



Planting date and cultivar selection to manage southern blight in potatoes in the mid-Atlantic United States

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ABSTRACT

Incidence of southern blight caused by *Sclerotium rolfii* Sacc. in potato (*Solanum tuberosum* L.) has increased across the mid-Atlantic region. To date, no potato cultivar is resistant to southern blight, and effective management with fumigants and fungicides has been inconsistent and uneconomical. This study evaluated impacts of four planting dates, ten commercial cultivars, and integrated effects of planting date and cultivar on southern blight incidence, yield, and tuber quality. Disease incidence varied by year, with fewer occurrences in 2019 (25%) than in 2018 (79%) or 2017 (64%), likely due to dry and warm weather. Despite the planting date by cultivar interaction, later plantings had greater disease incidence (85–94%) and lower tuber yield (1.8–9.4 Mg ha⁻¹) and quality (47–78% marketable tubers) than earlier plantings. Planting date effects were likely driven by humid, warm weather later in the season that was conducive to disease and detrimental to crop development. Though cultivar responses varied across planting date-years, ‘Accumulator’ had the lowest disease incidences (36%) and greatest tuber yield (20.2 Mg ha⁻¹) among tested cultivars. Conversely, ‘Adirondack Blue’ and ‘Dark Red Norland’ had the overall greatest incidence of *S. rolfii* (33–100%) while ‘Yukon Gold’ had the lowest yield (0.3–24.1 Mg ha⁻¹). Potato chipping cultivars tended to be less impacted by *S. rolfii* than fresh market cultivars; however, additional studies are needed to elucidate potential mechanisms of disease resistance. This study indicates early planting dates and cultivar selection are an effective management approach to reduce *S. rolfii* incidence on potato and maximize tuber yield.

1. Introduction

Southern blight of potato (*Solanum tuberosum* L.) is caused by *Sclerotium rolfii* Sacc. (teleomorph: *Athelia rolfii* (Curzi) Tu & Kimbrough), a necrotrophic fungal pathogen that attacks over 500 plant species (Farr and Rossman 2017; Mullen 2001). *Sclerotium rolfii* is present worldwide with more prevalence in tropical and subtropical regions (Aycock 1966; Mullen 2001). In the U.S. it is known to be more problematic in the southeast (Aycock 1966). The pathogen is mainly spread by sclerotia and mycelia. Mycelia can survive on dead organic matter, volunteer plants, or alternate hosts, and sclerotia survive in soil or manure and serve as overwintering structures (Mullen 2001). *Sclerotium rolfii* can grow between 8 and 40 °C, but conditions for optimal growth are warm temperatures (27–30 °C) coupled with high soil moisture and high

humidity (Aycock 1966; Mullen 2001; Punja 1985). When conditions are favorable, *S. rolfii* produces thick, white mycelial mats on plant parts 3–4 days after infection. Infection can occur at any host developmental stage and is most common at the soil line, with fungal growth extending a few centimeters up the stem (Mullen 2001; Roberts et al., 2014).

Over the past decade, *S. rolfii* has emerged as an economically important soilborne pathogen of vegetables in the mid-Atlantic U.S., and it threatens sustainable production of potato and other vegetable crops. The mid-Atlantic region produced over 281 thousand metric tons of potato tubers in 2018, with a value over \$77 million (USDA-National Agricultural Statistics Service 2019a, b). Several diseases limit yield and quality of potato produced in the region, and though in the past there were few reports of southern blight causing economic damage

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(Brittingham et al., 1963), it is an emerging disease in potatoes and other vegetables, such as table beets (*Beta vulgaris* spp. *vulgaris*), in Virginia and the rest of the mid-Atlantic (Pethybridge et al., 2019). Recent increases in southern blight incidence and severity coincide with reductions in fumigation of potato fields, increasing temperatures and excessive rainfall events, and adoption of reduced-tillage practices that can increase inoculum survival in fields (Bockus and Shroyer 1998; Punja 1985).

The effectiveness of fungicides, cultivar resistance, and cultural practices for management of *S. rolfisii* has been evaluated primarily for crops such as peanut (*Arachis hypogaea* L.) (Garren 1958; Garren and Bailey 1963; Garren and Duke 1958) and tomato (*Solanum lycopersicum* L.) (Bulluck III and Ristaino 2002; Keinath and DuBose 2017; Rivard et al., 2010). Although a few studies have evaluated control of *S. rolfisii* in potato (Browne et al., 2002; Kulkarni 2007; Voss et al., 1984), best management practices for potato southern blight have not been developed. Strobilurins (QoI fungicides, FRAC group 11) are recommended for *S. rolfisii* control in several crops, but few are labeled specifically for southern blight control in the mid-Atlantic region (Kuhar et al., 2019). Fumigation has the potential to reduce *S. rolfisii* inoculum in fields, but high cost, environmental regulations, and toxicity of fumigants to workers and handlers makes this approach uneconomical and impractical for potato production.

Due to a general lack of resistant cultivars, cultivar selection has not been widely applied to manage southern blight in potato or other vegetable crops (Mullen 2001). However, studies have reported some levels of host resistance in the peanut cultivar 'Florida-07' (Hagan et al., 2015) and the hosta cultivar 'Halcyon' (*Hosta* spp.) (Edmunds et al., 2003). Early studies on potato that screened for cultivar susceptibility to *S. rolfisii* showed no resistance to the pathogen (Aycock 1966; Edson and Shapovalov 1923). In India, two cultivars were rated as moderately resistant (33–47% incidence), while another 18 cultivars were rated as moderately to highly susceptible (>60% incidence) (Anahosur 2001). The Ute Russet cultivar, released in 1986, is considered resistant to *S. rolfisii* (Holm et al., 1987). Voss et al. (1984) reported on some cultivars and breeding lines that were at least partially resistant. Overall, little screening of potato for *S. rolfisii* resistance has been performed in the U.S.

Cultural practices such as planting date can be manipulated to increase the chances that a crop will develop during periods when environmental conditions are not conducive for pathogen growth, thereby allowing the crop to escape the disease. Effects of planting date on southern blight have been studied in some crops but influences on disease incidence and severity have been variable. Delayed planting that shifts the period of crop maturation to the fall, when cool temperatures are less conducive to disease, can reduce southern blight incidence by nearly 50% in peanuts (Hagan et al., 2001) and over 60% in carrots (*Daucus carota* L.) (Jenkins and Averre 1986). One early report on the impact of potato planting date on southern blight indicated that earlier plantings (April) had reduced disease severity by over 50% compared to late (May) planting for at least one of the *S. rolfisii* strains evaluated (Edson and Shapovalov 1923). However, altering planting date as a management practice has not been well documented for potato and no standardized recommendations have been developed.

Since warm, wet conditions favor southern blight development, we hypothesized that by manipulating potato planting date to earlier in the spring, it may be possible to reduce disease incidence and protect tuber yield and quality. In addition, though resistance to southern blight has not been identified in potato cultivars commercially grown in mid-Atlantic region, we hypothesized that cultivars will vary in their response to the disease and planting date. Thus, in the present study, our objective was to evaluate the impact of four planting dates, ten commercial potato cultivars, and the integrated effects of planting date and cultivar on southern blight incidence, yield parameters, and tuber quality.

2. Materials and methods

2.1. Field experiment establishment

Field experiments were established in 2017, 2018, and 2019 at the Virginia Tech Eastern Shore Agricultural Research and Extension Center (ESAREC) in Painter, VA (37.584779, -75.821014) on a Bojac sandy loam soil with a 0–2% slope (Natural Resources, 2017). There was no known history of *S. rolfisii* infestation in the experimental fields. Wheat was previously grown in the experimental fields in 2017 and 2018, and corn was grown in 2019. The land was prepared according to mid-Atlantic commercial vegetable production recommendations (Kuhar et al., 2019).

Annual experiments were arranged in split-plot designs with four replications, with planting dates as the main plots and cultivars as sub-plots. Potato tubers were planted on March 7, March 24, April 14, and May 10 in 2017; March 29, April 11, April 24, and May 9 in 2018; and April 3, April 17, May 2, and May 16 in 2019. Initial annual planting dates occurred as soon as soil temperature and moisture allowed for land preparations and included standard planting dates (March 10–April 5) recommended for commercial production of potato in the mid-Atlantic region (Kuhar et al., 2019). Ten commercial cultivars (Table 1), most of which are planted commercially in the mid-Atlantic, were evaluated for susceptibility to infection by *S. rolfisii*. Each main plot was 7.62 m long x 18.3 m wide, with a single guard row on each side and 6.1 m wide buffers between blocks. Sub-plots consisted of two rows per cultivar with 0.9 m between rows. Granular fertilizer (10N–10P–10K) at 673 kg ha⁻¹ was hand-banded into preformed split back ridges prior planting. Certified potato seed was hand-cut one to two days prior to planting and dusted with mancozeb (Nubark Mancozeb 6D; Wilbur-Ellis Company LLC, Fresno, CA) immediately after cutting (0.6 g of a.i. kg⁻¹ of potato seed). Seed were hand planted 0.25 m apart within rows in preformed split back ridges. Bifenthrin + imidacloprid (Brigadier 2SC at 253 g ha⁻¹ a.i.; FMC Corporation, Philadelphia, PA), azoxystrobin (Quadris 2.08SC at 96.1 g ha⁻¹ a.i.; Syngenta Crop Protection, LLC, Greensboro, NC), and mefenoxam (Ridomil Gold 4SL at 190.2 g ha⁻¹ a.i.; Syngenta Crop Protection, LLC, Greensboro, NC) were applied in-furrow at planting using a CO₂-pressurized sprayer with a single XR-80015 nozzle (TeeJet Technologies, Springfield, IL) calibrated to deliver 93.5 L ha⁻¹. No fungicide applied was known to have activity against *S. rolfisii*.

S-metolachlor (Dual II Magnum 7.64 EC at 0.96 L ha⁻¹ a.i.; Syngenta Crop Protection, LLC, Greensboro, NC) and metribuzin (TriCor 75DF at 420 g ha⁻¹, a.i.; United Phosphorus Inc, King of Prussia, PA) were applied within two days after planting for weed control. In 2018, only the first and second planting dates received herbicide, due to excessive rains that followed planting. Weeding was performed manually as needed to not confound results. Bed-mounding and cultivation were performed 2–3 weeks after emergence. Nitrogen (100 kg ha⁻¹ of urea 46% N) was broadcast evenly at bloom. Plots were periodically scouted for pests, and insect and foliar diseases were controlled with standard

Table 1
Description of the potato cultivars evaluated in a field study in Virginia from 2017 to 2019.

Cultivar ^z	Flesh color	Utilization	Maturity
Superior	White	Early fresh & chipping	Early-medium
Envol	White	Early fresh	Very early
Red Norland	White	Fresh	Early
Dark Red Norland	White	Fresh	Early
Russet Burbank	White	Fresh & processing	Late
Yukon Gold	Yellow	Fresh	Early
Adirondack Blue	Purple	Fresh Specialty	Early-medium
Atlantic	White	Chipping	Medium
Snowden	White	Chipping	Late
Accumulator	White	Chipping	Medium-late

^z All potato cultivars were purchased from certified potato seed producers.

practices for the mid-Atlantic (Kuhar et al., 2019).

2.2. Field inoculum preparation and application

A composite field inoculum utilizing two isolates of *S. rolfsii* (16-S1 and 16-S2) collected from the Eastern Shore of Virginia was prepared by adapting a previously described technique (Vagher et al., 2014). Each isolate was grown in a separate batch, and for each batch of inoculum, 500 cm³ of millet seed (*Pennisetum glaucum* L.) was placed in aluminum foil pans with 600 ml of deionized water, covered with aluminum foil, and autoclaved twice for 45 min. A seven-day-old *S. rolfsii* culture grown on potato dextrose agar (PDA) (Difco, Becton, Dickson and Company, Sparks, MD) was placed face-down on the autoclaved millet seed, double-covered with aluminum foil, and incubated in a growth chamber at 30 °C in the dark for 8–10 days. Infested millet seed was ground (≤ 5 mm pieces) and dried at room temperature. The final composite inoculum was prepared by mixing equal quantities by weight of the infested dried millet and consisted principally of mycelia with some sclerotia. Inoculum (40 g) was evenly scattered within each plot at blooming (42–73 days after planting). Cultivation was performed immediately after application of inoculum, except for the third planting date in 2019 where cultivation was done three days after application, due to rainy weather.

2.3. Data collection

Emergence was recorded regularly during the early part of the growing season until stems and leaves were fully developed for over 50% of plants. Disease incidence prior to harvest was assessed by counting the number of diseased plants per plot and converting to a percentage of diseased plants per plot. Plants with wilting (symptoms) and/or mycelia and sclerotia at the base of the stems (signs) were considered diseased (Aycock 1966; Mullen 2001; Weber 1943). Soil and air temperature, relative humidity, and rainfall data were collected hourly in 2018 and 2019 with HOBO micro weather station data loggers (Onset Computer Corporation, Bourne, MA) installed in the field. In 2017, the weather data were retrieved from the ESAREC weather station and relative humidity was not available.

Plots were harvested 93 to 114 days after planting (DAP) in 2017, 90 to 105 DAP in 2018, and 89 to 103 DAP in 2019. Harvest time was determined by an average maturity day of all cultivars or when plants withered or died in later planting dates. Each plot was machine lifted, and potato tubers were manually collected in bins. Tubers were weighed and graded according to USDA standards (Agricultural Marketing Service-USDA 2011). Tubers were considered diseased by *S. rolfsii* if symptoms included round sunken lesions that were brown, yellow, or tan, white mycelium, or soft tissue (Weber 1943). The marketable yield data were obtained from the sum of the weight of the tubers that met the diameter criteria (38–101 mm) to be classified as marketable tubers according to the USDA (Agricultural Marketing Service-USDA 2011). Total and marketable tuber yield per plot were converted to Mg ha⁻¹. The percentage of diseased tubers ([weight of diseased tubers/total tubers weight] \times 100) and percentage of marketable tubers ([weight marketable tubers/total tubers weight] \times 100) were calculated.

2.4. Statistical analyses

All statistical analyses were performed using SAS 9.4 (SAS Institute, Inc., Cary, NC). Since the number and timing of planting dates varied by year, data for each year of the study were analyzed separately with an analysis of variance (ANOVA). ANOVA was performed using the statistical procedures of a split-plot design in Mixed Model Procedures (Ott and Longnecker 2010). To meet ANOVA assumptions, arcsine-square root transformation was applied to the rate of incidence, percentage of marketable tubers, and percentage of diseased tubers. A square root transformation was applied for marketable tuber yield (McCune et al.,

2002). Non-transformed means are presented. The main effects of treatments (planting date and cultivars), block, and interactions were included in the model. Block was treated as a random effect, and planting date and cultivar were treated as fixed effects. When the interaction was significant, test slices were used to determine the effect of the cultivar at each planting date as described by Wludyka (SAS Institute Inc, 2017; Wludyka, 2015). The least squares mean comparisons were conducted using the Fisher's protected Least Significant Difference test (LSD) at a 5% significance level. A Spearman correlation analysis was carried out between disease incidence, marketable yield, percentage of marketable yield, and percentage of diseased potato tubers using PROC CORR. To determine the environment influence on *S. rolfsii* incidence, marketable yield, and tuber quality, a simple linear correlation analysis was performed between the means of final disease incidence, marketable yield, and percentage of diseased tubers for each planting date-year combination and mean weather parameters (average temperature, temperature oscillations, and total rainfall) across planting date-year combination using PROC CORR.

Due to the complex planting date-cultivar interaction across years, a site regression model (SREG) and biplot analysis of the *S. rolfsii* incidence and the marketable tuber yield were performed to evaluate the potato cultivars' performance across all years and planting dates of the study. The environmental variable consisted of each planting date-year combination (N = 12) and 10 cultivars. The SREG model and biplots allow to further study cultivar by environment interaction and the adaptability and stability of cultivars across environments (planting dates) (Castillo et al., 2012; Crossa et al., 2015; Vargas et al., 2015; Yan and Kang 2002). In the SREG model, the cultivar plus the cultivar by planting date-year interaction was included, and the latter was subject to a singular value decomposition (Crossa et al., 2015). Further, the first two significant principal components (PC1 and PC2) from the SREG model were used to construct the biplots.

3. Results

3.1. Impact of planting date and environmental parameters on disease incidence

Overall final *S. rolfsii* incidence varied across growing seasons. The mean disease incidence across planting dates and cultivars was greater in 2018 (79%) than in 2017 (64%) or 2019 (25%) ($P < 0.001$). Planting date influenced average southern blight incidence; however, the effect was inconsistent. In 2017, disease incidence main effect, averaged across cultivars, increased significantly from 36% for the 7 March planting date to 94% for the 10 May planting date ($P < 0.001$). Conversely, in 2019 a decrease in disease incidence was observed between the 3 April planting date (45%) and the 16 May planting date (7%) ($P = 0.002$). In 2018 there was not a significant difference in disease incidence among planting dates ($P = 0.228$), but incidence numerically increased from 73% for the earliest planting date (29 March) to 85% for the latest planting date (9 May).

Variation in disease incidence was associated with differences in rainfall and temperature across years and planting dates. The 2017 growing season had more accumulated precipitation (636 mm) than 2018 (394 mm) or 2019 (377 mm) (Fig. S1). Furthermore, in 2017 and 2018 all planting dates received above 362 mm and 296 mm of precipitation, respectively. Precipitation was more evenly distributed (days with rain events were more frequent) across the 2017 and 2018 growing season than in 2019. In 2019, precipitation was less than 277 mm for all planting dates except for the 17 April planting date (Table 2, Fig. S1). The mean temperature across the growing season was greater in 2019 (23.5 °C) than 2017 (21.1 °C) or 2018 (21.8 °C) (Table 2). Moreover, temperature progressively increased toward later planting dates in all years (Table 2). However, there was a positive relationship between mean temperature and mean disease incidence in 2017 and 2018 ($r = 0.80$, $P = 0.0179$) but not in 2019. In 2019 the lower rainfall and higher

Table 2

Summary of *Sclerotium rolfsii* incidence, marketable yield, and the weather parameters measured during the growing seasons in all plantings and years of the study.^z

Year	Planting date	Avg. temp (°C) ^y	Osc. ^x	Total rain (mm) ^y	Dis. incid (%) ^w	Mkt. tuber yield (Mg ha ⁻¹) ^y	Diseased tubers (%) ^y
2017	7-Mar	17.6	10.3	433	36	30.1	3
	24-Mar	20.3	10.2	382	33	30.0	10
	14-Apr	22.5	9.7	362	93	9.4	45
	10-May	23.8	9.8	423	94	1.8	33
2018	29-Mar	19.7	9.2	296	73	20.9	19
	11-Apr	20.9	9.4	298	78	13.9	37
	24-Apr	22.8	9.0	348	80	8.6	28
	9-May	23.7	8.9	319	85	4.9	35
2019	3-Apr	21.6	9.7	277	45	10.6	16
	17-Apr	23.2	9.9	315	24	8.3	15
	2-May	24.4	10.0	271	.	7.0	17
	16-May	24.8	10.1	264	7	4.8	13

^z Data were measured using Hobo Micro Station installed within the field where experiments were conducted in 2018 and 2019. For 2017, weather data were retrieved from the Eastern Shore Research Station database at Painter, Virginia.

^y Weather data were not recorded from May 9 to May 20, 2019.

^x Osc. = Oscillation. Average daily temperature oscillation determined as the difference between the max and the min daily temperature.

^w Final mean *S. rolfsii* incidence across planting dates and cultivars. Data not collected for the 3rd planting date in 2019.

^v Marketable tuber yield and percentage of diseased tubers averaged across planting dates and cultivars.

temperatures likely limited disease development. For example, the later planting dates in 2019 (May) had the least rain and highest average temperatures of any planting date-year combination (Table 2). Additionally, a significant negative relationship between temperature oscillation and disease incidence across planting date-year combinations was observed ($r = -0.63, P = 0.038$). The regression analysis indicated that rainfall ($\beta = 0.30, P = 0.023$) and temperature oscillations ($\beta = -56, P = 0.002$) explained 73% of final disease incidence variability.

3.2. Variation in disease incidence among cultivars and planting dates

The SREG analysis indicated a cultivar ($P < 0.001$), environment ($P < 0.001$), and cultivar by environment interaction ($P < 0.001$) effect on disease. Environment and cultivar explained 74% and 9% of the disease incidence variability, respectively, while 5% was attributed to the environment-cultivar interaction. The first two principal components accounted for 82.39% (PC1 69.05% and PC2 13.34%) of the total interaction variability (Fig. 1). The length of the vectors represents the influence of environments (N = 11) on cultivars, thereby allowing to differentiate cultivar performance against *S. rolfsii*. Thus, the long vector (environment 1B: March 24, 2017) with a greater PC2 score contributed to most of the crossover interaction. This is reflected in Table 3, where the March 24, 2017 planting date had a wider range of disease incidence (12–77%) than any other planting date-year combination and the cultivar ranking for disease incidence differed from other planting dates. Moreover, the last plantings of each year (May) were grouped in the upper right quadrant (higher average temperature environments), meaning they similarly influenced the cultivars' performance. The x-axis (PC1) indicates rank of cultivar disease incidence (cultivars' PC1 values were highly correlated to disease incidence across planting date-years; $r = 0.99, P < 0.001$), where greater positive values reflect greater disease incidence (e.g., 'Adirondack Blue' and 'Dark Red Norland'). This suggests that the cultivars on the left quadrants had less incidence of *S. rolfsii* (disease incidence below mean in at least 50% of the environments) (Fig. 1, Table 3). The y-axis (PC2) indicates the level of instability

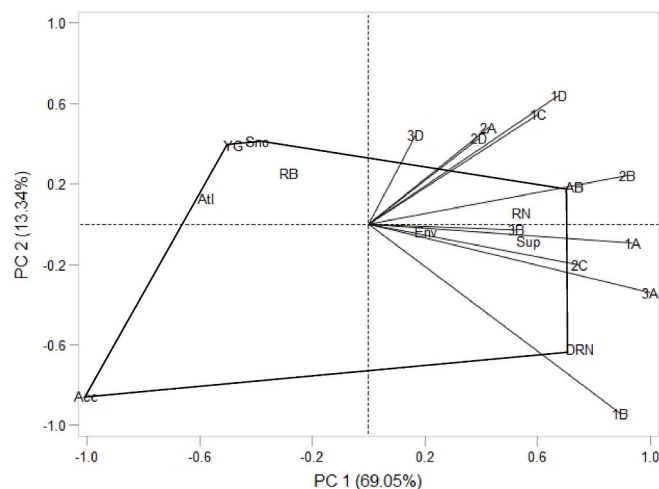


Fig. 1. Biplot of the first two components (PC1 & PC2) of the site regression model (SREG) for *Sclerotium rolfsii* incidence on 10 potato cultivars across 11 environments (planting dates) from 2017 to 2019. Cultivars are as follow: Sup = Superior, RN = Red Norland, DRN = Dark Red Norland, Env = Envol, Atl = Atlantic, Sno = Snowden, YG=Yukon Gold, RB = Russet Burbank, AB = Adirondack Blue, Acc = Accumulator. Numbers in environment vectors represent the year 1 = 2017, 2 = 2018, and 3 = 2019, while letters represent the first (A), second (B), third (C), and fourth (D), planting date within a year. The length of the vectors represents the influence of environments on cultivars, thus allowing to differentiate cultivars performance against *S. rolfsii*. PC1 values are correlated to cultivar incidence (greater values = greater susceptibility) and PC2 values to stability.

(Yan and Kang, 2002); therefore, cultivars with greater values (positive or negative) had a more variable response to *S. rolfsii* among environments ('Accumulator' and 'Dark Red Norland'). However, 'Adirondack Blue', by having a greater PC1 value and low PC2 value, was ranked as the cultivar with the most consistently high disease incidence across planting date-years. The polygon drawn in Fig. 1 connects the cultivars ('Accumulator', 'Dark Red Norland', 'Adirondack Blue', 'Snowden', and 'Yukon Gold') located farthest from the biplot origin; therefore, they are among the most responsive to the environments (either higher or lower than the average incidence of *S. rolfsii*).

When analyzed by year, there was a significant planting date-cultivar interaction in 2017 ($P < 0.001$) and 2018 ($P = 0.001$), but not in 2019 ($P = 0.111$). Thus, means were compared among cultivars by planting dates in 2017 and 2018 (Table 3). 'Accumulator' had lower than average disease incidence across all planting dates. In addition, it was either the lowest ranked or not statistically different from the lowest ranked cultivar for all years and planting dates (Table 3). In contrast, disease incidence for 'Adirondack Blue' was above average across all planting dates, and except for the March 24, 2017 planting dates, no other cultivar had greater disease incidence (Table 3). In the absence of significant interaction in 2019 and relatively low disease pressure, 'Snowden', 'Accumulator', 'Russet Burbank', and 'Yukon Gold' had similarly low disease incidence (Table 3). On the other hand, 'Adirondack Blue', 'Envol', 'Superior', 'Red Norland', and 'Dark Red Norland' had the greatest disease incidence (Table 3).

3.3. Impact of planting date and environmental parameters on potato tuber yield

Marketable tuber yield averaged across planting dates and cultivars varied by year with greater yield in 2017 (17.8 Mg ha⁻¹) than 2018 (11.4 Mg ha⁻¹) or 2019 (7.7 Mg ha⁻¹). Though overall yield varied by year, there was a planting date effect on marketable tuber yield in all years (2017, $P < 0.001$; 2018, $P = 0.005$; and 2019, $P = 0.002$). Overall, marketable yield was reduced by 94% in 2017, 76% in 2018, and 55% in

Table 3
Variation in southern blight incidence caused by *Sclerotium rolfisii* among potato cultivars and planting dates.

Cultivar	2017				2018				2019 ^z			Mean ^y
	7 Mar	24 Mar	14 Apr	10 May	29 Mar	11 Apr	24 Apr	9 May	3 Apr	17 Apr	16 May	
	Southern blight incidence (%) ^x											
Superior	53 ab ^w	48 b	97 ab	98 a-c	89 a	95 a	89 ab	83 bc	57	36	7	33 ab
Envol	44 bc	32 bc	92 bc	100 a	60 cd	77 b-d	81 bc	90 a-c	66	30	14	37 a
Red Norland	54 ab	32 bc	99 ab	99 ab	74 b	91 ab	95 a	93 ab	69	27	8	35 ab
Dark Red Norland	51 ab	77 a	98 ab	100 a	71 bc	90 ab	92 a	91 a-c	68	29	1	33 ab
Russet Burbank	25 de	19 cd	95 a-c	96 bc	75 bc	84 bc	72 cd	86 a-c	28	19	6	18 c
Yukon Gold	20 de	12 d	96 ab	100 a	65 bc	57 ef	60 d	86 a-c	35	17	3	18 c
Adirondack Blue	59 a	49 b	99 a	99 ab	89 a	94 a	91 a	95 a	59	38	17	38 a
Atlantic	13 e	17 d	89 c	93 c	76 bc	64 de	74 cd	81 cd	36	17	11	21 bc
Snowden	28 cd	15 d	92 bc	94 bc	81 ab	76 cd	77 c	93 ab	16	15	7	13 c
Accumulator	17 de	27 cd	71 d	66 d	52 d	48 f	67 cd	67 d	22	13	1	12 c
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	-	-	-	0.002

^z Data were not collected for the third planting date of 2019.

^y There was no significant interaction between cultivar and planting date in 2019. Thus, average disease incidence for cultivars across all three planting dates was compared.

^x Percentage of plants out of 30 per plot presenting wilting and/or mycelia and sclerotia at the base of the stems prior to harvest (85–112, 78–82, and 61–77 days after planting in 2017, 2018, and 2019, respectively). Arcsine-square root transformation was applied prior to data analysis. Non-transformed means are presented.

^w Column means followed by different letters are significantly different from each other based on Fisher’s protected LSD test at $P \leq 0.05$.

2019, between the earliest and the latest planting date (Table 2). March plantings in 2017 and 2018 had the greatest yields among all planting date-year combinations, which coincided with lower (<21 °C) temperatures (Table 2).

Temperature was the only measured environmental variable that correlated with yield, with yield decreasing as average temperature for a planting date-year increased ($r = -0.91$, $P < 0.001$). Though the mean temperature progressively increased toward later planting dates in all years, in 2019 temperatures remained above 21 °C for all planting dates, while cooler temperatures (<21 °C) were present in March and early April planting dates in 2017 and 2018 (Table 2).

3.4. Variation in marketable tuber yield among cultivars and planting dates

The SREG analysis indicated a cultivar ($P < 0.001$), planting date ($P < 0.001$), and cultivar by planting date interaction ($P < 0.001$) effect on yield. Environment and cultivar accounted for 73% and 11% of the total yield variability, respectively, while 6% was attributed to the environment-cultivar interaction. The first two principal components accounted for 87.8% (PC1 78.57% and PC2 9.23%) of environment-cultivar interaction (Fig. 2). The description above for the disease incidence biplot applies for the yield biplot, except that greater x-axis values (positive/negative) are cultivars with greater/poorer yield. Thus, cultivars on the left two quadrants (all fresh market) had below-average yield in most environments (Fig. 2). For example, ‘Yukon Gold’ had the poorest yield in 6 of the 12 planting dates (Table 4). On the other hand, ‘Accumulator’ was the highest yielding cultivar overall. The chipping cultivars ‘Atlantic’ and ‘Snowden’, with similar overall yield among them, were the next greatest yielding cultivars. Of the 12 planting date-year environments, environment 2B (April 11, 2018) and 2D (May 9, 2018) had the longest vectors indicating greater variability among cultivars (range 17.8–22.4 Mg ha⁻¹). Thus, these environments allowed for greater differentiation of cultivar performance. The last three planting dates in 2019 were clustered on the upper right quadrant meaning they had similar effects on cultivar yield.

Cultivar marketable tuber yield varied by planting date in all years (2017, $P < 0.001$; 2018, $P = 0.033$; and 2019, $P < 0.001$). Furthermore, yield varied among cultivars for every planting date in all years (Table 4). Despite the planting date by cultivar interaction, ‘Accumulator’ had greater than average marketable tuber yield across all planting dates, and it grouped with the top-yielding cultivars in 11 of the 12 planting dates. Though slightly less consistent, ‘Atlantic’ and ‘Snowden’ were also among the highest yielding cultivars across most

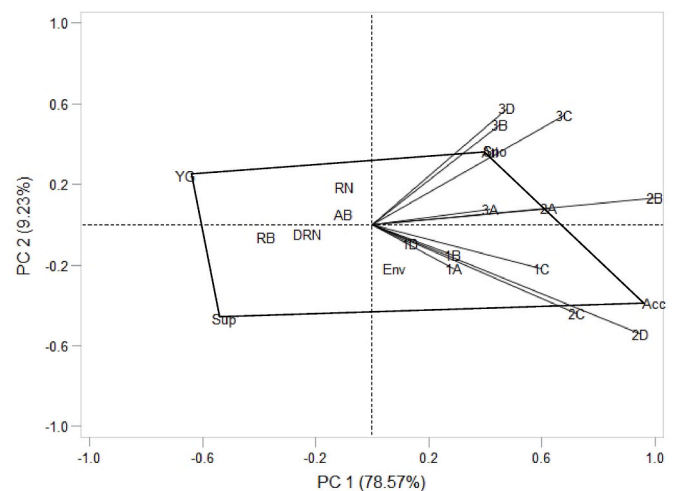


Fig. 2. Biplot of the first two components (PC1 and PC2) of the site regression model (SREG) for marketable tuber yield of 10 potato cultivars across 12 environments (planting dates) from 2017 to 2019. Cultivars are as follow: Sup = Superior, RN = Red Norland, DRN = Dark Red Norland, Env = Envol, Atl = Atlantic, Sno = Snowden, YG=Yukon Gold, RB = Russet Burbank, AB = Adirondack Blue, Acc = Accumulator. Numbers in environment vectors represent the year 1 = 2017, 2 = 2018, and 3 = 2019, while letters represent the first (A), second (B), third (C), and fourth (D), planting date within a year. The length of the vectors represents the influence of environments on cultivars, thus allowing to differentiate cultivars performance against *Sclerotium rolfisii*. PC1 values are correlated to tuber yield (greater values = greater yield) and PC2 values to stability.

planting dates. Conversely, ‘Yukon Gold’ had lower than average yield for all planting dates and grouped with the lowest-yielding cultivars across all planting date-year combinations evaluated (Table 4).

3.5. Relationship between disease and yield parameters

An inconsistent correlation between disease incidence and marketable tuber yield was observed. Disease incidence was negatively correlated to tuber yield in 2017 and 2018 but was positively correlated in 2019, although it was weaker than the correlations observed in the preceding years. As anticipated, the percentage of marketable tubers and diseased tubers were positively and negatively correlated, respectively, with marketable tuber yield in all years (Table 5). In addition to

Table 4Variation in potato marketable tuber yield among potato cultivars and planting dates in *Sclerotium rolfsii* infested fields.

Cultivar	2017				2018				2019			
	7 Mar	24 Mar	14 Apr	10 May	29 Mar	11 Apr	24 Apr	9 May	3 Apr	17 Apr	2 May	16 May
	Marketable tuber yield (Mg ha ⁻¹) ^z											
Superior	29.8 b-e ^y	29.5 b-e	6.3 d	2.8 ab	17.3 de	8.5 ef	5.9 cd	2.4 d	8.8 c	5.1 d	1.3 c	1.1 d
Envol	32.7 a-c	30.7 b-d	11.4 bc	2.4 a-c	15.9 de	16.2 bc	9.8 bc	6.3 bc	12.2 b	6.7 cd	5.2 b	4.8 bc
Red Norland	30.1 b-d	27.6 d-f	5.0 d	1.6 bc	18.8 cd	13.7 cd	7.3 b-d	3.7 b-d	9.5 c	7.7 c	5.8 b	6.7 ab
Dark Red Norland	32.4 bc	26.3 ef	6.0 d	2.0 a-c	17.7 c-e	11.6 de	8.6 b-d	3.5 cd	7.9 c	6.5 cd	6.1 b	4.3 bc
Russet Burbank	25.7 ef	32.3 a-c	9.2 c	0.3 d	17.9 c-e	8.1 ef	5.7 d	1.8 d	8.4 c	6.7 cd	5.1 b	1.7 d
Yukon Gold	24.1 f	23.7 f	6.3 d	1.4 c	13.4 e	6.2 f	2.9 e	0.3 e	8.4 c	6.1 cd	4.4 b	2.6 cd
Adirondack Blue	27.4 d-f	28.3 c-e	6.7 d	1.5 c	23.0 bc	14.3 cd	7.9 b-d	3.3 b-d	7.3 c	5.3 cd	5.5 b	6.0 ab
Atlantic	33.9 ab	33.0 ab	11.4 bc	1.6 a-c	26.6 ab	20.8 b	9.3 bc	5.2 bc	13.9 ab	12.2 b	11.5 a	7.9 a
Snowden	28.7 c-e	32.5 a-c	12.7 b	2.9 a	27.3 ab	18.6 bc	9.7 b	6.2 b	14.7 a	16.2 a	11.8 a	6.7 ab
Accumulator	37.3 a	36.6 a	19.6 a	2.4 a-c	33.4 a	28.6 a	21.5 a	18.1 a	15.4 a	10.2 b	13.2 a	6.2 ab
<i>P</i> -value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

^z Data were obtained by grading and weighing according to USDA standards (Agricultural Marketing Service-USDA 2011). To meet ANOVA assumptions, square root transformation was applied prior to data analysis only for 2017 and 2018. Non-transformed means are presented.

^y Column means followed by different letters are significantly different from each other based on Fisher's protected LSD test at $P \leq 0.05$.

Table 5

Relationships between percent diseased tubers, southern blight incidence, marketable yield, and percent marketable tubers for potatoes grown in field experiments in Virginia from 2017 to 2019.

Variable ^z	2017		2018		2019	
	Correlation coefficient ^y	<i>P</i> -value	Correlation coefficient	<i>P</i> -value	Correlation coefficient	<i>P</i> -value
INC vs. DT (%)	0.81	<0.001	0.34	<0.001	0.45	<0.001
INC vs. Mkt Yld	-0.79	<0.001	-0.41	<0.001	0.24	0.009
INC vs. Mkt (%)	-0.82	<0.001	-0.36	<0.001	-0.23	0.010
DT (%) vs. Mkt Yld	-0.76	<0.001	-0.70	<0.001	-0.48	<0.001
DT (%) vs. Mkt (%)	-0.90	<0.001	-0.98	<0.001	-0.82	<0.001
Mkt Yld vs. Mkt (%)	0.87	<0.001	0.75	<0.001	0.65	<0.001

^z Variables are abbreviated as follows: DT (%) = Percentage of diseased tubers, INC = final southern blight incidence, Mkt (%) = percentage of marketable tubers, Mkt Yld = marketable yield.

^y Spearman's correlation coefficients.

reducing the tuber yield, delaying planting date also decreased tuber quality (percentage of marketable tubers averaged across cultivars) by 48% and 23% in 2017 and 2018, respectively, and increased diseased tubers (tuber rot caused by *S. rolfsii*) substantially in both years (Tables S1 and S2).

4. Discussion

Over the last decade, southern blight caused by *S. rolfsii* has emerged as an economically important vegetable disease in the mid-Atlantic U.S. that threatens the sustainable production of potato and other crops. Therefore, it is essential to find sustainable approaches to combat southern blight that contribute to potato production resilience. To our knowledge, there have been no previous studies on the effect of planting date and modern potato cultivars on southern blight in the U.S. This three-year study evaluated whether altering the planting date can reduce the incidence of southern blight and risk of tuber yield loss for 10 commercially grown potato cultivars in the mid-Atlantic region. Even though there was a planting date by cultivar interaction, later planting dates were generally associated with warmer temperatures, greater disease incidence, and reduced potato tuber yield compared to earlier planting dates. Thus, delaying planting date is likely to have negative impacts on yield which are driven by a combination of environmental parameters and greater disease incidence. Though the ranking of some cultivars for disease incidence and yield varied with planting date, others were consistently the most resistant or susceptible to southern blight and among the highest and lowest yielding potato cultivars. This indicates that a combination of well-timed planting dates and cultivar selection are an effective management approach to reduce *S. rolfsii* impact in fields and maximize potato tuber yield.

The current study demonstrates it may be possible to manipulate

planting date so that environmental conditions are favorable for potato crop growth but unfavorable for growth and crop infection by *S. rolfsii*. Potato grows best between 16 and 25 °C (Thornton 2020) and although the growth period can take up to 160 days across the mid-Atlantic, harvest normally occurs 90–120 days post-planting. Conversely, *S. rolfsii* can grow between 8 and 40 °C but grows best at 27–35 °C with adequate soil moisture and high relative humidity (Mullen 2001; Punja 1985; Ramarao and Raja 1980). Thus, earlier planting dates can take advantage of cooler temperatures less conducive to disease but still favorable for crop growth (Browne et al., 2002; Nuñez and Aegerter 2019). This was demonstrated in the current study by a significantly lower incidence of southern blight resulting from earlier planting dates in March 2017, which were followed by the lowest temperatures of any planting dates in the study. Thus, most of the crop growth occurred prior to occurrence of temperatures that were favorable for disease development.

In contrast to earlier planting dates, overall *S. rolfsii* incidence was high (>80%) following late planting dates in two of the three growing seasons (2017 and 2018). These observations are consistent with previous reports in a potato evaluation two months post-transplanting, where May plantings in Virginia had above 80% *S. rolfsii* incidence compared to 33% incidence for potato planted in April; this was likely driven by warmer temperatures following the later planting dates (Edson and Shapovalov 1923). In contrast, studies in peanut and carrot within the U.S. have generally found that late plantings reduced *S. rolfsii* incidence by 50–60% (Bowen 2003; Hagan et al., 2001; Jenkins and Averre 1986). This difference is because, unlike potato, peanut is a warm season crop, and by delaying planting, the later stages of crop development occur during the fall when cooler temperatures are less conducive for disease development. However, in the current study, harvests occurred before August 13 and prior to temperatures that

would be unfavorable for *S. rolf sii*. Thus, it is likely that the high incidence of *S. rolf sii* following late plantings in the current study were driven by the synchronization of most of the crop growth with humid and warm periods (July through August) as indicated by the positive association between temperatures and disease incidence in 2017 through 2018. Unlike preceding seasons, in 2019 southern blight declined by delaying planting dates. This decline can be attributed to below-average rainfall in 2019 and dry conditions that likely limited the growth of *S. rolf sii*. In California, it has been reported that relatively dry topsoil was associated with low *S. rolf sii* incidence in potato (Browne et al., 2002).

Delaying planting dates negatively impacted potato tuber yield and quality in the current study. The overall yield reduction of more than 76% in 2017 and 2018 and more than 50% in 2019 reveals yield potential is limited when the crop is planted later than mid-April. In our study, the reduction was associated with greater disease incidence and warmer temperatures toward later planting dates. Although in 2019 the disease development was hindered by drier conditions, there was a consistent negative relationship between yield and disease incidence of plant in 2017 and 2018. Moreover, a consistent negative relationship between yield and the percent of diseased tubers was observed in all years. Earlier studies have noted similar effects where 75% of the plants in the April planting produced tubers compared to 42% of those in the May plantings (Edson and Shapovalov 1923). Moreover, Aycock (1966) suggested that losses to cool weather crops frequently occur when planting dates are delayed because the most development of the crops is through warm periods. The consistently strong negative correlation observed between yield and temperature in the current study supports this hypothesis. Thus, planting later than mid-April will reduce potato yield, as high temperatures from June through August will hamper tuber development.

In our study, no cultivar was completely immune to *S. rolf sii* infection; however, there was significant variation in southern blight incidence among cultivars. While disease severity was not assessed, the lower disease incidence observed for some potato cultivars suggested they are more resistant to southern blight. Previously, there were no reports of mid-Atlantic-grown potato cultivar responses to *S. rolf sii*. Though the response of cultivars varied across planting date-years, 'Accumulator' consistently had one of the lowest disease incidences. Conversely, 'Adirondack Blue' and 'Dark Red Norland' had the greatest incidence of *S. rolf sii* across planting date-years. This was also depicted in the biplot, where the processing and chipping cultivars were grouped in the left quadrants (in contrast to fresh market cultivars except 'Yukon Gold') and 'Accumulator' was ranked with less southern blight incidence (lower PC1 scores). Therefore, our results suggest that 'Accumulator' is less likely to become infected by *S. rolf sii* than all other cultivars evaluated. Differences in cultivar responses to *S. rolf sii* have been documented domestically and worldwide. For example, Voss et al. (1984) noted that 'Kennebec', 'White Rose', and several breeding lines showed some resistance compared to 'Centennial Russet', while almost a century ago Edson and Shapovalov (1923) documented that 'Irish Cobbler' and 'Bliss Triumph' were highly susceptible to *S. rolf sii*. Kulkarni (2007) found no differences among cultivars in a study in India, where all 10 cultivars evaluated were labeled as highly susceptible (50–80% incidence), and Anahosur (2001) reported that 18 of 20 cultivars evaluated were moderately to highly susceptible (>60% incidence) 60 days post-planting.

To our knowledge, there are no studies that directly compare the susceptibility among different potato utilization groups. However, reports have noted that the fresh market cultivar 'Monalisa', was more severely affected than the chipping cultivar 'Hermes' (Garibaldi et al., 2006). In studies by Voss et al. (1984), the greater susceptibility was attributed to fresh market cultivar 'Centennial Russet', while the chipping cultivar 'Kennebec' was ranked among the least diseased tubers. These studies suggest that the physiology and composition of the tubers likely influences differences in susceptibility between the potato

utilization groups. Cells with high starch content have been implicated in hampering *S. rolf sii* hyphae penetration (Aycock 1966); hence, the high starch (Bond 2014) and lower water content of processing and chipping cultivars (Bond 2014; Nzaramba et al., 2013) could contribute to greater resistance to *S. rolf sii* infection compared to fresh market cultivars. This is also supported by the lower percentage of diseased tubers observed in 'Atlantic', 'Snowden', and 'Accumulator' (Table S2). However, determining specifically the physical and chemical properties that contribute to resistance is beyond the scope of this study.

Though yield was considerably reduced for planting dates in mid-April through May compared to March planting dates for all cultivars, 'Accumulator' consistently out-yielded other cultivars in marketable tuber yield and quality. This was also shown in the cultivar-environment interaction biplot, where 'Accumulator' had the greatest yield in eight of the 12 environments (planting dates), thus demonstrating more yield stability across environments. Additionally, the chipping cultivars were grouped on the opposite side of the fresh market cultivars except for 'Envol', which indicates that 'Envol' excelled among the fresh market cultivars. In contrast, 'Yukon Gold' had overall poor yield. Though there was a clear relationship between yield and disease incidence, other factors such as warmer temperatures and inadequate moisture are associated with low yields as reported previously (Aycock 1966). Additionally, the lower yield of 'Yukon Gold' can be attributed to the lower stand count compared to the rest of cultivars (data not shown). However, when crop growing conditions were more adequate and disease pressure was relatively low, the chipping cultivars showed greater tuber yield and quality, indicating that under the right conditions, these cultivars are well suited to the mid-Atlantic U.S.

This study investigated potato southern blight management through the manipulation of planting date and cultivar selection. The results demonstrated that variation in environmental parameters such as precipitation and temperature among planting dates is a key factor in determining cultivar performance and disease development. Although disease incidence varied among planting dates in *S. rolf sii* infested fields, overall 'Accumulator' had the least disease incidence and greatest tuber yield across planting date-years. However, the significant increase in disease incidence and consistent reduction in yield and quality of all cultivars that resulted from delayed planting suggests that cultivar selection alone is not reliable and should be coupled with early planting dates to manage southern blight. Our results indicate that potato planted after the first week of April in the Eastern Shore of Virginia, where over 80% of the Virginia potato production is located, is at greater risk of being affected by *S. rolf sii* and impacted by warmer temperatures (mean daily temperature >21 °C) that are associated with lower yield and greater disease in the presence of adequate moisture. Moreover, although susceptibility was not measured per se, the greater disease incidence observed for cultivars such as 'Adirondack Blue' and 'Dark Red Norland' across planting dates suggests that these cultivars are highly susceptible to southern blight and should not be planted in fields with a history of *S. rolf sii* infestation. Further characterization of the cultivars less affected by southern blight can elucidate sources of resistance for breeding. Furthermore, because of consistently low yields and an intermediate disease incidence for 'Yukon Gold', this cultivar is considered the least adapted to the mid-Atlantic region. Since yield is suppressed by warmer temperatures that favor southern blight development, mid-Atlantic potato growers should avoid planting after mid-April so that a majority of the crop development will occur prior to periods when average daily air temperatures are likely to exceed 21 °C.

CRediT authorship contribution statement

J. Garcia-Gonzalez: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration, Visualization, Formal analysis. **H.L. Mehl:** Writing – original draft, Writing – review & editing, Methodology, Resources, Formal analysis. **D.L. Langston:**

Conceptualization, Methodology, Writing – review & editing. **S.L. Rideout**: Conceptualization, Resources, Writing – review & editing, Methodology, Supervision, Formal analysis, Funding acquisition.

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. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cropro.2022.106077>.

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