels were found in plots with cereals as the companion crop species, whereas in the other year, the reduction was greatest with grass-clover as a companion. Ditzler et al. (2021) also found that *P. infestans* infection scores were consistently lower in the strip-crop than in the potato monoculture across their six year measurement period. While these studies have provided valuable insights, demonstrating the potential of strip cropping in suppressing potato late blight, it is unclear how different companion crop species, especially those of different stature, influence the suppression of *P. infestans* in strip cropping.

The stature of the companion crop likely influences important mechanisms for disease suppression in intercrop systems, such as barrier effects and microclimate alteration (Boudreau, 2013). *P. infestans* primarily spreads through the dispersal of spores. Primary infection sources of *P. infestans*, such as infected seed tubers, unharvested tubers or harvested tubers dumped on refuse piles produce spores that can be dispersed by wind or rain to healthy potato plants (Zwankhuizen et al., 1998). Under conducive conditions, the spores then germinate, infect, and initiate new disease cycles. Disease development during the growing season is influenced by temperature and relative humidity (optimum temperatures between 10 and 27°C and relative humidity > 90 % (Zwankhuizen and Zadoks, 2002)). A tall companion crop species could act as a barrier for the initial spores, and spores produced by the in-field infections, thus limiting spread within the field, whereas a short companion crop species could potentially change the microclimate in the host canopy to be less conducive for infection, lesion growth and sporulation. Both tall and short companions would provide a dilution effect in relation to within field spread of the disease across strips. Experiments comparing the effects of strip cropping with different companion species provide information on which companion species are suitable candidates for further research towards practical implementation

The objective of this study was to investigate the effect of strip cropping potato with companion crop species of different stature on the epidemic development of *P. infestans* and tuber yield. Either grass, faba bean, or maize were chosen as companion crop species, since they are shorter than potato (grass), slightly taller than potato (faba bean), and considerably taller than potato (maize). Strip cropping with maize was chosen because it may lead to more effective disease suppression than with other cereals, such as wheat. Maize is taller and has a less dense stand than wheat and could provide a barrier against incoming spores while still allowing adequate air circulation to enable drying of the potato foliage. Furthermore, earlier work on intercropping potato with maize had shown a clear reduction in disease severity (Xiahong et al., 2010). Strip cropping with grass was chosen, because its low height can facilitate more air movement in the neighboring potato canopy than when potatoes are grown in monoculture. Improved airflow can reduce the relative humidity and shorten the leaf wetness period in the potato canopy, making conditions less conducive for the development of potato late blight. Strip cropping with faba bean was chosen because of its intermediate height between maize and grass. Furthermore, various papers have reported on disease reduction in intercrops with faba bean (Hauggaard-Nielsen et al., 2008; Luo et al., 2021; Zhang et al., 2019).

2. Materials and methods

2.1. Field experiments

Field trials were conducted in 2021, 2022 and 2024 at the organic experimental farm of Wageningen University & Research, located in Wageningen (51.99°N, 5.65°E), The Netherlands. The fields were managed organically; organic fertilizer was used and no pesticides or irrigation (see Supplementary information Table A.1 for detailed information). Soil at the experimental site is a sandy soil.

The summer of 2021 was warm and wet, with average daily temperatures around 18 °C during June and July and a total of 191 mm of rain (Fig. 1). The summer of 2022 was also warm, with the same average daily temperature of around 18 °C during June and July, but it was drier, with a total of 129 mm of rain. Important to note is the high mean temperature of 26.2 °C on 19 July 2022, with a maximum of 36.6 °C measured on that day. This is relevant because the viability of *P. infestans* lesions declines fast at temperatures above 27 °C, and no new sporangia are formed (Minogue and Fry, 1981; Rotem et al., 1970). The summer of 2024 was somewhat cooler with average daily temperatures around 17 °C during June and July and the rainfall was intermediate: a total of 157 mm.

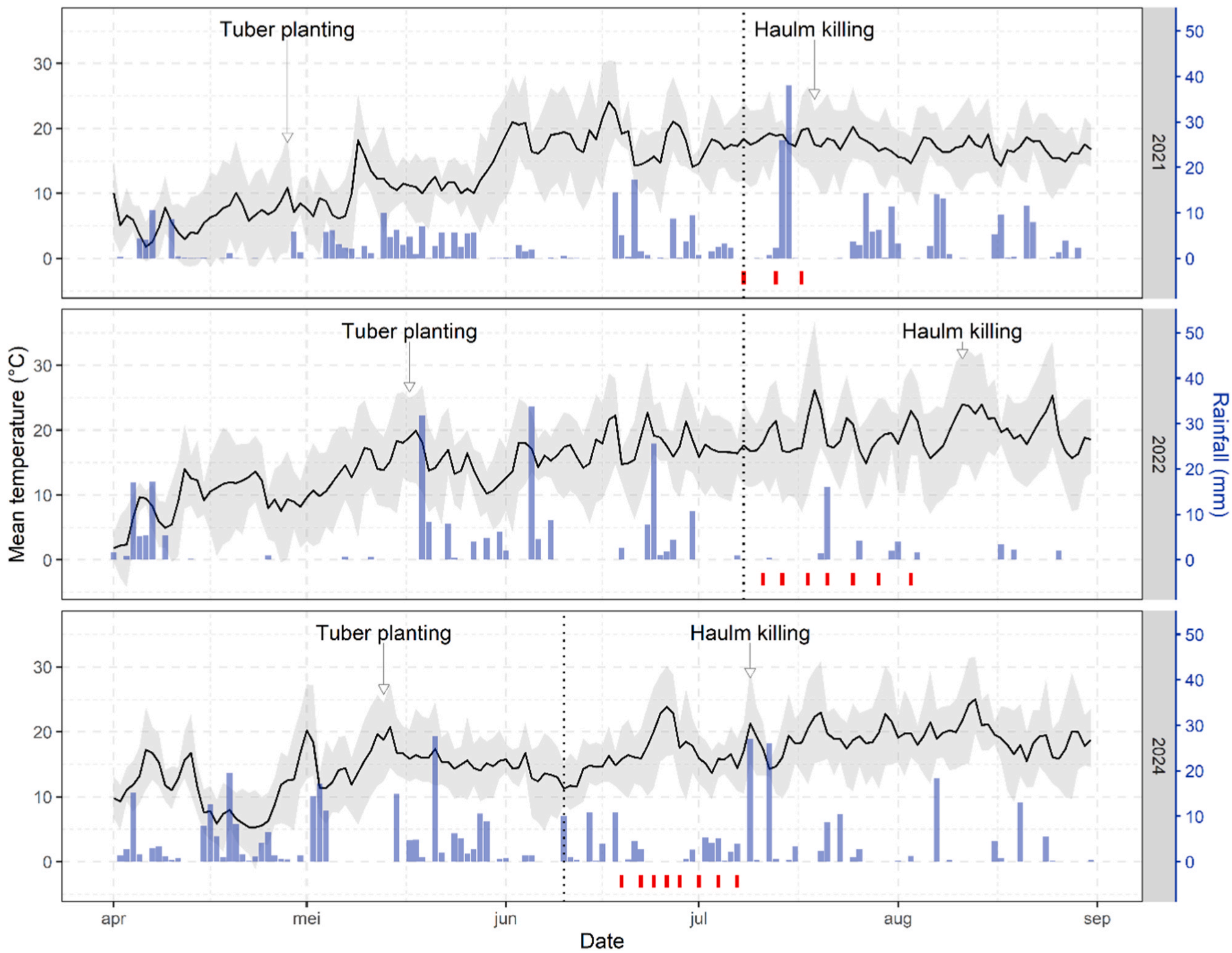

Fig. 1. Weather conditions during the 2021 (top), 2022 (middle) and 2024 (bottom) growing seasons. Red ticks on the x-axis mark late blight assessment dates, vertical dotted lines mark the first detection of late blight in each year. Black lines show mean temperature (degrees Celsius), gray ribbons span daily minimum and maximum temperatures, and blue bars are the total daily precipitation (mm). The dashes on the x-axis indicate the first of each month. Data was obtained from weather station De Veenkampen operated by Wageningen University, located approximately 3 km west of the experimental site.

Although the prevailing wind direction in the Netherlands is from the southwest, the wind direction during June and July was variable in the three years (Supplementary information Fig. A.2).

Three experimental treatments were tested: potato (*Solanum tuberosum* cv. Agria) grown in monoculture, potato strip-cropped with maize (*Zea mays*), and potato strip-cropped with English ryegrass (*Lolium perenne*) (Fig. 2). In 2022 and 2024, a fourth treatment was added: potato strip-cropped with faba bean (*Vicia faba* cv. Cartouche). In 2021, the maize cultivar used was Benedictio, in 2022 a mixture of two maize cultivars was used, namely 73 % autens KWS and 27 % LG30.179. The potato cultivar used (Agria) is moderately susceptible in the foliage and fairly resistant in the tuber to potato late blight (The European Cultivated Potato Database, 2005).

The experiment was laid out as a randomized design with two replicates of each treatment in 2021, four replicates in 2022, and two replicates in 2024, except for the strip-crop with faba bean, which had three replicates in 2024. In 2022, the experiment was split over two sites, with two replicates of each treatment at each site, and an approximate distance of 850 m between the sites. Using two sites in the same year allowed us to explore variability of the treatment effects due to possible differences in e.g., soil humidity or initial inoculum load between the sites. Moreover, it reduced the risks associated with inter-plot interference, which can be substantial with *P. infestans* because of its large and rapidly expanding disease foci. Each strip-crop plot consisted of alternating 3 m-wide strips of the two species (Fig. 2). Strips were planted in an east-west direction, in alignment with the expected prevailing westerly wind direction (See Fig. A.1. for the field arrangement of the plots). Each strip was 3 m wide and consisted of either four rows of potato (row width of 75 cm), four rows of maize, six rows of faba bean, or 20 rows of grass. The monoculture plot had a similar size as the strip-crop plots, but was planted with only potato. Plots were separated by a 6 m strip of grass. Plots measured 21 m × 24 m.

Potato was planted on 28 April 2021, and grass and maize were sown on 7 May 2021. Maize had not reached its final height at the time of the first late blight symptoms in 2021, therefore, to obtain a greater barrier effect in 2022, potatoes were planted later, on 17 May, in 2022. Grass and maize were sown on 29 April 2022 and faba bean was sown on 3 May 2022. In 2024, potato was planted on 13 May, faba bean was sown on 21 March, grass on 29 April, and maize on 2 May.

2.2. Disease assessment

Foliar late blight severity caused by natural infections was assessed in all plots, using three assessment methods: (1) counting the number of leaflets with lesions per plant, (2) estimating the percentage diseased leaf area per plant, and (3) scoring the remaining percentage green leaf area cover shortly before crop desiccation (see below). In the early stages of the epidemic, it was more accurate to count the number of

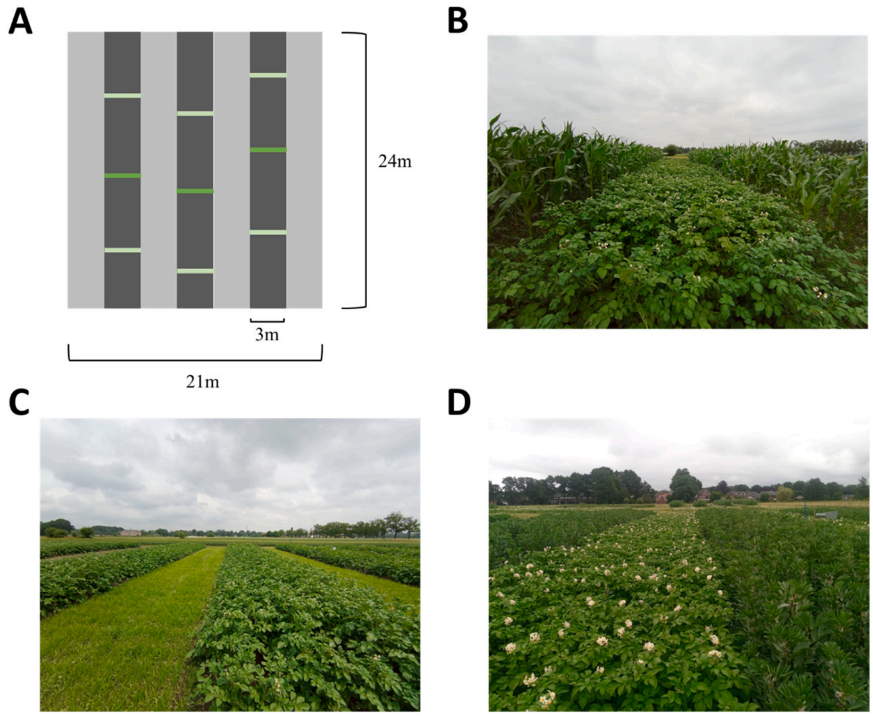

Fig. 2. Schematic arrangement of one experimental strip cropping plot (A), and pictures of potato strip-cropped with maize (photo taken on 16 July 2021) (B), grass (photo taken on 29 June 2021), and (C) faba bean (photo taken on 11 July 2022) (D). Strips of each crop species were 3 m wide, and oriented east-west. The plots had a size of 21 m x 24 m. The dark gray strips in the schematic arrangement represent potato, and the light gray strip either maize, grass or faba bean. The lines perpendicular to the strips represent the transects (consisting of four plants, one per row) on which disease assessments were done. Transects were placed at random locations in each strip. We used three transects per strip in 2021 and two transects per strip in 2022 and 2024.

leaflets with lesions per plant, rather than to estimate a very low percentage of diseased leaf area. As the epidemic progressed, counting the number of diseased leaflets was not possible anymore, due to high disease severity, and only the percentage diseased leaf area per plant was recorded, following the classification scheme of James (1971). We assessed the disease using both methods on 13 July 2021, 14 and 15 July 2022, and 24, 26 and 28 June 2024 and then performed a regression to convert the number of diseased leaflets into a percentage diseased leaf area (see Supplementary information Method A.3). This allowed for the combination of the two assessment methods into a single metric, hereafter referred to as disease severity.

To quantify disease severity, we randomly selected in each of the three potato strips in a plot three transects perpendicular to the strip, with each transect comprising four plants (Fig. 2). This resulted in a total sample of 36 plants per plot for measuring blight severity. In 2021, the first late blight symptoms were observed on 8 July. Assessments were done three times (8, 13 and 17 July) from the moment the epidemic started until the haulm of the potatoes had to be desiccated (19 July) due to late blight severity passing the legal threshold. In 2022 and 2024, we quantified severity on 6 transects per plot (2 per strip), each transect consisting of 4 plants, resulting in a total sample of 24 plants per plot. In 2022, first symptoms were again observed on 8 July, and assessments were made seven times during the epidemic (on 12, 15, 19, 22, 26, 30 July and 4 August at site A, and on 11, 14, 18, 21, 25, 29 July and 3 August at site B). In 2022, the plants were desiccated on 11 August 2022. In 2024, first symptoms were observed on 10 June, and assessments were made eight times during the epidemic (on 19, 22, 24, 26, 28 June and 1, 4, 7 July). In 2024, the plants were desiccated on 9 July. In all cases, desiccation was necessary because of the legal limit to blight severity in the field (Minister van Landbouw, Natuur en Voedselkwaliteit, 2021).

Finally, in all years, a few days before haulm killing (i.e. destruction of the potato foliage (haulm) prior to harvest), the remaining green leaf area cover (%) was assessed across the entire area of each potato plot. Per meter length within a potato row, a score was given from 1 to 5, whereby 1 represents 0–10 % green soil cover, 2 = 10–50 % green, 3 = 50–90 % green, 4 = 90–99 % green, and 5 = between 99 % and 100 % green soil cover (hence note that the numbers inversely indicate percentage diseased leaf area).

2.3. Potato yield

Within each strip-crop plot, potato tubers were harvested from two 1.5 m-long sections in each of the three strips. Thus, per plot 27 m^2 area was harvested (3 $\times$2$\times$1.5 $\times$3 m^2). Tubers were harvested separately for each of the four rows in a strip to quantify border row effects reflecting competition with the companion species (e.g., Gou et al., 2016; Zhang et al., 2007). Likewise, in the monoculture treatment, potatoes were harvested from six 1.5 m-long sections of 4 rows each, also representing a harvest area of 27 m^2 per plot. Fresh weight was converted to tons per hectare potato area (t ha^{-1}) to make the yields in the sole crop and strip crops directly comparable.

2.4. Data analysis

A suite of analysis methods was used to analyse the effects of treatments on disease severity, average disease severity over the observation period, green leaf area cover, and yield. The experimental data from the three years, and two sites in 2022, were analysed together as four site-years (4 levels, 2021, 2022 site A, 2022 site B, and 2024). Furthermore, differences between inner and outer rows of the strips were analysed within treatments. Inner rows are those that have only potato rows as direct neighbors whereas outer rows are those bordering the companion species.

The choice of method was determined by the type and distribution of the data and the way observations were made, taking into account nested observations by using the appropriate random effects (for fitted models see below; Table 1). Models were fitted in R (R Core Team, 2022).

2.4.1. Disease severity

The increase in proportion disease severity ($x(t)$, severity/100) over time was analysed using a beta regression, using the day of the first assessment as t=0 (model 1 and 2, Table 1). To account for the nested structure and the distribution of the data, we used a generalized linear mixed model (GLMM), using the package glmmTMB (Bolker, 2016; Magnusson et al., 2017). We used as random effects site-year, plot, strip and transect (i.e. assessment location within the strip), with transect nested in strip, strip nested in plot, and plot nested in site-year. With these models, we estimate the parameters of the logistic function $x(t) = \frac{1}{1+\left(\frac{1}{x_0}-1\right)*\exp(-r*t)}$, with x_0 the proportion disease severity at the first assessment day, and r the apparent infection rate (i.e. the relative rate of increase in proportion disease severity, day^{-1}). A beta distribution with a logit link was applied to the proportion of the severity data (Table 1). To avoid fitting a beta distribution model to data with zeros (which results in singularities) the observed proportions were linearly transformed according to Maier (2014) and Douma and Weedon (2019):

$$p* = \frac{p(n-1) + \frac{1}{2}}{n}$$

with p being the observed proportions of disease severity, p^* the transformed proportions and n the total number of observations.

As an additional analysis of the late blight epidemic, we calculated the average severity over the measurement period by dividing the area under the disease progress curve (AUDPC) by the duration of the observation period in each year. This metric is also called the standardized AUDPC (sAUDPC; Campbell and Madden, 1990). The period from the first assessment date to the last (in 2022 until the epidemic halted) was taken, resulting in an observation period of 9 days in 2021, 11 days in 2022, and 18 days in 2024. Similar to the analysis of disease severity, a GLMM with beta distribution (with logit link), and a nested random effect was applied to the sAUDPC data (model 3, Table 1).

2.4.2. Green leaf area cover

Final green leaf cover was classified into five classes of cover (see above). The resulting categorical data were analysed using a multinomial mixed-effect logit model. This analysis shows whether a specific green-cover class was more often scored in one treatment compared to another. For this purpose, the function `multinom` in the R package `nnet` was used (Ripley and Venables, 2022). The four site-year combinations were analysed in one model, with the interaction of site-year and treatment as predictor (model 4, Table 1). Plot and strip were defined as random effects, with strip nested in plot. Additionally, we tested whether a shift in the distribution of green cover classes between treatments could be detected by assigning each class a representative value, which was the midpoint of the corresponding percentage range (resulting in class 1 = 5 %, class 2 = 30 %, class 3 = 70 %, class 4 = 94.5 %, and class 5 = 99.5 %). These midpoint values were analysed using a beta regression, including plot as random effect (model 5, Table 1). To account for heteroscedasticity, '*Treatment*' and '*Site_Year*' were added in the *dispformula* argument of the glmmTMB function (Brooks et al., 2017).

2.4.3. Yield

Yield data were analysed with ordinary regression using normal error distribution (models 6, 7, 8, Table 1). Similar to the analysis of disease severity, a nested random effect was added. The normal error assumption was checked by plotting the distribution of residuals. In 2022, the potatoes were harvested at the same location as where the disease assessments were made. For this year, we determined the correlation between proportion disease severity at the last assessment date before haulm killing and yield (model 9, Table 1).

The goodness of the fit of the GLMM to the disease severity assessments (model 1, Table 1) was checked visually. To assess the goodness of the fitted error model, data were generated based on the estimated model parameters (including the θ of the beta distribution), and these generated data were compared to the observations (see Supplementary information Method A.4 for more information). Using a Gompertz distribution for fitting the GLMM did not improve the model fit in terms of AIC, nor did it affect the conclusions about the significant differences between treatments in their estimates. Hence the model with the beta distribution was chosen.

Table 1
Summary of the fitted models to the data. Model 3 is a multinomial mixed effect model, all others are generalized linear mixed models. + means additive effects are assumed, while * means main effects and interactions are estimated. A slash / before a random effect means that it is nested in the preceding random effect to the left of it.

Model #	Response variable	Distribution	Link function	Predictors	Random effects	Dispersion parameter
1	Disease severity	Beta	logit	Treatment * Year * DAFA	Site-year/ plot/strip/ transect	
2	Disease severity in each strip-crop	Beta	logit	Row * Year * DAFA	Site-year/ plot/strip/ transect	
3	sAUDPC	Beta	logit	Treatment + Year	Site-year/ plot/strip/ transect	
4	Green leaf area cover scores	Multinomial	Multinomial logit	Treatment * Site_Year	Plot/strip	
5	Midpoint green leaf classes	Beta	logit	Treatment + Site_Year	Plot	Treatment + Site_Year
6	Yield	Gaussian	-	Treatment * Year	Site-year/ plot/strip/ transect	
7	Yield in the strip-crop with grass	Gaussian	-	Row + Year	Site-year/ plot/strip/ transect	
8	Yield in the strip-crop with maize or faba bean	Gaussian	-	Row * Year	Site-year/ plot/strip/ transect	
9	Yield	Gaussian	-	Disease severity * Treatment	Site-year/ plot/strip/ transect	

Note: *Treatment* in models 1, 3, 4, 5 and 9 is a categorical variable with four levels; monoculture, strip-crop with grass, strip-crop with maize, and strip-crop with faba bean. *Row* represents the position of the rows within the strip, and has two levels, inner and outer (i.e. those in direct contact only with other potato plants, or with both potato and the companion crop). *DAFA* is the time at which disease assessments were made, in days after the first assessment. *Year* is a categorical variable with three levels, 2021, 2022, and 2024.

3. Results

3.1. Disease severity

3.1.1. 2021

The wet conditions in the Netherlands in the summer of 2021 were ideal for the spread of *P. infestans*. Therefore the epidemic during this year spread fast in the potato monoculture, from not diseased on 8 July to on average 50 % disease severity on 17 July, i.e. in less than 10 days (Fig. 3A). On the last assessment day, average disease severity was the lowest in the potatoes that were strip-cropped with grass (23 %, 95 % confidence interval (CI) [10,45]), and highest in the potato monoculture (50 %, 95 % CI [24,76]). While the difference was not significant in 2021, it was similar in magnitude and direction to the significant difference found in 2022 and 2024 (see below). Strip cropping potato with maize resulted in a disease severity of 35 % (95 % CI [16,60]) that was intermediate between the potato-grass and potato monoculture and not significantly different from either. There was substantial variation in disease severity between the two replicates of the grass strip-crop treatment in 2021. One plot had on average only 8 % disease severity whereas the other had 48 % severity on the last measuring day (Fig. 3A).

3.1.2. 2022

In the dry and warm summer of 2022, *P. infestans* did not spread as fast as in the wetter summer of 2021. The epidemic progress was halted around 19 July, when the weather was very hot with maximum temperatures reaching up to 36.6 °C, effectively killing all foliar lesions. After that, the disease did not develop much further, and we therefore present data until this point. The full time series is provided in Supplementary information Fig. A.6. Similar to 2021, average disease severity was lowest in the potatoes strip-cropped with grass before the epidemic halted (13 % (95 % CI [10,17]) at site A and 15 % (95 % CI [12,18]) at site B), which was significantly lower than potato monoculture (23 % (95 % CI [17,30]) at site A and 44 % (95 % CI [38,49]) at site B) (Fig. 3B and C). Maize as a companion crop suppressed potato late blight to a similar extent as grass at both sites (Fig. 3).

At site A, the faba bean did not establish well, presumably due to a soil-borne disease. There was no significant difference in disease severity between the potato strip-cropped with faba bean and sole potato at this site (Fig. 3B). At the other site, faba bean grew normally, and strip cropping with faba bean at site B suppressed potato late blight to a similar extent as maize did (disease severity of 19 % (95 % CI [16,23]) at the last assessment day) (Fig. 3C).

3.1.3. 2024

In 2024, the first symptoms of *P. infestans* occurred very early; only 28 days after planting the first symptoms were observed in the field. Similar to the previous two years, average disease severity was lowest in the potatoes strip-cropped with grass (Fig. 3D). On the last assessment day, average disease severity in the potatoes strip-cropped with grass was 5 % (95 % CI [3,7]), which was significantly lower than the potato monoculture (12 %, 95 % CI [8,16]). The potatoes strip-cropped with maize and faba bean had similar disease severities as the monoculture (12 %, 95 % CI [8,17] and 15 % (95 % CI [11,20], respectively).

No significant difference in disease severity was found between the inner and outer rows of the strip (i.e. those in direct contact only with other potato plants, or with the companion crop species). This applied to all strip-crop treatments in all years.

3.1.4. Disease progress

In 2021, the apparent infection rate (measured as the relative rate of increase in disease severity, ***r*** in Table 2) was significantly lower in potatoes grown with grass or maize than in the monoculture (($P=0.02$ and $P<0.0001$, respectively), Table 2, Fig. 4). In 2022, the apparent infection rates in the three strip-crop treatments were not significantly different from that in the monoculture. Nevertheless, because of a lower

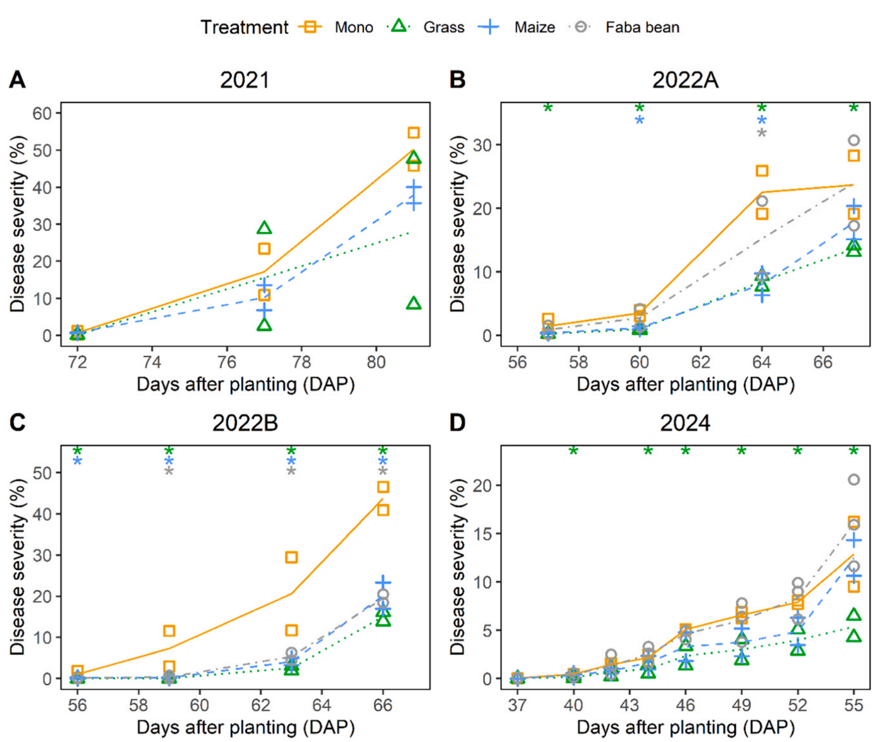

Fig. 3. Disease progress curves for potato late blight on potato in 2021 (A), 2022 at site A (B) and site B (C), and 2024 (D). The points (symbols) represent the mean disease severity per plot based on visual observations on 36 (A), or 24 (B, C and D) plants per plot. The lines are drawn between the midpoints of the two plots for each treatment. □ = potato monoculture; △ = potato strip-cropped with grass; + = potato strip-cropped with maize; ○ = potato strip-cropped with faba bean. Stars indicate a significant difference between the strip-crop and the monoculture on a given day; top asterisk (green) for the strip-crop with grass, middle asterisk (blue) for the strip-crop with maize, and lowest asterisk (gray) for the strip-crop with faba bean.

Table 2
Summary of estimated parameters for logistic fits[a] with beta regression to disease progress curves for the proportion disease severity of potato late blight of potatoes grown in monoculture (Mono), or strip-cropped with grass, maize or faba bean for the 2021, 2022 and 2024 growing season. And the estimated sAUDPC for each treatment across the three years.

Treatment	2021		2022		2024		sAUDPC
	x_0	r	x_0	r	x_0	r	
Mono potato	0.008±0.28ab	0.543±0.011a	0.011±0.21b	0.371±0.007c	0.007±0.29ab	0.171±0.006d	0.105 ± 0.16a
Strip-crop potato-grass	0.004±0.28ab	0.506±0.012b	0.003±0.22a	0.372±0.010c	0.005±0.29ab	0.143±0.007 f	0.040 ± 0.15c
Strip-crop potato-maize	0.007±0.28ab	0.476±0.012b	0.004±0.22a	0.392±0.010c	0.005±0.29ab	0.182±0.006de	0.053 ± 0.15bc
Strip-crop potato-faba bean	-	-	0.005±0.21ab	0.377±0.009c	0.006±0.24ab	0.194±0.005e	0.072 ± 0.17ab

[a]Logistic function $x(t) = \dfrac{1}{1+\left(\dfrac{1}{x_0}-1\right)*\exp(-r*t)}$, with x_0 the proportion of disease severity at the first assessment day, and r the apparent infection rate (day^{-1}).

Letters indicate significant differences for each parameter at P < 0.05.

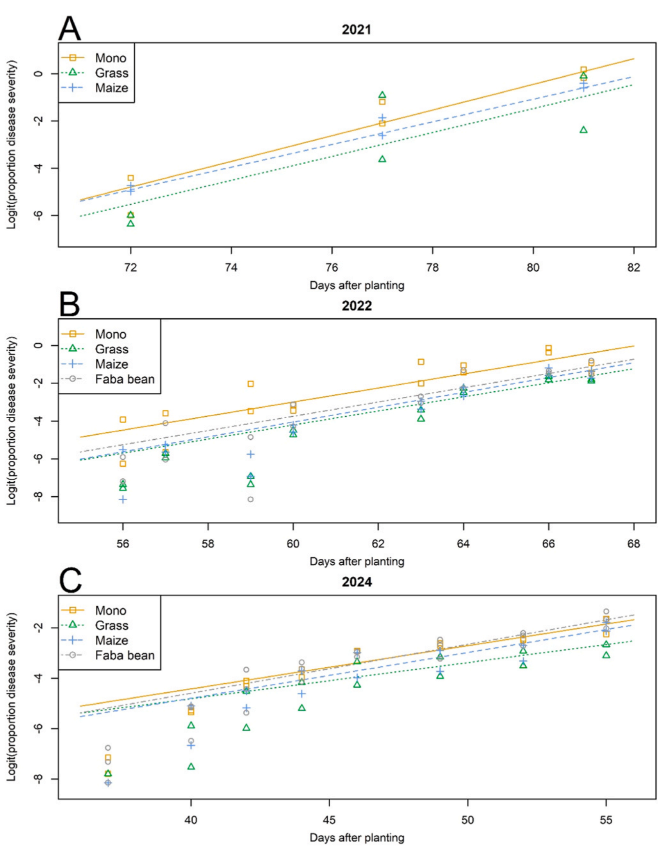

Fig. 4. Estimated logistic disease progress curves for proportion disease severity (plotted on logit scale) during the 2021 (A), 2022 (B) and 2024 (C) growing season for potatoes grown as monoculture (Mono), or as strip-crops with grass, maize, or faba bean. The points (symbols) represent the mean observed proportion leaf area diseased per experimental plot.

initial disease severity, the severity remained lower in the strip-crops compared with the monoculture over the growing season (Fig. 4B). As in 2021, in 2024 the apparent infection rate was significantly lower in the potatoes strip-cropped with grass than in the monoculture (P<0.001). The apparent infection rate was not significantly different between the strip-crop with maize and the monoculture, while potatoes strip-cropped with faba bean had a significantly higher apparent infection rate than the monoculture (P=0.002).

The average proportion severity over the observation period (sAUDPC) was highest in the potato monoculture (0.105), followed by bean (0.072), maize (0.053) and grass (0.040). The sAUDPC of the strip-crop with grass or the strip-crop with maize was significantly lower than the monoculture (P<0.001 for both cases) across the three years (Table 2), but the faba-bean strip crop was not significantly different from the monoculture (P=0.067). There was no significant difference in sAUDPC between the strip-crop with grass and maize, or between the strip-crop with maize and faba bean. The strip-crop with grass had a significantly lower sAUDPC than the strip-crop with faba bean (P=0.006).

3.1.5. Delay in disease progress

From the logistic fits, we calculated the difference in time (in days) that potatoes in strip crops or monoculture reached given proportions of disease severity (Fig. 5). In 2021, the grass strip-crop system reached a severity of 10 % approximately 1.8 days later than the monoculture (Fig. 5A). For this disease level, the strip-crop with maize had a delay of approximately 0.9 days compared with the monoculture. In 2022, the delays were longer; potatoes strip-cropped with grass, maize or faba bean reached 10 % severity approximately 3.2, 2.6 and 1.9 days later, respectively, than the monoculture (Fig. 5B). In 2024, the delay was even longer for potato strip cropped with grass (5.3 days to reach 10 % severity), but the strip-crop with maize or faba bean were less effective (1.2 days delay and 0.6 day advance, respectively) (Fig. 5C).

3.2. Green leaf cover in different treatments before crop termination

We made an assessment of the green leaf cover over the whole plot area at the time of haulm killing, and assessed differences between treatments within each scoring class. The results are in line with the results from the analysis of disease severity. In 2021, lower greenness classes, 1 (0–10 % green) and 2 (10–50 % green), were significantly more frequently observed in the potato monoculture than in the potatoes strip-cropped with grass or maize (Fig. 6A) (P < 0.001 for all class comparisons). This indicates that the monoculture canopy was the least green out of the three treatments. Potatoes that were strip-cropped with grass on the other hand had mostly scores in class 3, 4 and 5, indicating that potatoes strip-cropped with grass had more green leaf cover than potato monocultures.

Likewise, in 2022, potatoes grown in monoculture were mostly scored in the lower greenness classes. The monoculture had a significantly greater proportion of scorings in class 1 than the other treatments at site B, and in class 2 at both sites (Fig. 6B and C) (P < 0.01 for all comparisons). Potatoes strip-cropped with grass were significantly more frequently scored in class 4 (90–99 % green) than the other treatments at site A (Fig. 6B) and class 4 and 5 at site B (Fig. 6C).

In 2024, potatoes strip-cropped with either grass or maize had a significantly higher frequency of scores in class 3 and 4 than the monoculture (P < 0.001 for all comparisons). The monoculture and strip crop with faba bean were more often scored in class 1 or 2 (Fig. 6D). Potatoes strip-cropped with faba bean had a similar green leaf cover as the monoculture indicating this treatment had not controlled late blight.

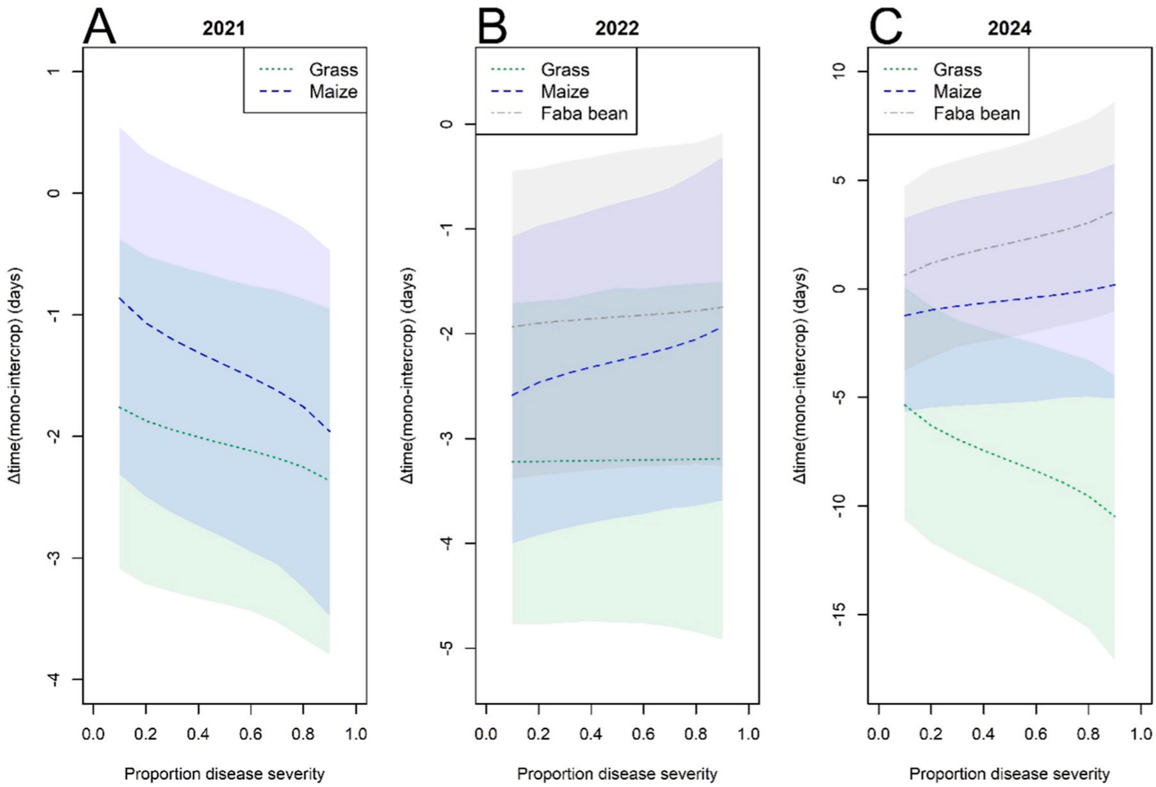

Fig. 5. Estimation of the time difference (in days) between the strip-crop system with grass or maize and the monoculture to reach a proportion disease severity, for the 2021 (A), 2022 (B) and 2024 (C) growing season. Estimation was done using the fitted disease progress curves of potato late blight (Fig. 4). The colored bands around the dotted lines represent the 2.5 % and 97.5 % quantiles, which represent the uncertainty in the delay due to uncertainty in the estimates of x_0 and r (Table 2) (see Supplementary information Method A.5 for more information).

Analysis of the shift in the distribution of all five greenness classes between treatments confirmed that strip cropping with grass significantly shifted towards the higher greenness classes compared with the monoculture across the three years (P < 0.001). In the strip-crop with maize, the distribution was marginally shifted towards the greener classes compared with the monoculture (P = 0.06) The strip-crop with faba bean did not significant shift the distribution (P =0.34).

3.3. Tuber yield

The rapid progression of late blight in 2021, and the early onset of late blight in 2024, shortened the growth duration of potato substantially, which is apparent in the lower yields in these years as compared with 2022 (Fig. 7 A). In 2021 and 2022 potatoes strip-cropped with grass had significantly higher yields per unit potato area (25.9 t ha^{-1} potato area in 2021 and 38.9 t ha^{-1} potato area in 2022) than potatoes grown in monoculture (19.8 and 29.2 t ha^{-1}) (P=0.039 in 2021, and P<0.001 in 2022). In 2024, no significant difference between treatments was found. The maize strip-crop treatment had a similar yield as the monoculture across the three years (Fig. 7 A). In 2022, potatoes strip-cropped with faba bean (34.3 t ha^{-1}) had a significantly higher yield than potatoes grown in monoculture (P=0.014), but in 2024 no differences were found.

The outer rows of the potato strips strip-cropped with grass had on average 1.8 t ha^{-1} higher yield (P=0.02) than the inner rows across the three years (Fig. 7B). For the strip-crop with maize an interaction with year was found. The outer rows had on average 3.4 t ha^{-1} higher yield than the inner rows (P=0.02) in 2021. However, in 2022 and 2024 this was reversed, and the inner rows produced on average 2.9 and 2.4 t ha^{-1} higher yield than the outer rows, respectively (P<0.001 in both cases). The outer rows of the potato strips strip-cropped with faba bean tended to yield slightly higher than the inner rows in 2022 (p=0.06), and tended to yield lower in 2024 (P=0.053) (Fig. 7B).

The yield loss relationship between proportion disease severity and total tuber yield was analysed for the 2022 growing season (Fig. 8). Slopes of the relationship for monoculture and potato/maize strip cropping were both negative, −17.0 and −35.8 t ha^{-1} yield per unit disease severity, respectively, both significantly different from zero, but not significantly different from each other. No significant relationship was found between disease and yield for the strip-crop with grass or the strip-crop with faba bean.

4. Discussion

4.1. Epidemic progress

The main objective of this study was to investigate the effect of strip cropping potato with different companion crop species on epidemic development of *P. infestans*. Three companion crop species, contrasting in stature, were strip-cropped with potato: grass, faba bean or maize. Disease intensity was measured in various ways, and although there was some variation across the three years, together these metrics confirm the disease-suppressive effect of strip cropping with either grass or maize (Table 3). Overall, strip cropping with grass or maize lowered the average severity during the observation period (sAUDPC) across three years, slowed down the epidemic progress (for both grass and maize in 2021, and for grass in 2024) and lowered disease severity at the last assessment day (for both grass and maize in 2022, and for grass in 2024) compared with potatoes grown in monoculture. Furthermore, in each of the three years, the potatoes strip-cropped with grass or maize had more green leaf cover remaining at haulm killing than the monoculture. Out of the three companion crop species, grass was the most effective at suppressing potato late blight (Table 3). Although potatoes strip-cropped with maize had similarly low disease severity as those strip-cropped

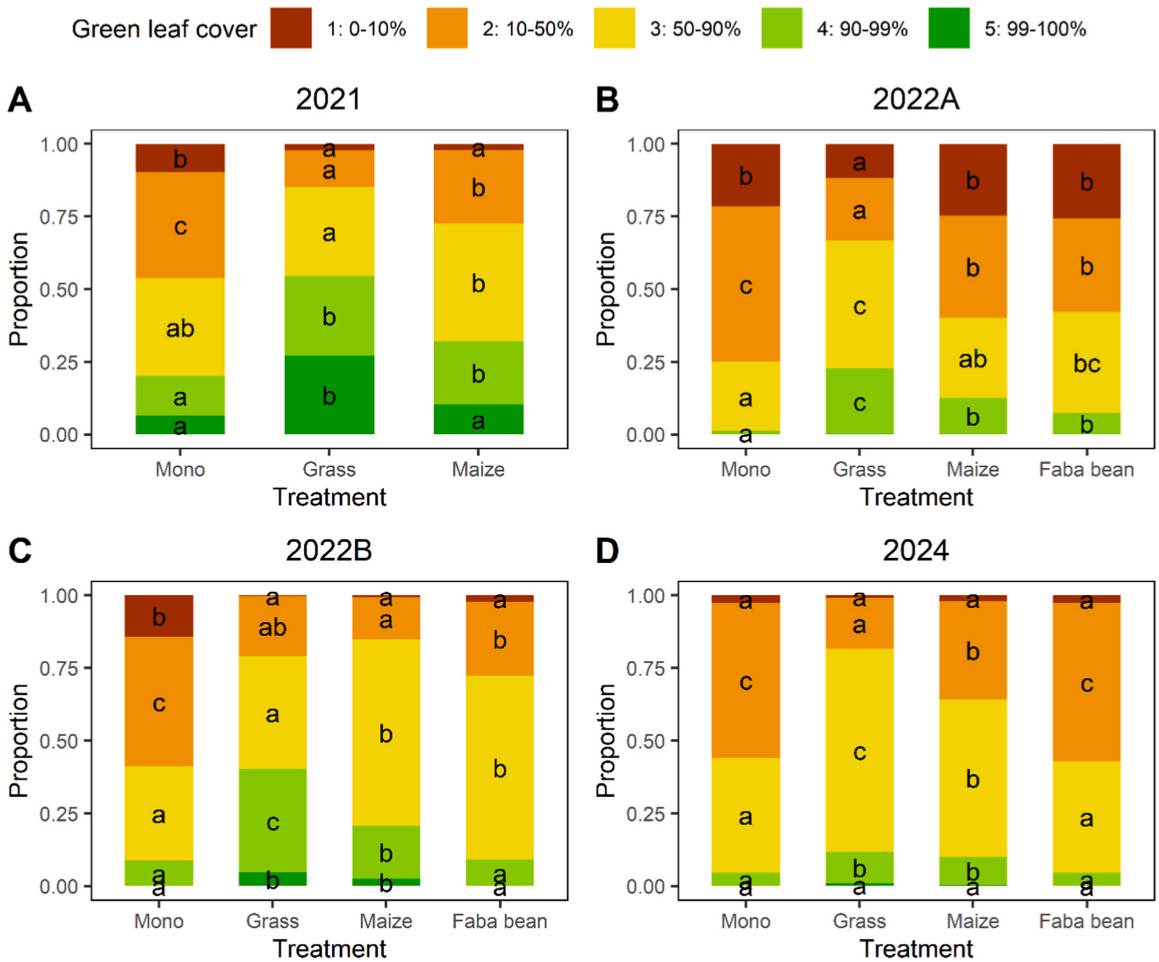

Fig. 6. Green leaf cover scorings of potatoes infected with potato late blight in 2021 (A), 2022 site A (B), and B (C), and 2024 (D). Potatoes were either grown in monoculture (Mono), strip-cropped with grass (Grass), strip-cropped with maize (Maize), or strip-cropped with faba bean (Faba bean). Every one meter in each potato row was given a score from 1 to 5, whereby 1 = 0–10 % green leaf cover, 2 = 10–50 % green, 3 = 50–90 % green, 4 = 90–99 % green, and 5 = between 99 % and 100 % green leaf cover. Letters indicate significant differences between treatments within each scoring class for each year at $P < 0.05$. These letters can be used to interpret the shift in green leaf cover between treatments.

with grass, the strip-crop with maize had less green leaf cover remaining at haulm killing than the strip-crop with grass in 2021 and 2022.

Strip-cropping with faba bean was not consistent at suppressing late blight compared with strip-cropping with the other companion crops. In 2022 at site A and in 2024, this strip cropping treatment had comparable levels of disease severity as the potato monoculture. Faba bean reaches tall stature relatively early in the season especially compared to maize. This could lead to an increased humidity in the potato strips next to faba bean. At the same time, the faba bean canopy might not be tall enough to form a barrier for spore influx into the canopy from outside or spore dispersal between potato strips. This suggests that both final stature and the temporal height growth dynamic of a companion may influence its effectiveness in suppressing late blight. Since the strip-crop treatments with grass or maize reduced late blight severity to a similar extent (i.e., being not significantly different from each other), a reduced density of potatoes, increased spatial distance between potato strips leading to a loss of spores to the companion crop canopy seems like an important mechanisms behind this reduction.

The weather and disease conditions during the three years were very contrasting; in 2021 the epidemic started at the usual time in the Netherlands, but progressed fast due to the humid conditions (74 % relative humidity and 191 mm of rain during June and July). In 2022 the epidemic started at the same time as in 2021, but went fairly slow because of lower humidity (66 % relative humidity and 129 mm of rain during June and July). In 2024, weather conditions were intermediate (77 % relative humidity and 157 mm of rain during June and July), but there was a very early onset of late blight. The experiments were conducted across four site-years with limited replicates of each treatment in each site-year due to the large plot size (21x24m). While this could be seen as a concern, under the mentioned contrasting conditions, the findings were consistent. Strip cropping with grass or maize consistently suppressed potato late blight, with grass as a companion crop species showing slightly higher efficacy in all years, as seen in the strip-crop with grass maintaining more green leaf cover at the time of haulm killing than the strip-crop with maize or bean. Additionally, the relatively large experimental plots likely played a role in mitigating interplot interference and increased independence between plots. Our strip-crops hence significantly reduced potato late blight compared with the monoculture, underscoring the sufficient statistical power of the experimental design, despite the limited number of replicates.

The relative contribution of different mechanism behind the observed disease suppression of strip-crops likely varied given the differences in weather conditions. During the favorable conditions of 2021 (prevalence of humid weather conditions), strip cropping significantly lowered the apparent infection rate (Table 2). This could indicate that under conducive weather conditions (such as those in 2021), the suppressive effect of strip cropping is mostly mediated by its modification of the microclimate, i.e., making it less conducive to disease spread. Conversely, in 2022, when the weather was much drier, strip cropping appeared to have a more pronounced effect on reducing the initial

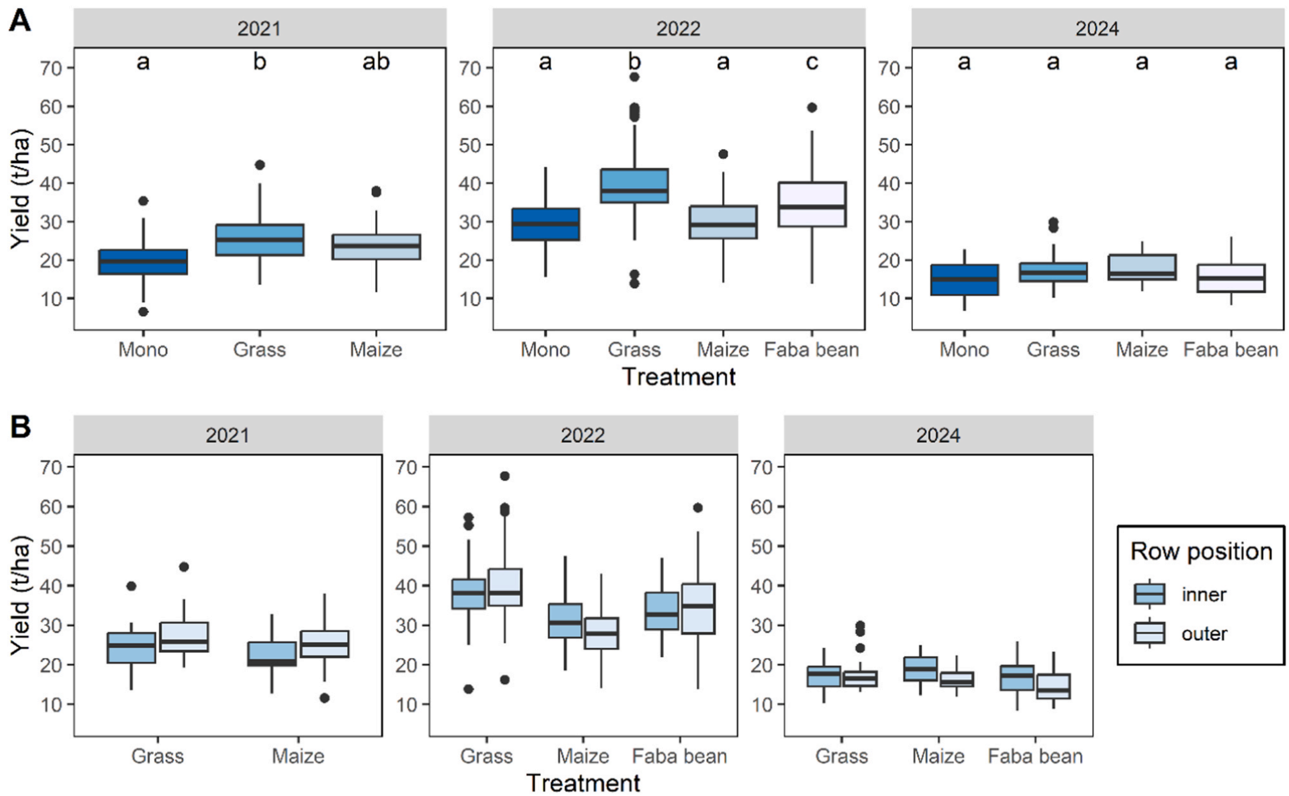

Fig. 7. . (A) Tuber yield (t ha^{-1}) per area of the potato crop either grown in monoculture (Mono), or strip-cropped with grass, maize or faba bean, for the 2021, 2022 and 2024 growing season. Letters indicate significant differences between treatments for each year at P < 0.05. (B) Differences in potato yield between inner and outer rows of potato strips in strip cropping treatments.

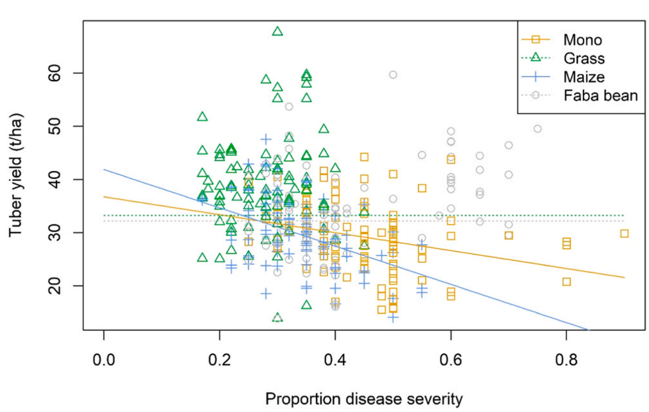

Fig. 8. Regression of proportion disease severity of potato late blight at the last assessment date and tuber yield (t ha^{-1}) in potatoes planted in monoculture (Mono, regression slope p-value = 0.03), or strip-cropped with either grass (regression slope p-value = 0.19) or maize (p-value = 0.001) or faba bean (p-value = 0.64) during the 2022 growing season. Points represent each assessment (24 locations per plot). □ = potato monoculture; △ = potato strip-cropped with grass; + = potato strip-cropped with maize; ○ = potato strip-cropped with faba bean.

inoculum load. In all years the dilution effect will have additionally contributed. Thus, strip cropping appears to be able to lower disease severity under varying weather conditions.

In a previous study, Ditzler et al. (2021) also found that *P. infestans* severity was significantly lower in potato-grass strip-crops than in potato monoculture. They also showed that narrower strips of potato (from 48 m width down to 3 m width) tended to have lower apparent infection rates compared with wider strips. Bouws and Finckh (2008) strip-cropped potato with either spring wheat or a grass-clover mix. They found 4 – 20 % reductions in foliar late blight severity in the strip-crop compared with pure stands of potato, i.e., lower reductions than in our experiments (between 52 % and 62 %). One explanation for this difference in disease suppression could be the width of the strips; in our experiment, we used strips of three meters, whereas Bouws and Finckh (2008) used strips of six meters. This is in accordance with the results from Ditzler et al. (2021), who showed that narrower strips reduce disease more than wider ones. The disease-suppressive effect of strip cropping might thus be even larger with strips smaller than 3 m width.

Not only is there variation in the efficacy of strip cropping in reducing potato late blight between experiments, but there are also substantial differences between experimental plots of the same treatment within a site. For instance, in 2021, one of the grass strip-crop experimental plots had an extremely low disease severity (8 %) at the end of the epidemic, whereas the other experimental plot reached similar levels as the monoculture (48 %) (Fig. 2A). Potato late blight epidemics usually start focal (resulting from an initial spot infection, e.g., volunteer tubers or incoming spores from outside the trial e.g., from waste piles or volunteer potatoes) (Dong and Zhou, 2022). There is randomness in where the first spores land, and the location of this focal point can greatly influence the disease severity; if a focal point is in an assessment location within an experimental plot, this plot will have a higher disease severity than when the focal point is not in an assessment location. Due to this focal characteristic of the disease, the efficacy of strip cropping in reducing late blight might be variable, even with the same companion crop species or strip width, although it is expected that when strip cropping is employed on large fields, these patch effects will even out.

Table 3
Summary of the performance of the strip-crop with either grass or maize, compared with the potato monoculture, using different metrics for determining disease intensity. All comparisons are significant, if the comparison was not significant in a specific year, this is indicated by *ns*.

Metric	Reference in text	Strip-crop potato-grass	Strip-crop potato-maize	Strip-crop potato-faba bean
sAUDPC	Table 2	Lower (0.040) than the monoculture (0.105), across three years	Lower (0.053) than the monoculture (0.105), across three years	Not significantly different
Apparent infection rate (r)	Table 2, Fig. 4	2021: Lower (0.506 day^{-1}) than the monoculture (0.543 day^{-1}) (7 % reduction) 2022: *ns* 2024: Lower (0.143 day^{-1}) than the monoculture (0.171 day^{-1}) (16 % reduction)	2021: lower (0.476 day^{-1}) than the monoculture (0.543 day^{-1}) (12 % reduction) 2022: *ns* 2024: *ns*	2022: *ns* 2024: Higher than the monoculture
Initial disease severity (x_0)	Table 2, Fig. 4	2021 and 2024: *ns* 2022:lower	2021 and 2024: *ns* 2022: lower	2022 and 2024: *ns*
Final disease severity	Fig. 3	2021: *ns* 2022: lower at both locations (severity of 13–15 %), compared with the monoculture (23–44 %) (reduction of 42–66 %) 2024: lower (5 %) compared with monoculture (12 %) (reduction of 58 %)	2021 and 2024: *ns* 2022: lower at both locations (18–20 %), compared with the monoculture (23–44 %) (reduction of 25–54 %)	2022: lower at one location 2024: *ns*
Green leaf cover	Fig. 6	2021, 2022 and 2024: significantly more green leaf cover remaining at haulm killing than the monoculture	2021, 2022 and 2024: intermediate levels of green leaf cover; marginally more green than monoculture	2022: intermediate levels of green leaf cover, more green than monoculture 2024: comparable green leaf cover as monoculture

4.2. Yield

In practice, it is not realistic to consider epidemics up to 100 % disease severity; crops are terminated when severity reaches a certain threshold. In the case of potato late blight, this is done especially to reduce the risk of tuber blight (Cooke et al., 2011), to protect surrounding potato fields from infection, and to limit prolonged production of inoculum on the foliage, which stimulates pathogen adaptation (Fry et al., 2015). It could therefore be of great importance for tuber yield if strip cropping could delay the start of the epidemic or slow down the disease progress. No clear delay in the first observation of late blight symptoms was observed in the strip-crop treatments in the field, but strip cropping with either grass or maize lowered the apparent infection rate compared with the monoculture in 2021, and lowered the initial severity in 2022. As a result, the strip-cropped potatoes reached a disease severity of 10 % on average between 1 and 3 days later than potatoes grown in monoculture. In 2024, the delay was even more pronounced for potatoes strip-cropped with grass, estimated to reach 10 % severity 5.3 days later than the potato monoculture. Although this number of days is a rough estimate, with some uncertainty, it indicates that farmers can potentially slightly delay the termination of their potato crop when strip-cropped. These extra days of growth could enhance the total tuber yield, since a potato canopy can produce 700–900 kg/ha fresh weight per day (Möller et al., 2006). A larger yield advantage might be attainable if strips can be terminated separately based on their individual disease severity. In the Netherlands, each strip is officially seen as a separate field (Rijksdienst voor Ondernemend Nederland, 2021), therefore, it is allowed to terminate each strip separately. The legal threshold for compulsory crop desiccation due to excessive late blight in the Netherlands is however quite low, around 1 % severity (Minister van Landbouw, Natuur en Voedselkwaliteit, 2021).

Nevertheless, late blight epidemics can, and often will, progress very rapidly. Despite the reduction in the apparent infection rate in the strip-crop treatments, the rate remained relatively high. The estimated few days delay in crop termination might give incentive for organic growers to adopt strip cropping practices, since they cannot use fungicides to prevent the disease. However, for conventional farmers, fungicides provide more certainty for crop protection, with longer delays in the start of the epidemic (Wiik, 2014) and thus crop termination than what can be achieved solely by strip cropping. The practice of strip cropping would need to be integrated with other control measures, which can be challenging because strip cropping can make crop management more complex (Himanen et al., 2016; Huss et al., 2022). In short, even though strip cropping can lower the apparent infection rate and disease severity, to effectively employ this practice, more work is needed to integrate this practice with other control measures.

Potatoes strip-cropped with grass yielded significantly more than both the monoculture and the maize strip-crop treatment, even though in this experiment, all treatments were terminated at the same time. Lower disease severity was observed in the grass strip-crop treatment, however, this might not be the only explanation for the higher tuber yield. Other strip crop studies showed that the more dominant crop in the mixture often overyields, especially in the border rows, whereas the less dominant crop has lower yields in border rows than outer rows (Gou et al., 2016; Li et al., 2001; Wang et al., 2020). This effect of competition probably played a major role in the observed yield increase of potato strip-cropped with grass, because grass does not strongly compete for light with potato. Additionally, it was observed that potato plants in the outer rows often took up space over the neighboring grass, and those outer plants also yielded the most. Although maize was also able to suppress late blight severity in the neighboring potatoes, potatoes strip-cropped with maize had approximately the same yield as the potato monoculture. Competition with maize for light likely led to no additional yield. This competition effect is visible in the different performance of the inner and outer rows of the potatoes strip strip-cropped with maize. Due to a cold spring in 2021, the maize plants grew slowly, and started to surpass the potatoes in height only around the beginning of July. The outer rows, potentially experiencing little competition from the shorter maize plants, relative to competition from potatoes in the inner rows, had higher yields than the inner rows. By contrast, during 2022, when maize surpassed the height of the potato canopy for the majority of the growing season (starting from around 20 June), the outer rows of the potato strip had lower yields than the inner rows.

To evaluate the performance of the strip-crop treatments, not only the performance of the potato crop should be evaluated, but an assessment of the productivity and profitability of the companion crop species is also required. This includes the yield (and other ecosystem service) of the companion crop species, its market value, and the costs associated with establishing and maintaining the strip of the companion crop species (e.g., nutrient input, water, labor). Since the strip of the companion crop species occupies land within the farming system, it should offer a return on the investment made. By conducting a more inclusive analysis of these aspects, a more informed choice for the companion crop species can be made.

4.3. Practical considerations when choosing a companion crop species

Farmers experience barriers when considering the adoption of crop diversification practices, such as strip cropping. Such barriers include the lack of practical knowledge and the lack of resources for investing in new machinery (Meynard et al., 2018; Mortensen and Smith, 2020; Revoyron et al., 2022). Farmers who grow potatoes in the Netherlands rarely grow maize as potato is an arable crop grown by arable farmers while maize is grown mostly on pig farms or cattle farms. Grass-clover, on the other hand, is often used as a break crop in arable crop rotations (Toorop et al., 2017), and can be exchanged with dairy farmers for manure (de Wit et al., 2006). Potato growers are more likely to have the knowledge and machinery for growing grass strips in between potato than maize strips. Furthermore, harvesting potatoes involves a harvester operating side-by-side with a trailer into which the harvested potatoes are deposited (Juventia et al., 2022). This means that at present the neighboring strip needs to be driven on at the time of harvest. Since maize is not ready to be harvested before potato, due to the longer growing season of maize, having a maize strip next to potato will interfere with harvesting. However, with the development of a single row potato harvesters (Johnson and Auat Cheein, 2023), this constraint on the companion crop species would be overcome. Thus, besides the effect companion crop species can have on potato late bight, their productivity and profitability, farmers' knowledge and their available tools, as well as practical considerations need to be taken into account in the selection of a companion crop species.

5. Conclusion

We compared the effects of strip cropping potato with grass, maize or faba bean on natural epidemics of *P. infestans*. Strip cropping with grass or maize suppressed foliar potato late blight severity. Furthermore, strip cropping with grass led to a significantly higher tuber yield per unit potato area than achieved in monoculture, due to the low severity and low (aboveground) competition from grass. While our data is specifically about grass, these results could be transferrable to other companion crop species with similar characteristics, because underlying disease-suppressive mechanisms might work similarly with other short crops, and placing potato next to other non-competitive crops could likely lead to higher tuber yield. The outcomes of these experiments suggest that growers might want to choose a short, non-competitive companion crop species that fits into their system, to ensure both effective reduction in late blight, while enhancing yields compared with potato monoculture. However, as only half the plot area was used for growing potato, it is important to consider also the production or non-production value of the companion crop and the agronomic feasibility of strip cropping it with potato. While strip cropping can suppress epidemic development and late blight severity, it is important to recognize that it will not provide complete control of the disease. Therefore, it needs to be integrated with other effective control measures. Strip-cropping could thus be an addition to the existing disease management practices to move towards more sustainable disease management.

CRediT authorship contribution statement

Niels P.R. Anten: Writing – review & editing, Funding acquisition, Conceptualization. **Zohralyn Homulle:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Jacob C. Douma:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Geert J.T. Kessel:** Writing – review & editing, Conceptualization. **Wopke van der Werf:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Tjeerd Jan Stomph:** Writing – review & editing, Conceptualization.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2024.109595.

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