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Challenges in integrated pest management: A case study of onion thrips and bacterial bulb rot in onion

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ABSTRACT

Most agricultural production systems face challenges with multiple arthropods, plant pathogens and/or weed species, but few studies address the impact of multiple pests when developing integrated pest management programs. In onion production, onion thrips and bacterial bulb rot are primary constraints, and choice of onion cultivar, fertility regime and insecticide use may be important tactics to manage both. In a two-year study in New York, two independent field trials were conducted concurrently. The first experiment included either a moderately thrips-resistant cultivar ('Avalon') or a thrips-susceptible cultivar ('Bradley'), multiple nitrogen rates (0, 67, 84, 118, and 151 kg/ha) and either a season-long, action threshold-based insecticide program or no insecticide program (20 treatments total). The second experiment included the same cultivars and insecticide programs but evaluated phosphorous rates (0, 56, 112, and 168 kg/ha) (16 treatments total). In both trials and years, 'Avalon' experienced lower thrips densities, but suffered 58% more bacterial rot, which reduced onion yields overall by 9%. Nitrogen and phosphorus fertilizer had limited impact on onion thrips, bacterial rot, and onion yield. Although, higher rates of nitrogen fertilizer increased bacterial bulb rot in 2017. In both years, low rates of fertilizer (67 kg/ha N or 56 kg/ha P) produced statistically similar yields to plants supplemented with the highest rates of fertilizer. Insecticide use reduced thrips densities and increased bulb yield in both years but did not consistently reduce bacterial bulb rot. Therefore, growers can optimize onion production by reducing rates of fertilizer and using an action-threshold based insecticide program. Furthermore, our results indicate that IPM programs should be evaluated to consider multiple biotic constraints simultaneously within an agricultural production system as IPM tactics can be counterproductive.

1. Introduction

Integrated pest management (IPM) is the primary paradigm to manage pests in agriculture. This approach combines management tactics to reduce pest damage, maximize crop yield and limit negative off-target effects (Stern et al., 1959; Pedigo et al., 1986; Pedigo, 1989). However, IPM strategies for a crop typically focus on a single pest. An agricultural production system is dynamic and crops often face challenges with multiple pests simultaneously within a season. Consequently, management tactics with this singular focus, for example, could create or exacerbate problems managing other pests that damage the crop. Such a scenario would be a disservice to practitioners of IPM (i.e. growers, land managers) and ultimately hinder the sustainability of agriculture (Kogan, 1998). Therefore, it is critical to develop an IPM program that reduces economic damage caused by multiple pests to provide the greatest overall benefit to sustainable crop production (Kogan, 1998).

In onion production, several major pests and pathogens damage the crop (Brewster, 2003; Schwartz and Mohan, 2008), but onion thrips (*Thrips tabaci*) and bacterial bulb rots (many *spp.*) are the most destructive and difficult to control. Onion thrips feed directly on leaf tissue and use their rasping-sucking mouthparts to remove mesophyll tissue. Onion thrips feeding can reduce bulb yields by 60% as well as transmit plant pathogens and exacerbate plant diseases (Rueda et al., 2007; Gill et al., 2015; Leach et al., 2017; Leach et al., 2020). Bacterial bulbs rots compromise the internal integrity of bulbs and render bulbs unmarketable, which causes significant yield losses (Stivers, 1999). Bacterial bulb rot is caused by a complex of bacterial species, which vary based on the onion-production region. In New York (USA), *Burkholderia spp.*, *Enterobacter cloacae*, *Pantoea ananatis* and *Rahnella spp.* have been

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identified as the primary bacterial pathogens of onion (Beer et al., 2010). While both pests are difficult to manage, choice of fertility regime, onion cultivar and insecticide use may be important management tactics.

Host plant resistance is a cornerstone of IPM, as it aims to prevent insect and pathogen damage (Pedigo et al.,1989). While no cultivar is completely resistant to thrips feeding, some have moderate resistance and support lower densities and less feeding damage. Cultivars with semi-glossy wax and yellow-green leaves tend to have fewer thrips than those with waxy, blue-green leaves (Diaz-Montano et al., 2012; Boateng et al., 2014; Ferreira et al., 2017) which may be explained, in part, by the amount of a ketone, hentriacontanone-16 (H16), present (Damon et al., 2014). Onion cultivars vary greatly in susceptibility to bacterial rot (Schroeder et al., 2010; Wohleb and Waters, 2016; Stumpf et al., 2017); however, no plant characteristics have been identified as responsible for this variation. Some studies have postulated that epicuticular wax may play a significant role in onion disease susceptibility (Mohan and Molenaar, 2005; Leach et al., 2017). Nevertheless, choice of onion cultivar is likely to impact feeding damage and disease severity caused by onion thrips and bacterial rot.

Crop fertilization can impact the attractiveness and susceptibility of crops to pests and pathogens (Abawi and Widmer, 2000; Altieri and Nicholls, 2003). Previous studies have shown that onion thrips populations in onion decrease by 23–70% with lower rates of nitrogen fertilizer (Malik et al., 2009; Buckland et al., 2013). Although untested in onion, Chen et al. (2004) found 2.3 times fewer thrips (*Frankliniella spp.*) on plants fertigated with lower rates of phosphorus (1.28 mM P vs. 0.32 mM P.). Increased nitrogen fertilization can also increase the incidence of bacterial bulb rots and reduce onion bulb quality (Wright, 1993; Diaz-Perez et al., 2003). Pfeufer and Gugino (2018) found that early-season nitrate levels as well as foliar nitrogen values in onion were positively related to the incidence of bacterial bulb rots. Currently, the relationship between phosphorus levels and bacterial bulb rot is understudied, although some research has indicated that bulb rot may increase with increasing rates of phosphorus fertilizer (Shock et al., 2015; Bekele, 2018). Thus, a reduction in nitrogen and phosphorus fertilizers may be an effective cultural control tactic for onion thrips and bacterial bulb rot in onion.

Insecticide use is the primary tool for managing onion thrips and previous studies have optimized its use in onion production (Nault and Shelton, 2010; Nault, 2015; Nault and Huseth, 2016). Nault and Huseth (2016) showed that integrating partially thrips-resistant cultivars into insecticide programming resulted in 36% fewer insecticide applications compared with managing thrips with insecticides on a thrips-susceptible cultivar. Since onion thrips have been positively associated with bacterial bulb rots caused by *Pantoea spp.*, the use of insecticides to reduce onion thrips damage may reduce bacterial disease in onion (Dutta et al., 2014; Grode et al., 2019). Further research is needed to determine if insecticide use will indirectly and successfully reduce the incidence of bacterial bulb infections.

There is a need to identify a robust IPM program to effectively manage both of these major biotic constraints to onion production. The purpose of our study was to evaluate combinations of onion cultivars (with or without thrips resistance), various nitrogen and phosphorous fertility regimes, and insecticide use (yes or no) on 1) onion thrips densities 2) bacterial bulb rots, and 3) onion bulb yield. We hypothesized that the combination of using a moderately thrips-resistant cultivar ('Avalon'), reduced levels of nitrogen and phosphorous, and an action-threshold based insecticide program would provide optimal management of onion thrips and bacterial bulb rot, thereby increasing marketable bulb yield.

2. Materials and methods

2.1. Experimental design

Trials were conducted on a commercial onion farm with 'Carlisle' muck soil in Orleans County, NY in 2017 and 2018 (NRCS, 2016). On this farm, two independent trials were executed simultaneously that included different onion cultivars, nitrogen or phosphorus fertilizer regimes and insecticide use combinations. The same general field site was used in both years and had been continuously mono-cropped with onion. The grower reported a previous history of bacterial disease and onion thrips in the field. The field site had low initial levels of soil nitrate (10–30 ppm) and was previously managed using little to no nitrogen fertilizer (<45 kg/ha). Similarly, phosphorus values were low and tested below 67 kg/ha. Two onion cultivars that differ in their resistance to onion thrips were selected based on leaf waxiness and color (Diaz-Montano et al., 2012; Damon et al., 2014). 'Avalon' (Crookham Co., Caldwell, ID) is moderately resistant to thrips feeding and has yellow-green, semi-glossy foliage, whereas 'Bradley' (Bejo Seeds, Inc., Oceano, CA) has blue-green, waxy foliage that is susceptible to thrips (Leach et al., 2017). Both cultivars are intermediate to long-day, yellow onions with similar days to harvest. Nitrogen and phosphorus trials were planted with a vacuum seed planter (646,000 onion seeds per hectare) on 15 Apr 2017 and 21 Apr 2018 (see 2.5 for management of other pests and pathogens).

2.1.1. Nitrogen trial

A total of 20 treatments (2 onion cultivars x 5 nitrogen rates x 2 insecticide treatments) were replicated 5 times. Onion cultivars were 'Bradley' and 'Avalon'; Nitrogen rates were 0, 67, 84, 118 and 151 kg/ha; insecticide treatments were insecticide treated and an untreated control. The treatments were arranged in a split-split plot design in which cultivar was the main plot factor, nitrogen fertilizer was the subplot factor and insecticide was the sub-sub-plot factor. Cultivars were arranged in long strips (3 beds wide; 15 rows) across the field. Nitrogen treatments were randomly assigned to plots nested within each cultivar strip and each plot was bisected into subplots randomly assigned to the insecticide treatments.

Urea nitrogen (46-0-0) was applied twice, at-planting and during the pre-bulbing stage (3–5 leaves per plant). Rates and timings were 0 kg/ha (no nitrogen applied), 67 kg/ha (67 kg/ha applied at planting), 84 kg/ha (split into two applications, 67 kg/ha applied at planting and 17 kg/ha applied pre-bulbing), 118 kg/ha (split into 67 kg/ha applied at planting and 51 kg/ha applied pre-bulbing), and 151 kg/ha (split into 67 kg/ha applied at planting and 84 kg/ha applied pre-bulbing). Nitrogen rates were based off current recommendations from Cornell University (recommended rate = 112–168 kg/ha) (Reiners et al., 2017). To reduce the chance of urea fertilizer volatilizing, 3 cm of overhead irrigation was applied immediately after the fertilizer was applied. Experimental plots were supplemented at planting with the appropriate rates of potassium (potassium chloride; 0-0-60; N–P–K) and phosphorus (triple superphosphate; 0-46-0; N–P–K) per fertility guidelines (Reiners et al., 2017). Fertilizers were broadcast and incorporated into the soil. Each experimental plot was 1.5 m wide x 9.1 m long and consisted of five rows of onion plants, and subplots within each plot were 1.5 m wide x 4.5 m long. The entire experiment was 32 m wide x 52 m long. Experimental plots were surrounded by either 1.5 m of bare ground or unfertilized onions to minimize fertilizer movement between plots. Soil samples were used to confirm nitrogen rates in the field (Supplemental Table 1).

Decisions to apply insecticides were made on a weekly basis. Experimental subplots receiving insecticide were sprayed when the onion thrips population met or surpassed an action threshold of 1 larva per leaf (Nault and Shelton, 2010; Nault and Huseth, 2016). The untreated control was never sprayed with insecticides. Subplots were scouted weekly beginning on 19 Jun 2017 and 19 Jun 2018, and insecticide program treatments were initiated when treatments reached a mean density of 1 larva per leaf on 8 Aug 2017 and 1 Jul 2018.

Insecticide applications were made in accordance with current insecticide resistance management guidelines (Leach et al., 2018). The following sequence of insecticides and rates were used during each experiment: spirotetramat at 0.08 (AI) kg/ha (Movento; Bayer CropScience, Research Triangle Park, NC), cyantraniliprole at 0.1 (AI) kg/ha (Exirel; DuPont, Wilmington, DE), and spinetoram at 0.07 (AI) kg/ha (Radiant SC; Dow AgroSciences, Inc., Indianapolis, IN). Each insecticide was applied no more than twice consecutively; if the action threshold was not exceeded for a week, no insecticide was applied. Insecticides were applied with a CO_2-pressurized backpack sprayer with four, twin flat-fan nozzles (TJ-60-8003VS; TeeJet Technologies Harrisburg, PA) calibrated to deliver 337 L per hectare at 276 kPa. All insecticides were co-applied with an adjuvant at 0.5% v:v (Induce; Helena, Collierville, TN) to increase efficacy (Nault et al., 2013).

2.1.2. Phosphorus trial

A total of 16 treatments (2 onion cultivars x 4 phosphorus rates x 2 insecticide treatments) were replicated 5 times. The same onion cultivars and insecticide treatments evaluated in the nitrogen trial were included in this trial. Similarly, the treatments were arranged in a split-split plot design in which cultivar was the main plot factor, phosphorous fertilizer was the sub-plot factor and insecticide was the sub-sub-plot factor. Arrangement of the cultivars, phosphorus treatments and insecticide applications were the same as described in the nitrogen trial. Phosphorus rates were 0, 56, 112, and 168 kg/ha. Phosphorus rates were based off current soil tests and recommendations from Cornell University (recommended rate = 168 kg/ha) (Reiners et al., 2017). Triple superphosphate (0-46-0; N–P–K) was applied at planting. Experimental plots were supplemented at planting with the appropriate rates of nitrogen (Urea; 46-0-0; N–P–K) and potassium (potassium chloride; 0-0-60; N–P–K) per fertility guidelines (Reiners et al., 2017). All fertilizers were broadcast and incorporated into the soil. Plots were the same size and orientation as those in the nitrogen trial; the total area of the trial was 32 m wide x 41 m. Soil samples were used to confirm phosphorus rates in the field (Supplemental Table 2).

Initiation of the insecticide sequence was executed in the same manner as described in the nitrogen trial. Subplots were scouted weekly beginning on 19 Jun 2017 and 19 Jun 2018, and insecticide program treatments were initiated when treatments reached a mean density of 1 larva per leaf, which occurred on 8 Aug 2017 and 1 Jul 2018. In 2017, 'Avalon' did not surpass the action threshold at any point, and thus no insecticide was applied.

2.2. Onion thrips population assessments

In both fertility trials, numbers of larvae were counted weekly in every subplot. Only onion larvae were recorded, as previous studies have indicated that adults do not significantly contribute to crop damage (Coudriet et al., 1979; Leach et al., 2017). Ten plants, randomly selected from the inner three rows, were visually examined for thrips larvae. Counts began early in the growing season, when plants had approximately 3–4 leaves, and concluded when 80% or more of the plants matured. Numbers of onion thrips larvae were binned into three sampling periods based on onion development; pre-bulbing (19 June to 10 Jul 2017, 19 June to 10 Jul 2018), bulbing (11 Jul to 7 Aug 2017; 11 Jul to 31 Jul 2018), and post-bulbing (8 Aug to 28 Aug 2017; 1 Aug to 15 Aug 2018).

2.3. Bacterial rot assessment

Within-season assessment. In mid to late season, plants in the nitrogen and phosphorus trials were examined for bacterial rot symptoms. Onions displaying typical bacterial rot symptoms including bleached and wilted inner leaves were considered infected (Schwartz and Mohan, 2008). Plants from the inner three rows of onions in each subplot were visually inspected, and the number of infected plants were counted. Subplots were evaluated on two dates during the growing season, 30 Jul 2017 and 15 Aug 2017; 1 Aug 2018 and 15 Aug 2018. Due to the later insecticide application timing in 2017, the number of onions with bacterial rot symptoms was only assessed in untreated control subplots. All insecticide treatment subplots were assessed for bacterial rot in 2018.

At harvest assessment. Onions were cured in the field for at least one week before they were evaluated for bacterial bulb rot (see details about harvest below). A subsample of approximately 40 bulbs (diameter of >5 cm, weight of >90g) were cut longitudinally and inspected for bacterial decay. Incidence of bacterial rot was determined for each subplot (*n* rotten onion bulbs/total onion bulbs in subsample). To confirm bacterial infection in the symptomatic bulbs, bacterial species were identified from a random subsample of 20 onion bulbs per cultivar. Bacteria from a subset of symptomatic bulbs were recovered using a semi-selective onion extract medium (Zaid et al., 2012). Bacteria were identified by sequence analysis of a portion of the gyrB gene or the 16S gene, or in the case of lactic acid bacteria, the RpoA gene, amplified by PCR (Asselin et al., 2016, 2017, 2019). The gene portions were sequenced by the Cornell Biotechnology Resource Center (Ithaca, NY) and sequences were compared to preexisting entries in GenBank.

2.4. Management of other pests and pathogens

Onion plants in both the nitrogen and phosphorus trials were managed to reduce damage by other pests in the production system. To ensure crop establishment, seeds were treated with FarMore FI500 (mefenoxam (0.15 g ai/kg), fludioxonil (0.025 g ai/kg), azoxystrobin (0.025 g ai/kg), spinosad (0.20 mg ai/seed), thiamethoxam (0.2 mg ai/seed)) and Pro-Gro (carboxin (7.50 g ai/kg)) and Thiram (thiram (12.50 g ai/kg)). Active ingredients in the seed treatment were no longer present by trial initiation and are not known to impact onion thrips or bacterial bulb rot. Other than onion thrips, no insect pests damaged onions in this experiment. Symptoms of iris yellow spot disease, which is caused by iris yellow spot virus and transmitted by onion thrips, was nearly absent in 2017 and low in 2018. Weeds and foliar plant pathogens were successfully managed using pesticides following Cornell vegetable management guidelines and recommendations (Reiners et al., 2017).

2.5. Onion bulb yield

For each fertility trial, onion plants were undercut when 80% or more of each onion cultivar had senesced and then cured in the field for one week before harvest. Onions were harvested on 30 Aug 2017 and 18 Aug 2018. Bulbs were graded by bulb diameter and assigned a size class of either 'boiler' (2.5 cm–4.8 cm), 'standard' (4.9 cm–7.6 cm), or 'jumbo' (≥7.7 cm) and then weighed. Bulbs that were either 'standard' or 'jumbo' were considered marketable, and 'boiler' bulbs unmarketable (AMS, 2014). Yields of marketable bulbs were estimated on a mean metric ton per hectare basis by multiplying mean bulb weight in each size class by the density of plants in the plots. Adjusted marketable yields were calculated for each subplot by subtracting the percent of bulbs with bacterial rot from the estimated yield (see 2.3 for bacterial rot assessment).

2.6. Statistical analysis

Data within each year were analyzed independently since environmental conditions and thrips pressure were different between years in both fertility trials (Supplemental Table 3). Data were analyzed using generalized linear mixed models (R version 3.5.2; 'lme4', Bates et al., 2015). Models were fit with fixed effects of onion cultivar, fertilization rate, insecticide use, and all their interactions, and included random effects of strip and plot nested within strip as well as subplot nested within plot nested within strip.

A combination of Poisson and negative binomial distributions were used to model dependent variables that were either right skewed or overdispersed counts. The mean number of larvae per leaf were analyzed assuming a negative binomial distribution. The count of onion plants with bacterial rot within the growing season was analyzed using a Poisson distribution. Bacterial rot incidences were analyzed as a binomial distribution as the objective of this dataset was to determine the probability of observing rot within each treatment. Soil fertility values and adjusted marketable yield were analyzed assuming normal distributions. Models were tested for appropriateness by examining distribution of residuals, overdispersion and zero inflation with R packages, blmeco and Dharma (Korner-Nievergelt et al., 2015; Hartig, 2018). No insecticide applications were applied in the 'Avalon' in the phosphorus trial in 2017, which precluded the three-way analysis between phosphorus rate, onion cultivar, and insecticide use. Treatments in each analysis were compared using least squared means ($P < 0.05$) ('emmeans', Lenth, 2018).

3. Results

3.1. Onion thrips densities

3.1.1. Nitrogen trial

Densities of onion thrips increased as the season progressed both years; however, thrips populations were greater in 2018 than 2017 (season total mean of 0.6 larva/leaf in 2017 vs. season total mean of 13.2 larvae/leaf in 2018 in the untreated control). On average, thrips densities were lowest during the pre-bulbing and bulbing stages and peaked during the post-bulbing stage.

2017. Seasonal thrips densities were significantly impacted by cultivar, nitrogen rate, and the interaction of cultivar and nitrogen rate (Fig. 1a, Supplemental Table 5). Unfertilized 'Avalon' and 'Bradley' had the highest mean seasonal number of thrips (0.8 thrips/leaf), and 'Avalon' fertilized with 67 kg/ha had the lowest mean seasonal larval density (0.2 thrips/leaf) (Fig. 1a). Insecticide use also significantly impacted thrips, and higher densities were recorded in the untreated control (0.59 ± 0.02 thrips per leaf) as compared with the insecticide treatment (0.48 ± 0.01 thrips per leaf). These relationships were consistent throughout the growing season and onion cultivar, nitrogen rate, and the interaction of onion cultivar and nitrogen rate significantly impacted thrips densities during all developmental stages in 2017 (Supplemental Table 4e) (Supplemental Figs. 1a–d).

2018. Seasonal thrips densities were significantly impacted by insecticide and the interaction of cultivar and insecticide use, but not by either cultivar or nitrogen rate alone (Fig. 1b, Supplemental Table 5). 'Avalon' treated with insecticide had the lowest seasonal thrips density (1.6 thrips/leaf) compared with insecticide-treated 'Bradley' (2 thrips/leaf) and untreated 'Avalon' and 'Bradley' (6.7 thrips/leaf) (Fig. 1b). During the growing season, thrips densities were significantly impacted by onion cultivar and insecticide use during the bulbing and postbulbing stages, but not the prebulbing stage (Supplemental Table 4, Supplemental Fig. 1).

3.1.2. Phosphorus trial

Similar to the nitrogen trial, thrips densities increased throughout the season in both years, but infestation levels were much higher in 2018 than 2017 (season total mean of 0.4 thrips larvae/leaf in 2017 vs. season total mean of 12.1 in 2018).

2017. Seasonal thrips densities were only impacted by onion cultivar

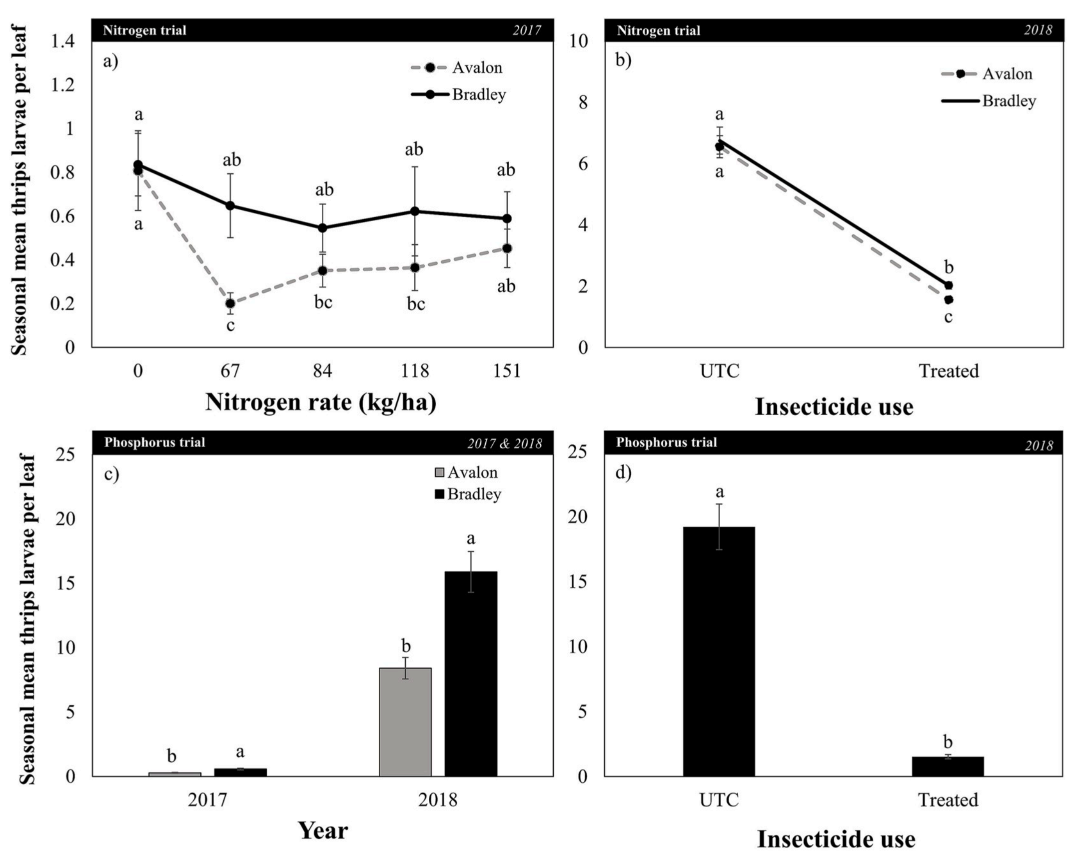


Fig. 1. Significant effects of the interaction of cultivar and insecticide (a), and interaction of onion cultivar and nitrogen rate (b), onion cultivar (c), insecticide use (d) on seasonal larval onion thrips densities (±SE) in 2017 (a, c) and 2018 (b, d). Five different rates of nitrogen were applied through the growing season; 0 kg ha-1, 67 kg ha-1, 84 kg ha-1, 118 kg ha-1 and 151 kg ha-1. Phosphorus rates were 0, 56, 112, and 168 kg ha-1. 'Avalon' is moderately thrips resistant and 'Bradley' is susceptible to thrips feeding. Every fertilizer treatment and onion cultivar combination were either treated with insecticide or left untreated. Means sharing a letter are not significantly different (least-squared means, $P < 0.05$).

(Fig. 1c, Supplemental Table 6). Thrips densities were reduced in 'Avalon' compared to 'Bradley' (Fig. 1c), which was consistent throughout the growing season (Supplemental Table 7; Supplemental Fig. 2).

2018. Seasonal thrips densities were significantly impacted by cultivar and insecticide use which was consistent with trends during the growing season (Fig. 1d, Supplemental Fig. 2, Supplemental Tables 6 and 7). Mean seasonal number of larvae per leaf in 'Avalon' was significantly lower than the seasonal value for 'Bradley' (Fig. 1c). Thrips numbers were also lower in insecticide-treated plots compared to those not treated (Fig. 1d).

3.2. Bacterial rot

3.2.1. Nitrogen trial

Incidences of bacterial rot differed between years. Overall incidences of rot, pooled across all treatments at harvest, were 6.6% and 9.3% in 2017 and 2018, respectively. In 2017, the following bacterial species and frequencies were detected: *Lactobacillus plantarum* (20/42), *Pseudomonas spp*. (12/42),*Klebsiella oxytoca* (6/42), *Rahnella spp.* (4/42), *Pantoea spp.* (2/42), and *Leuconostoc pseudomesenteroides* (1/42) were detected. In 2018 *Burkholderia spp.* (30/40), *Enterobacter ludwigii* (17/40), *Kosakonia cowanii* (4/40), and *Rahnella spp.* (2/40) were detected.

Within-season. Onion cultivar significantly impacted the number of plants with bacterial infection in both years and nitrogen rate impacted numbers of infected plants in 2017; insecticide use had no impact in either year (Supplemental Table 5). On average, twice as many 'Avalon' plants displayed symptoms of bacterial infection compared with 'Bradley' (Fig. 2a). In 2017, the number of plants displaying bacterial symptoms increased with increasing rates of nitrogen (Fig. 2b). The greatest number of infected plants was recorded in the two highest rates of nitrogen, followed by the intermediate rates and unfertilized control.

At harvest. In 2017, nitrogen rate and insecticide use significantly impacted the percent bulbs with bacterial rot at harvest, but not cultivar (Supplemental Table 5). Bulbs fertilized with nitrogen (67 kg ha^{-1} N or higher) experienced significantly greater levels of bacterial rot as compared with unfertilized onions (Fig. 3a). Insecticide use also significantly impacted the incidence of bacterial rot, as insecticide treated plots had twice the amount of bacterial rot as compared with the percentage of rot in untreated plots (Fig. 3b). In 2018, onion cultivar and insecticide use significantly impacted bacterial bulb rot (Supplemental Table 5). 'Avalon' had twice the amount of bacterial rot as 'Bradley' (Fig. 3c). Insecticide use also influenced bacterial rot; however, the relationship was opposite as that observed in 2017. Plots treated with insecticide had significantly less rot as compared with levels in the untreated controls (Fig. 3d). However, thrips densities (mean number and total number per plot) were not significantly associated with incidence of bacterial rot in 2017 or 2018 ($p > 0.05$).

3.2.2. Phosphorus trial

Greater levels of bacterial rot were detected in 2018 compared to 2017 (2017: 2.8% incidence of rot at harvest; 2018: 10.1% incidence of rot at harvest). The following bacterial species and frequencies were isolated from bulb samples in 2017: *Lactobacillus plantarum* (30/36), *Rahnella spp.* (7/36), and *Pantoea agglomerans* (1/36). In 2018, *Enterobacter ludwigii* (30/45)*, Burkholderia spp.* (21/45)*, Kosakonia cowanii* (10/45), and *Rahnella* species (4/45) were detected.

Within-season.

In both years, only onion cultivar significantly impacted the number of plants exhibiting bacterial rot symptoms (Fig. 2c). Phosphorus rate and insecticide use, and their interactions had no impact on plants with bacterial rot symptoms (Supplemental Table 6). Overall, 'Avalon' had greater numbers of plants with bacterial rot symptoms in both years (Fig. 2c).

At harvest.

In 2017, onion cultivar, phosphorus rate, insecticide use, and the interactions between cultivar and phosphorous had no impact on the incidence of bacterial rot (Supplemental Table 6). While only 'Bradley' was treated with an insecticide in 2017, interactions among some of the main effects on bacterial rot were omitted from the analyses. Nevertheless, insecticide use in 'Bradley' did not significantly impact the incidence of bacterial rot in 2017. Similar to the nitrogen trial, thrips

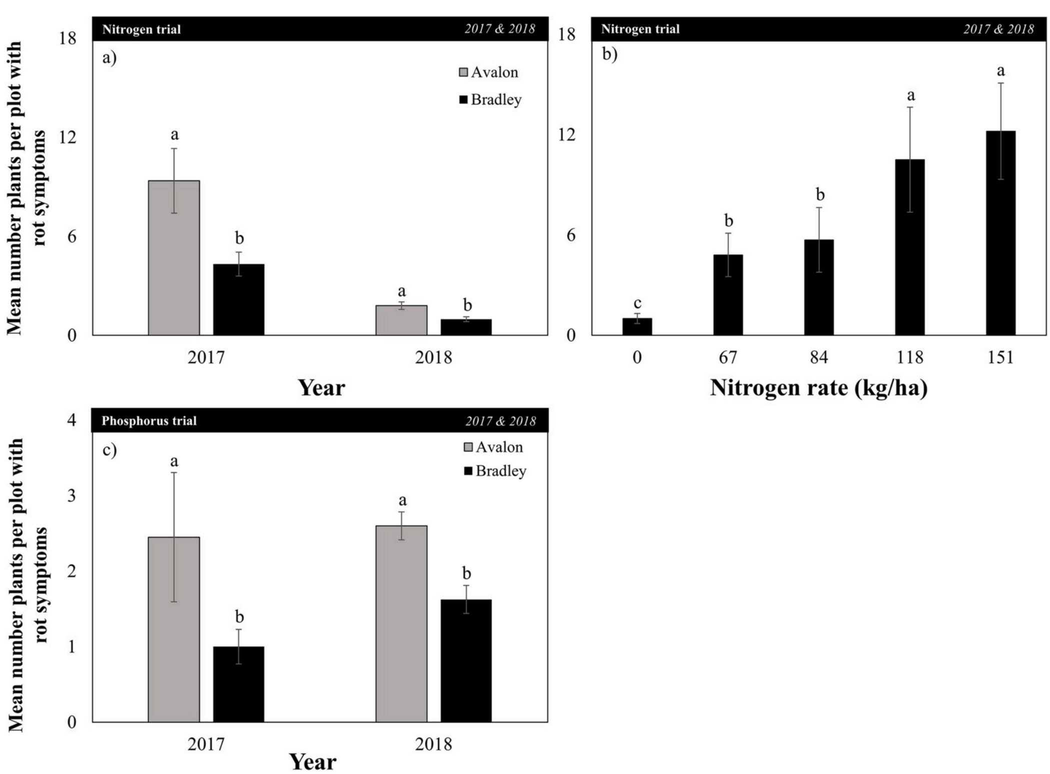


Fig. 2. Significant effects of nitrogen rate (a) and onion cultivar (b, c) on the number of onions with bacterial bulb rot symptoms (±SE) in 2017 (a, b, c) and 2018 (a, c). Five different rates of nitrogen were applied through the growing season; 0 kg ha-1, 67 kg ha-1, 84 kg ha-1, 118 kg ha-1 and 151 kg ha-1. Phosphorus rates were 0, 56, 112, and 168 kg ha-1. 'Avalon' is moderately thrips resistant and 'Bradley' is susceptible to thrips feeding. Every fertilizer treatment and onion cultivar combination were either treated with insecticide or left untreated. Means sharing a letter are not significantly different (least-squared means, $P < 0.05$).

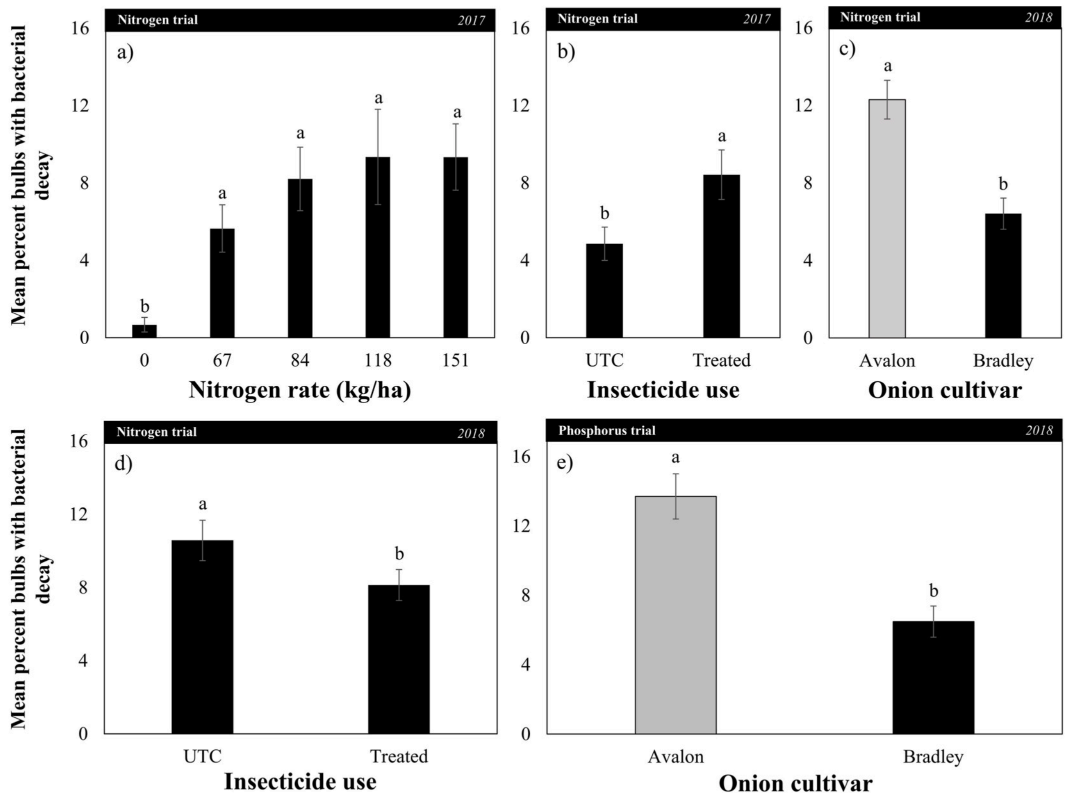


Fig. 3. Significant effects of nitrogen rate (a), insecticide use (b, c), and onion cultivar (d, e) on the incidence of bacterial rot (±SE) in marketable onions in 2017 (a, b) and 2018 (c, d, e). Five different rates of nitrogen were applied through the growing season; 0 kg ha-1, 67 kg ha-1, 84 kg ha-1, 118 kg ha-1 and 151 kg ha-1. Phosphorus rates were 0, 56, 112, and 168 kg ha-1. 'Avalon' is moderately thrips resistant and 'Bradley' is susceptible to thrips feeding. Every fertilizer treatment and onion cultivar combination were either treated with insecticide or left untreated. Means sharing a letter are not significantly different (least-squared means, $P < 0.05$).

densities were not significantly associated with incidence of bacterial rot in either year ($p > 0.05$). In 2018, percent bacterial rot was significantly affected by onion cultivar, but not phosphorus rate or insecticide use (Supplemental Table 6). Greater percentage of bacterial rot was recorded in 'Avalon' (13.7 ± 1.2%) compared with 'Bradley' (6.4 ± 0.9%) (Fig. 3e).

3.3. Onion yield

3.3.1. Nitrogen trial

In 2017, adjusted marketable yields were significantly impacted by cultivar and nitrogen rate, but not insecticide use (Fig. 4b, Supplemental Table 5). Yields in 'Bradley' were 9% higher than those in 'Avalon' (Fig. 4b). Fertilized treatments had 74% greater adjusted marketable yields compared to unfertilized treatments (Fig. 4a). In 2018, Adjusted marketable yields were significantly impacted by cultivar, insecticide use and the interaction between onion cultivar and insecticide use. Untreated controls for both cultivars had the lowest yields, followed by 'Avalon' treated with insecticide and then 'Bradley' treated with insecticide (Fig. 4c).

3.3.2. Phosphorus trial

In 2017, adjusted marketable yields were significantly impacted only by phosphorus rate, but not onion cultivar, insecticide program or their interaction (Supplemental Table 6). Unfertilized controls had the lowest yields, whereas plots treated with 56 and 168 kg ha-1 P had 10–12% higher yields (Fig. 4d). In 2018, Adjusted marketable yield was only impacted by insecticide treatment (Supplemental Table 6). Treated plots had 42% greater yields compared with untreated controls (Fig. 4e).

4. Discussion

Few IPM programs identify tactics that can be used in tandem to manage multiple pests within an agricultural production system. For example, onion production is challenged by multiple insects and plant pathogens (i.e. onion thrips and bacterial bulb rot), but no IPM program has identified multiple tactics to manage these pests. Thus, in this study, we examined the effect of a multipartite IPM program to reduce onion thrips densities and bacterial bulb rot (Table 1). We hypothesized that a thrips-resistant cultivar combined with a reduced fertility regime and an action-threshold based insecticide program would have the greatest success in managing onion thrips and reducing bacterial bulb rot, thereby increasing marketable yields. While we found that the combination of the moderately thrips-resistant cultivar ('Avalon') and action threshold-based insecticide program significantly reduced thrips densities, the reduction in fertility (nitrogen and phosphorous) had little impact on thrips densities (Table 1). Despite a reduction in thrips densities using 'Avalon' and an action-threshold based program, the incidence of bacterial bulb rot was not reduced consistently. Moreover, 'Avalon' had much greater levels of bacterial rot and reduced marketable yields than the thrips-susceptible 'Bradley' (Table 1). Consequently, the highest marketable yields were observed in the cultivar 'Bradley' that was fertilized with minimal amounts of nitrogen and phosphorous and treated with an action-threshold based insecticide program. Our study highlights the importance of selecting IPM tactics that optimize management for multiple pests within a production system.

Host plant resistance shows great promise as a preventative tactic for onion thrips management in onion. Consistently, 'Avalon' had fewer onion thrips than 'Bradley' regardless of any additional management tactic implemented (insecticide use or fertility regime). Findings from previous studies indicated that thrips prefer onion cultivars with high

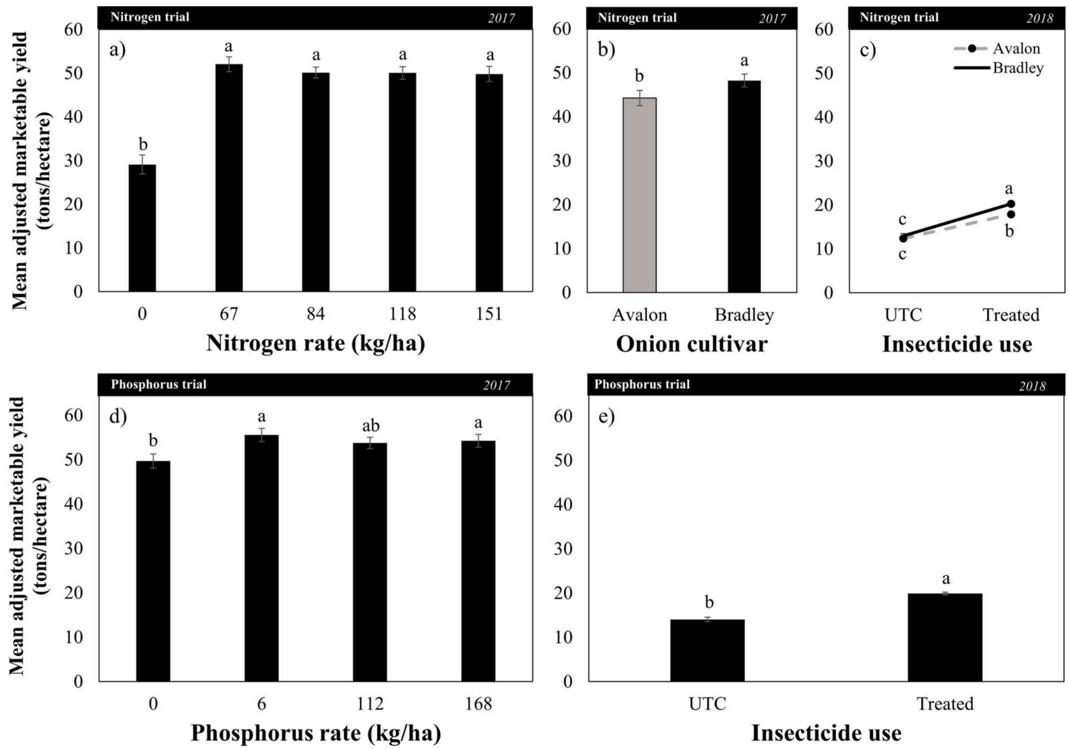


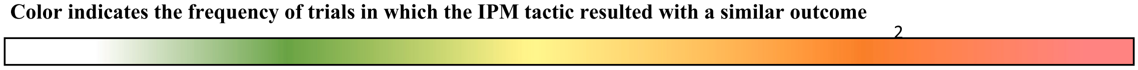
Fig. 4. Significant effects of fertilizer rate (a, d), onion cultivar (b), interaction of onion cultivar and insecticide use (c), and insecticide use (e) on adjusted marketable yield (±SE) in 2017 and 2018. Five different rates of nitrogen were applied through the growing season; 0 kg ha-1, 67 kg ha-1, 84 kg ha-1, 118 kg ha-1 and 151 kg ha-1. Phosphorus rates were 0, 56, 112, and 168 kg ha-1. 'Avalon' is moderately thrips resistant and 'Bradley' is susceptible to thrips feeding. Every fertilizer treatment and onion cultivar combination were either treated with insecticide or left untreated. Means sharing a letter are not significantly different (least-squared means, $P < 0.05$).

Table 1
Summary of the net effects of three IPM tactics implemented to manage onion thrips and bacterial bulb rot in onion in New York.

IPM tactic	Thrips densities	Bacterial bulb rot	Onion yield	Recommended practice for onion growers
Thrips-resistant cultivar	**Decrease**	**Increase**	**Decrease**	**No**
Reduced rate of fertilizer	**Decrease** [a]	**Decrease**	**Decrease** [c]	**Yes**
Insecticide use	**Decrease**	**Increase/Decrease** [b]	**Increase**	**Yes**

Color indicates the frequency of trials in which the IPM tactic resulted with a similar outcome

1
2



0/4 **1/4** **2/4** **3/4** **4/4**

[a] Thrips-susceptible onion cultivar, 'Bradley', did not experience fewer thrips at lower fertility regimes
[b] Insecticide use increased the incidence of bacterial rot in 2017, but decreased in 2018
[c] Only observed decrease was in unfertilized treatments compared with fertilized ones

amounts of certain epicuticular waxes, which is characteristic of 'Bradley' but not 'Avalon' which has less of these waxes (Diaz-Montano et al., 2012; Boateng et al., 2014; Damon et al., 2014). However, epicuticular waxes may be important for onions to resist foliar plant pathogens. Mohan and Molenaar (2005) reported that onion cultivars with lower amounts of epicuticular wax (glossy leaf phenotypes) were more vulnerable to powdery mildew caused by *Leveillula taurica* than waxier cultivars. In our study, 'Avalon' consistently had fewer thrips, but approximately 77% more bacterial rot as compared to 'Bradley'. Thus, the slight to moderate advantage that 'Avalon' had for reducing thrips damage was surpassed by its greater disadvantage of succumbing to moderate to high levels of bacterial rot. Therefore, 'Avalon' is not appropriate for an onion production system where onions are continuously grown in the same fields that have moderate to high bacterial rot inoculum levels and are in climatic areas that are wet and conducive for bacterial diseases.

Previous studies have shown that red onion and Spanish onion cultivars tend to have a higher incidence of bacterial rot than other cultivar types and may be predisposed to these pathogens in certain climates (Schroeder et al., 2010; Pfeufer et al., 2015; Wohleb and Waters, 2016; Stumpf et al., 2017). While unreported in this study, we consistently observed differences between 'Avalon' and Bradley' including variations in plant development, maturity, and susceptibility to foliar plant pathogens. These differences may explain, in part, the predisposition of 'Avalon' to rot, as other studies have indicated the importance of onion development and curing in the incidence of bacterial rot (Wright et al., 2001). Nevertheless, further research should address the mechanisms behind cultivar susceptibility to bacterial rots.

Some studies have indicated that onion thrips play a role in transmitting *Pantoea spp.* to onion, thereby causing bacterial bulb rot (e.g. Dutta et al., 2014). Thus, management of onion thrips using insecticides has been suggested as a strategy for reducing bacterial diseases in onion (Grode et al., 2017, 2019). In our 2-yr study, the incidence of bacterial bulb rot in onion was reduced in only one of four trials when using insecticides to manage onion thrips. Admittedly, *Pantoea spp.* were not identified in most of our symptomatic onion bulbs (<5%), which may explain why we failed to confirm a relationship between onion thrips densities and bacterial bulb rot. Furthermore, the bacterial complex found in New York may be different from other onion production areas in the U.S. (Beer et al., 2010). While we identified a number of known pathogenic bacterial species, a number of opportunistic or weakly pathogenic bacterial species were also identified, which may indicate secondary infections of the bulbs sampled. Therefore, it is possible that the bacterial species identified may not have been the initial colonizer or the cause of the infection. Nevertheless, it should be noted that only one laboratory trial has implicated onion thrips in the development of bacterial bulb rot (Dutta et al., 2014), and all other reports have only identified a relationship between bacterial leaf blight and onion thrips (which was not examined in our study) (e.g. Grode et al., 2017; Grode et al., 2019). Consequently, it is possible that thrips contribute to foliar bacterial diseases, such as those reported in Grode et al. (2017) and Grode et al. (2019), but do not necessarily increase the incidence of bacterial bulb rot in the field.

Plant fertilization may not be an effective cultural control tactic for onion thrips in muck onion production. Studies conducted on mineral soil report a reduction in onion thrips densities with decreasing rates of nitrogen but reports from muck soil have shown that pest damage is not affected by differing fertility regimes. For example, Westerveld et al. (2003) did not observe differences in insect feeding damage in onion grown in muck soil treated with nitrogen at rates: 0, 90, and 180 kg/ha. Similarly, Leach et al. (2017) found no significant differences in thrips densities in onions grown in muck soil treated with 67, 101 and 140 kg of nitrogen/ha. Thus, results from our study are consistent with these previous reports and suggest that reducing fertilizer in muck soils will not improve thrips management.

Phosphorus fertilizer did not significantly impact seasonal mean larval densities in 2017 or 2018. Chen et al. (2004) reported a 40% decrease in the number of western flower thrips on impatiens flowers when fertigated with a 0.32 mM (mM) rate/pot of phosphorus compared with those fertilized with the 1.28 mM rate/pot. In our study, thrips were not significantly impacted by phosphorus, but amendments also did not significantly impact plant growth, which may explain why we failed to find differences in onion thrips densities. Thus, further evaluation is needed to determine if phosphorus may be an effective cultural control of onion thrips in mineral onion production. To the authors' knowledge, this is the first study to evaluate the effect of phosphorus fertilizer on onion thrips in onion.

The significance of nitrogen fertilizer on levels of bacterial bulb rot differed between years in our study. In 2017, bacterial rot significantly increased with nitrogen fertilization, which is consistent with previous reports (Wright, 1993; Batal et al., 1994; Diaz-Perez et al., 2003). However, nitrogen fertilizer did not significantly impact bacterial bulb rot levels in our study in 2018, which may have been attributed to the different weather conditions between the years. Although it should be noted that onions treated with lowest levels of nitrogen generally had numerically decreased levels of bacterial bulb rot in 2018. Therefore, it may benefit growers to reduce nitrogen application rates to 67 kg/ha, as greater amounts of nitrogen fertilizer may significantly increase bacterial bulb rot. Phosphorus fertilizer did not significantly impact bacterial bulb rot; however, we did not observe any differences in plant growth and minimal differences in onion yield. Thus, if bacterial rot is significantly impacted by plant growth, further evaluation should address phosphorus fertilizer amendments when plants are responsive to the phosphorus fertilization.

Low rates of nitrogen and phosphorus fertilizer (67 kg/ha N and 56 kg/ha P) produced statistically similar yields to plants fertilized with highest rates of fertilizer in both years. In fact, adjusted marketable yields in the following rates of nitrogen (84 kg/ha, 118 kg/ha, or 151 kg/ha) decreased by 8–10% due to greater levels of bacterial bulb rot in 2017. Muck soils are unique as they are rich in organic matter, and naturally high in nitrogen (Harmer and Lucas, 1956). Multiple studies have documented that less fertilizer is typically needed in muck agriculture (Haynes, 2012; Gonzalez et al., 2016), and current recommended rates of nitrogen can be as low as 67 kg/ha (Warncke et al., 2004). However, in New York, growers regularly fertilize with approximately 118 kg/ha N annually (Nault and Hoepting 2014; *unpublished*). Our study suggests that a large majority of fertilizer remains in the soil, as we consistently observed higher rates of soil nitrate with higher rates of nitrogen fertilizer, which is similar to other studies (Boyhan et al., 2007). Therefore, growers should critically evaluate their soil fertility programs to maximize yields, but also reduce fertilizer loss from leaching or runoff.

5. Conclusions

Pest management in agricultural production systems, like onion, is inherently complex as these systems are challenged by multiple pests and pathogens. Kogan (1998) argued that the progress of IPM relies on the integration of multiple pest management tactics at increasing agricultural scales. Recently, the relevance of IPM has been questioned (Peterson et al., 2018), with many urging researchers to create programs that will manage multiple pest interactions within an agroecosystem. Our study illustrates the importance of curating an integrated pest management program to address multiple pests in a production system (i.e. onion thrips and bacterial rot). In our case, we found that an integrated pest management tactic (thrips-resistant onion cultivar 'Avalon') was effective in reducing densities of an important onion insect pest, but highly susceptible to bacterial rot pathogens. Additionally, an integrated pest management tactic (reducing fertilizer levels) that reduced insect densities in other onion production systems did not consistently reduce insect densities in our system. However, we found decreasing rates of fertilizer did not compromise levels of marketable yield, and in one year it decreased the incidence of bacterial rot. Future research should continue to develop pest management programs that holistically evaluate their impact on major pests within production systems, such that growers can observe maximum benefits from the programs and increase sustainability.

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.

CRediT authorship contribution statement

Ashley Leach: Conceptualization, Data curation, Formal analysis, Writing - review & editing. **Stephen Reiners:** Conceptualization, Writing - review & editing. **Brian Nault:** Conceptualization, Data curation, Formal analysis, Writing - review & editing.

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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.2020.105123.

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