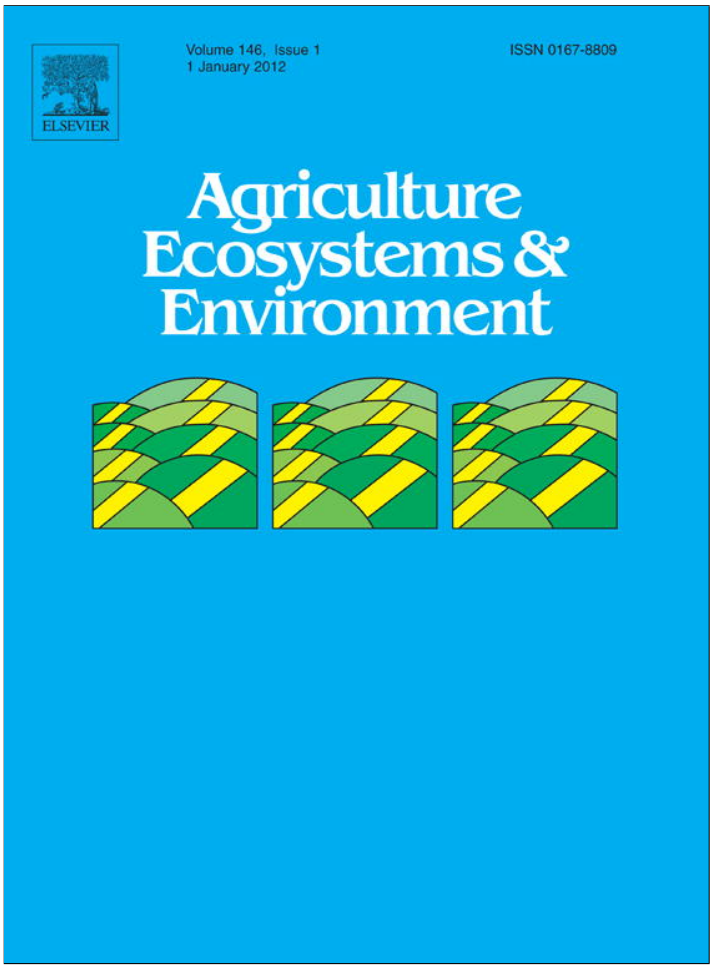

Agriculture, Ecosystems and Environment 177 (2013) 63–74

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

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

Effects of nitrogen fertility and crop rotation on onion growth and yield, thrips densities, Iris yellow spot virus and soil properties

K. Buckland[a,*], J.R. Reeve[a], D. Alston[b], C. Nischwitz[b], D. Drost[a]

[a] Department of Plants, Soils and Climate, 4820 Old Main Hill, Logan, UT 84322-4820, United States
[b] Department of Biology, 5305 Old Main Hill, Logan, UT 84322-5305, United States

ARTICLE INFO

Article history:
Received 28 March 2013
Received in revised form 7 June 2013
Accepted 10 June 2013

Keywords:
Onion
Onion thrips
IYSV
Nitrogen fertilizer
Biostimulant
Crop rotation

ABSTRACT

Onion thrips and Iris yellow spot virus (IYSV) are two primary yield reducing factors in onion production worldwide. Current management practices rely on heavy use of insecticides and fertilizers, threatening the sustainability of onion systems. Little is known about how cultural practices such as reduced fertility, soil biostimulants, and crop rotation affect onion yield, thrips densities, soil properties, and IYSV incidence. In a replicated field experiment, reduced nitrogen (N) (134 kg N ha^{-1}, one-third the standard grower rate), slightly decreased yield and onion size. Adult thrips populations were 23 to 31% lower in the reduced as compared to standard N (402 kg N ha^{-1}) and biostimulant treatment, respectively. Growing onions following a one year cycle in corn rather than wheat reduced onion thrips in one of two years. The addition of a biostimulant had no effect on soil properties, but may have slightly increased yield, attracted adult thrips, and increased thrips populations. IYSV incidence was not influenced by fertilizer rate or crop rotation. Soil microbial biomass and readily mineralizable carbon were greater following wheat, while soil nitrate (NO_3^-) accumulation was greater in standard N treatments. Soil microbial activity, as measured by dehydrogenase enzyme potential, may have been adversely affected by high N rates. Results suggest that reduced N, without biostimulant, sustained onion yields, decreased onion thrips densities and potential for IYSV incidence, created a more favorable soil environment for microbial activity, and reduced the risk of NO_3^- leaching

1. Introduction

Allium cepa L., bulb onion, is a high value crop grown in the western United States and in many regions of the world. Farmland planted annually to onions in Utah exceeds 800 ha with a value between 4 and 10 million dollars (NASS, 2006). Due to the value of the crop, onions are intensively managed, frequently with short rotations, high fertilizer rates, and aggressive use of insecticides to suppress *Thrips tabaci* Lindeman, onion thrips (OT). Despite intensive management, yield loss due to thrips and diseases can be severe (Kendall and Capinera, 1987; Gent et al., 2006). Primary thrips control in the temperate U.S. is through almost weekly applications of several classes of insecticides, including pyrethroids, carbamates, spinosyns, and others from June through August (DeFrancesco, 2012). As a result, high input costs, removal of beneficial insects, and increased insecticide resistance are a growing concern (Larentzaki et al., 2007; MacIntyre Allen et al., 2005). In addition to economic losses associated with feeding damage, OT also vector Iris yellow spot virus (IYSV). IYSV causes lenticular shaped lesions on leaves that can lead to a substantial decline in photosynthesis and resulting bulb size, and has emerged as a serious threat to onion production worldwide (Pappu et al., 2009). Conservative estimates of 5–10% yield loss to IYSV have been reported in bulb production in Colorado (Gent et al., 2006). While some onion varieties appear less susceptible to the virus, no resistant variety is currently known (Gent et al., 2006; Shock et al., 2008). Excessive rates of fertilizers, increasing insecticide resistance, and continued crop loss from thrips and IYSV threaten the sustainability of onion production in the western United States.

To date, most research studies have focused on a single aspect of onion crop management at a time, such as improved methods of thrips control; however, an integrated or systems approach is necessary to examine the complex interactions between multiple farm components that affect production (Drinkwater, 2009; Doré et al., 2011). By examining the farm as a whole, the goal is to identify system-wide drivers of pest pressure, for example, and identify cultural practices that synergistically enhance production and ecosystem function for improved sustainability. As such, a whole farm approach should seek to optimize production by manipulating key components such as crop rotation, integrated pest management, and nutrient cycling.

* Corresponding author. Tel.: +1 435 797 3192; fax: +1 435 797 3376.
E-mail address: kristine.buckland@aggiemail.usu.edu (K. Buckland).

0167-8809/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agee.2013.06.005

Altering cultural management practices such as crop rotation may be an effective method to suppress insect and disease pressure while maintaining yields. Modern agriculture favors shorter crop rotations for ease of management and perceived higher profits; however, this practice allows polyphagous pests such as OT to sustain populations between ideal hosts (Milne and Walter, 1998). Longer term, more diverse crop rotations have long been used effectively to prevent pests. Rotations that include fewer favorable hosts can interrupt resource requisites in time and/or space, such as oviposition sites or highly nutritious food sources, which may limit the success of insect populations as well as reduce virus incidence (Altieri, 1999; Zitter and Simons, 1980). Soils under longer crop rotations have also been shown to suppress soil borne pathogens, including fungi and nematodes (Peters et al., 2003). Successful management of a plant virus and its vector may require a broad approach with multiple changes in cultural practices, such as crop rotation and nutrient management (Zitter and Simons, 1980).

Nutrient management in onions is challenging due to the shallow root system of the crop. Nitrogen application rates as high as 450 kg ha^{-1} are common in order to increase bulb size and market value. However, high application rates of fertilizer may increase N in onion tissues and crop apparency to pests (White, 1984). Onions treated with a series of N applications showed highest OT populations at highest N application rates, 70% higher than in untreated control plots, with no increase in thrips populations at N application rates of 100 kg ha^{-1} or less (Malik et al., 2009). Moreover, fertilizer use efficiencies (FUE) in highly managed onions can be as low as 15% (Halvorson et al., 2002). Following an onion crop with highly efficient N users, such as corn to maximize nutrient recovery, may increase net nutrient capture to only 39% over two seasons (Halvorson et al., 2002). Nitrate contamination of ground and surface waters has been well documented as a by-product of intensive agricultural practices and associated with significant health risks and environmental impacts (Doran and Zeiss, 2000). Concern for excessive nitrate N (NO_3^-N) leaching in onion has prompted a re-evaluation of fertilizer application rates and timing. Reduced total inputs applied in slow release formulations have proven effective in maintaining high onion yields and large bulb size (Drost and Koenig, 2002).

There is also a growing interest in the concept of soil health as a means to reduce inputs and improve the sustainability of farming systems. Soil health can be described as "the capacity of soil to function as a vital living system to sustain biological productivity, promote environmental quality, and maintain plant and animal health" (Doran and Zeiss, 2000). The addition of organic amendments can greatly improve soil health through enhanced long-term fertility and physical properties of soils, as well as increasing microbial biomass and activity (Gunapala and Scow, 1998; Bulluck et al., 2002). The relative size and activity of the soil microbial biomass is an important indicator of the availability of labile C and N compounds, nutrient cycling potential, and the overall sustainability of management practices (Doran and Zeiss, 2000). Soil microbes can also serve important roles in disease suppression (Peters et al., 2003; Gil-Sotres et al., 2005; Larkin, 2008). High rates of N fertilizer have been shown to result in lower microbial biomass and activity (Gunapala and Scow, 1998) which in turn may exacerbate plant pests (Hines et al., 2006).

Growers seeking to improve the health of their soils for pest suppression and increased plant growth sometimes turn to biostimulant applications in lieu of organic matter additions and other inputs. Little is known about the impact of these amendments since the composition between products can vary widely; however, most biostimulants increase plant health and growth through improvements in nutrient availability as a result of soil microbial activity (Russo and Berlyn, 1990). Experimental results have been variable. Russo and Berlyn (1990) found improved root growth and better resistance to environmental stress with an organic biostimulant. Conversely, Chen et al. (2002) compared two commercially available formulations and concluded applications may reduce available N over time. As these products are increasingly marketed to growers as a low cost means of improving soil health and crop performance, it is important that these products are thoroughly evaluated.

Table 1
Fertilizer application rates and timing (rates are expressed as kg ha^{-1}, except biostimulant amendments which are in L ha^{-1}) for three fertilizer treatments in 2009 and 2010.

Time of year	Standard rate (*S*)	Reduced rate + biostimulant (*B*)	Reduced rate (*R*)
Fall	56.0 N[a]	28.0 N[a] 46.8[b]	28.0 N[a]
Spring	65.6 N[c]	13.1 N[c]	13.1 N[c]
Pre-plant	222 P[c]	44.6 P[c]	44.6 P[c]
	51.3 K[d]	10.5 K[d] 46.8[b]	10.3 K[D d]
June	140 N[e]	79.6 N[e] 46.8[b]	79.6 N[e]
July	140 N[a]	13.1 N[c] 46.8[b]	13.1 N[c]
Total	401 N 222 P 51.3 K	137 N 44.8 P 12.3 K 140[b]	133 N 44.6 P 10.3 K

[a] Urea ammonium nitrate (UAN).
[b] More life.
[c] 10-34-0.
[d] 0-25-17S.
[e] Ammonium sulfate.

The goal of this study was to evaluate the effects of two N fertilizer rates, addition of a soil biostimulant, and two common crop rotation sequences on onion growth and yield, thrips populations, IYSV infection, soil health as measured by biological and biochemical indicators, and the potential for environmental risks from excess-N leaching. We hypothesized that applications of high N fertilizer rates will not consistently enhance onion growth and yield, but will, however, increase crop attractiveness to thrips and increase IYSV incidence levels while reducing soil health and increasing the potential for NO_3^- N leaching.

2. Materials and methods

2.1. Field design

Two replicated trials were conducted from 2008 to 2010 at the Utah Agricultural Experiment Station in Kaysville, Utah. Each trial utilized a completely randomized design (CRD) and spanned two growing seasons. The treatment design included two factors: (1) crop rotation [wheat (W) or corn (C)] and (2) fertilizer [standard rate (*S*), reduced rate (*R*), or reduced rate plus biostimulant (*B*)]. The six treatment combinations were each replicated four times. The soil was a Kidman fine sandy loam (Soil Survey Staff, 2010) that had been fallow for several years prior to commencement of the trial. In the growing season prior to onion production, plots measuring 7.62 m by 15.24 m were planted to either field corn (*Zea mays* var. 'Dahlco 2146' in 2008 and 'Pioneer 31G65' in 2009) or wheat (*Triticum aestivum* var. 'Jefferson' in 2008 and 2009) with no addition of fertilizer or insecticide. The corn was removed as silage and the wheat harvested in late summer, and remaining residues incorporated into the soil followed by fall fertilizer application and bed preparation (Table 1). A spring application of fertilizer was applied on March 12, 2009 and March 29, 2010 prior to onion seeding (Table 1). *Allium cepa* var. 'Vaquero' (Nunhems Seeds, Parma, Idaho), bulb onion, was seeded in 90 cm beds with four rows per

bed, approximately eight beds per plot, on March 21, 2009 and April 12, 2010 with targeted plant populations of 460,000 seeds ha^{-1}. Split fertilizer treatments were also applied on June 3 and July 2, 2009 and June 9 and July 9, 2010 to improve N availability in the root zone and decrease leaching potential. Fertilizer treatments that included biostimulant application (*B*) utilized a commercially available product in the region (MoreLife). Analysis results showed a total N content of approximately 2.2%, total C content of 10.5% and small levels of various micronutrients.

A typical grower management strategy of herbicide applications was planned for both years with glyphosphate at pre-emergence and pendimethaline (Prowl) at delayed pre-emergence. In 2009, overly wet field conditions prevented the pre-emergence applications. Subsequent herbicide applications were bromoxynil at two and four true-leaves (Buctril, at 0.58 and 1.17 L ha^{-1}, respectively) and oxyflourfen, at four and six true-leaves (Goal, at 0.44 and 1.17 L ha^{-1}, respectively). Due to heavy emergence of *Setaria viridis* (L.) P. Beauv., green foxtail, a one-time application of clethodim (Select at 0.44 L ha^{-1}) was made in late May, 2010. Hand-weeding was conducted throughout the season as needed. No insecticides were applied at any time during the experiment. Plots were sprinkler irrigated in 2008 and 2009 two times per week with a total water application of 5–7 cm. In 2010, plots were drip irrigated (TSX T-Tape Model 506-08-170) on a similar schedule delivering the same total amount of water.

2.2. Onion yield and quality

Plant growth samples were collected mid-month from May through August in 2009 (May 18, June 16, July 15, and August 17) and 2010 (May 17, June 16, July 13, and August 16). Ten whole plants were removed in the center four beds of each plot, washed, and stored at 4 °C. The total number of leaves per plant, total leaf area per plant (LI-3100, LI-COR Biosciences, Lincoln, NE), leaf chlorophyll indexes (CCM-200, Opti-Sciences, Hudson, NH), and total wet weight were recorded. Tissues were dried at 60 °C and analyzed for total N by loss on ignition (LECO TruSpec CN, LECO Inc., St Joseph, MI) as described in the operating manual. Plots were surveyed on September 1 and 18 in 2009 and August 28, September 3, 11, and 22 in 2010 for onion maturation by measuring leaf lodging using a visual rating of 1 to 5 which corresponded to 25%, 50%, 60%, 80% or 90% of the plant population lodged. After more than half the field was mature, onions were lifted, topped and bagged from two 2.44 m and two 1.52 m sections of bed per plot on September 26 and 27 in 2009 and 2010, respectively. Bulbs were sized (USDA-AMS, 1995), counted, weighed for yield analysis, and then re-bagged for storage under commercial conditions at the Utah Onion storage facility in Corinne, UT until February 11 and 10 in 2010 and 2011, respectively. After storage, onions were visually assessed and rotten onions removed. Marketable onions were then weighed for loss during storage.

2.3. Thrips

Onions were sampled for thrips at approximately two week intervals in 2009 (May 29, June 15, July 7, July 22, August 5, August 19) and 2010 (June 10, June 24, July 8, July 28, August 11, August 25). Two whole plants per plot were selected out of the center rows, cut at ground level and immediately submerged in a container with soapy water. Containers were sealed and transported to the laboratory. In the lab, the onions were washed in soapy water over a 220-mesh sieve and all insects collected with 70% ethanol into a glass vial for storage until counting. During the washing process, the third youngest leaf from each of the two plants was removed and placed into a 125 mL HDPE plastic bottle (Fisher Scientific Inc., Pittsburgh, PA) to stain thrips eggs for counting. The two leaves were stained with an acid fuchsin technique described by Bowling (1979). The leaves and stain were heated to first boil in a microwave oven to facilitate absorbance of the stain through the thick, waxy leaf cuticle. The stained leaves were then de-stained in a lactic acid solution to remove stain from leaves while leaving protein in the eggs a darker color for contrast. Leaves were then sectioned and placed between glass plates. Thrips adults, larvae, and other insects in ethanol, and eggs in stained leaves were counted with the aid of a dissecting microscope at 20–30× magnification.

Hatch of thrips larvae from eggs within leaves was also measured. The third youngest leaf from each of two additional plants in each plot was collected, placed in a sealed plastic bag, and transported to the laboratory in a cooler with blue ice. Leaves were rinsed vigorously under running water to remove external insects, placed into a sealed plastic bag with moist filter paper (Sharkskin 18.5 cm diam, Fisher Scientific Inc., Pittsburgh, PA), and placed into an incubator at 25 °C for 7 days. At the end of incubation, the two leaves, filter paper, and the inside of the bag were washed with water over a 220-mesh sieve to collect the hatched thrips larvae. The thrips were washed with 70% ethanol into a glass vial for storage until counting as described above.

2.4. Iris yellow spot virus

The presence and severity of IYSV in the plots was measured using a commercially available double antibody sandwich enzyme linked immunosorbent assay (DAS-ELISA) test (Agdia, Elkhart, IN). Plots were sampled on June 11, August 19 and September 20 in 2009, and on August 9 and September 9 in 2010. One leaf from each of twenty plants per plot was selected at random, individually bagged and stored at −20 °C until processing. Each leaf sample was extracted individually using general Extract Buffer (Agdia, Elkhart, IN). The ELISA plates were analyzed using a BioTek ELx 800 plate reader (BioTek, Winooski, VT) and samples were considered positive for IYSV in accordance with the manufacturer's protocol.

2.5. Soil chemistry

Soils were sampled on the same dates as onion plant growth samples described above. Six soil subsamples per plot were collected from 0 to 30 cm using a 2.5 cm corer and combined in the field. Soils were sieved through a 4 mm screen, stored in re-sealable plastic bags and refrigerated at 4 °C until processing within 10 days. Nitrate and ammonium N (NH_4^+ N) was extracted in 1 M KCl, and analyzed by Lachat (Quickchem 8500, Hach Company, Loveland, CO) using sulfanilamide and salicylate methods, respectively (Gavlak et al., 2003). Soil pH was measured in a 1:2 soil:water suspension for each plot once per season on soils collected on May 18, 2009 and August 16, 2010. Soil P and K levels were measured in samples collected in July, following final field applications of fertilizer, using the Olsen method (Gavlak et al., 2003). Total N was measured by combustion according to the manufacturer's protocol (LECO TruSpec CN, LECO Inc., St Joseph, MI). On May 5 and November 3, 2010, a 7.6 cm soil auger was used to collect soil at depths of 0–0.3, 0.3–0.6 and 0.6–0.9 m for nitrate leaching analysis. Two subsamples at each depth per plot were combined in the field. Soil was stored, sieved and analyzed for NO_3^- N and NH_4^+ N as described above. Suction lysimeters (Model 1900 Soil Moisture Water Sampler, Soilmoisture Equipment Corp, Santa Barbara, CA) were installed in May of each year at 0.6 and 1.2 m depths to collect soil water for NO_3^- N and NH_4^+ N analysis as above. Due to low soil moisture at 0.6 and 1.2 m depth by mid-season, leachate was only collected on June 6 and July 9, 2009 and March 4, April 17, and June 2, 2010.

2.6. Soil microbial activity

To assess microbial characteristics, soils were sampled at 0–10 cm on the same dates as plant growth samples. The sampling protocol and storage methods were as described for other soil samples. Dehydrogenase enzyme activity, as measured by the reduction of triphenyl tetrazolium chloride (Tabatabai, 1994), was used to determine microbial activity. Soil samples were analyzed using 2.5 g oven-dry weight equivalent (od eq) soil at 17% moisture. The resulting color intensity was measured using a microplate reader (Spectramax M2, Molecular Devices, Sunnyvale, CA). Mineralizable carbon (minC), soil basal respiration (BR) and active microbial biomass were also measured on the same soils collected in May and July according to the method of Anderson and Domsch (1978). Sealed vials containing 5 g od eq soil at 17% moisture content were incubated at 25 °C. Carbon dioxide (CO_2) measured in the headspace after 11 days was considered MinC. Vials were uncapped, flushed for one minute using moisture saturated air, and then recapped and the hourly rate of CO_2 production measured for BR after exactly 2 h. Active microbial biomass was measured on the same samples by adding 0.5 mL of 60 g L^{-1} aqueous solution of glucose, resting the samples for 1 h uncapped, recapping the vials for 2 h, and then removing headspace CO_2 samples for analysis. An infrared gas analyzer (model 6251, LICOR Biosciences, Lincoln, NE) was used to measure CO_2 in the headspace. All samples per test were started on the same day within 10 days of sampling, conducted on moist soil, and measured in triplicate.

2.7. Statistical analyses

Year, crop rotation, and fertilizer treatment comprised a three-way factorial in a completely randomized mixed model design where plot was the experimental unit with month as a repeated measure. A mean was computed at the plot level for all subsamples. Different plots were used in different years; therefore year was a fixed effect. The response variables of onion growth and yield, numbers of thrips, IYSV incidence, and soil chemical and biological measures were assessed using analyses of variance with PROC MIXED in the statistical analysis system for Windows version 9.2 (SAS Institute, Cary, NC). The covariance structure for repeated measures was selected using the smallest Akaike's information criteria (AIC) and varied based upon the response data set. Variables were square-root or log transformed prior to analysis to better meet assumptions of normality and homogeneity of variance. Pairwise comparisons between means were aided by the macro PDMIX800 (Saxton, 1998). Data is presented by year or by month when a significant interaction with year or month occurred. The soil N leaching data were analyzed as a two-way factorial with rotation and fertilizer as main effects. Each depth was analyzed separately. Pearson's correlations were carried out between thrips populations, onion growth data, and onion tissue N levels over both years. For presentation purposes, results were grouped by similarity of interactions in tabular format.

For results and discussion purposes, multiple means comparisons are presented as LSMeans. Adjusting for family-wise Type I error rate is known to increase Type II error in systems studies that are typically under-replicated due to cost considerations (Moran, 2003; Garcia, 2004). Results from post hoc tests using a Bonferroni correction are also presented in the tables for comparison purposes. Likewise, we present *P*-values for main effects (ANOVA) that have not been corrected for the number of parameters analyzed. In addition to correcting for multiple comparisons within a given parameter, a Bonferroni correction for the 34 parameters measured would result in a significance threshold for main effects ANOVA results of $P \leq 0.002$ which would eliminate some but not all of the study's significant results.

3. Results

3.1. Onion growth, yield and storage

Relative response of onion growth measurements to fertilizer and crop rotation treatments were similar between years, although plant dry weight, leaf number, and leaf area were significantly greater in 2009 than 2010: plant dry weight, 8.64 g (±1.02) and 3.73 g (±0.56), respectively, $P < 0.0001$; leaf number, 6.62 (±0.26) and 5.59 (±0.36), respectively, $P < 0.0001$; and leaf area, 344.09 cm^2 (±24.72) and 137.73 cm^2 (±18.84), respectively, $P < 0.0001$. Leaf area was positively correlated with onion dry weight within each sample date, except in August of 2010 (data not shown). Fertilizer treatment, but not crop rotation, strongly influenced the amount of total tissue N (Table 2), the timing of onion maturation as measured by lodging, and bulb yield (Table 3) in both years. Onion leaf tissue N was greater in 2009 than in 2010 (Table 2). There was a significant year × fertilizer × month interaction for tissue N (Fig. 1). N uptake was greatest in June of each year but was delayed and reduced in 2010 compared to 2009. Within each month, N in leaf tissue was always significantly greater in *S* than *R* and *B* with the exception of July 2009 and June 2010 where no differences were noted. The ranking of *R* and *B* within each month varied. Also, there was no difference between *S* and *B* in August 2010 (Table 2).

There was a strong effect of year on onion lodging rate (Table 2). A significant year × month inter action indicated lodging occurred later in 2010 than 2009 (data not shown); however, the effect of fertilizer rate on the percentage of lodged plants was similar in both years, with significantly ($P < 0.001$) greater lodging in *S* than *R* and B treatments.

Total weight of onion bulbs was significantly greater in 2009 than 2010, and significantly affected by fertilizer with higher yield in *S* than *B* ($P = 0.001$) and *R* ($P = 0.040$) treatments which did not differ from each other (Table 3). The size category of onions was also impacted by fertilizer treatment in 2010. The total weight and number of jumbo-sized bulbs was greater in *S* than *R* and *B* (total weight, $P = 0.013$ and $P = 0.001$; total number, $P = 0.011$ and $P = 0.001$, respectively). There were more cull onions by weight in *R* and *B* ($P = 0.004$ and $P = 0.007$, respectively) than in *S*, although the number of cull onions did not differ among fertilizer treatments. All other size class categories were similar among fertilizer treatment. Rotation did not affect yield. There were no significant effects of crop rotation or fertilizer treatment on storage loss in either year (data not shown).

3.2. Thrips and Iris yellow spot virus

Year and fertilizer treatment significantly influenced adult and larval OT populations (Table 4). The *R* fertility treatment significantly decreased densities of thrips adults compared to *S* and *B* treatments ($P = 0.004$ and $P = 0.016$, respectively) (Table 4 and Fig. 2). Adult OT populations were positively correlated with tissue N on both 1 June and 15 June ($P = 0.019$ and $P = 0.004$, respectively) over both years (data not shown). The number of thrips larvae per plant was also lower in *R* than *S* treatments ($P = 0.012$), but intermediate in *B* (Table 4 and Fig. 2). Thrips populations peaked later in the season in 2010 than in 2009, with adult and larvae cumulative totals 2–5 times greater in 2010 than 2009. Cumulative thrips densities were in contrast to onion growth and yield which were greater in 2009 than 2010. There was a significant year × rotation × month interaction for adult OT densities (Table 4 and Fig. 3). In 2009,

Table 2
Means ($n = 4$) for N levels in onion tissue and soil nitrate are presented for main effects (year, rotation, and fertilizer) and significant interactions. Upper case letters designate LSMeans comparisons and lower case letters Bonferroni adjusted means comparisons. All statistics are presented when treatment effects were significant ($P < 0.05$).

Effect	Tissue N mg kg^{-1}	Nitrate N mg kg^{-1} soil		
Year				
2009	3.23$^{A\ a}$	86.6$^{A\ a}$		
2010	2.93$^{B\ b}$	40.1$^{B\ b}$		
Rotation		*2009*	*2010*	
Wheat	3.09	107$^{A\ a}$	43.2	
Corn	3.06	66.4$^{B\ b}$	37.0	
Fertilizer				
Standard	3.36$^{A\ a}$	87.9$^{A\ a}$		
Reduced	2.91$^{B\ b}$	41.5$^{B\ b}$		
Biostimulant	2.97$^{B\ b}$	43.9$^{B\ b}$		
*Rotation*Month*				
Wheat May	–	37.4$^{C\ c}$		
Corn May	–	24.6$^{D\ de}$		
Wheat June	–	90.4$^{A\ ab}$		
Corn June	–	73.6$^{B\ b}$		
Wheat July	–	122$^{A\ a}$		
Corn July	–	80.2$^{B\ ab}$		
Wheat August	–	49.8$^{C\ cd}$		
Corn August	–	28.5$^{E\ e}$		
	2009	*2010*	*2009*	*2010*
*Year*Fertilizer*Month*				
Standard May	4.45$^{AB\ ab}$	4.01$^{BC\ ab}$	42.0$^{FGH\ efg}$	33.2$^{HI\ fgh}$
Reduced May	3.56$^{D\ bc}$	3.17$^{DEF\ bc}$	35.4$^{GH\ efg}$	17.6$^{JK\ hi}$
Biostimulant May	3.48$^{CD\ b}$	3.40$^{DE\ bc}$	40.7$^{GH\ efg}$	17.4$^{JK\ hi}$
Standard June	4.52$^{A\ a}$	4.32$^{AB\ a}$	127$^{B\ b}$	61.5$^{D\ be}$
Reduced June	4.12$^{B\ ab}$	4.18$^{B\ ab}$	105$^{BC\ bcd}$	53.2$^{DEF\ ef}$
Biostimulant June	4.15$^{B\ ab}$	4.27$^{B\ ab}$	98.4$^{C\ bcd}$	46.9$^{EFG\ ef}$
Standard July	3.07$^{EF\ c}$	2.94$^{F\ c}$	252$^{A\ a}$	107$^{BC\ bcd}$
Reduced July	3.08$^{F\ c}$	2.22$^{G\ d}$	72.7$^{DE\ cde}$	57.4$^{DEF\ def}$
Biostimulant July	3.03$^{EF\ c}$	2.25$^{G\ d}$	69.9$^{DE\ cdef}$	47.8$^{DEFG\ efg}$
Standard August	2.04$^{H\ d}$	1.50$^{IJ\ ef}$	138$^{BC\ abc}$	15.6$^{JKL\ hi}$
Reduced August	1.61$^{I\ e}$	1.38$^{K\ ef}$	32.4$^{F\ ghi}$	10.6$^{L\ i}$
Biostimulant August	1.62$^{I\ e}$	1.49$^{JK\ f}$	25.5$^{F\ ghi}$	13.3$^{K\ Li}$
ANOVA P values				
Year (Y)	<0.0001	<0.0001		
Month (M)	<0.0001	<0.0001		
Rotation (R)	0.4369	<0.0001		
Fertilizer (F)	<0.0001	<0.0001		
$Y \times R$	0.2769	0.0072		
$R \times M$	0.6901	0.0412		
$Y \times F \times M$	<0.0001	<0.0001		

Table 3
Means ($n = 4$) for soil phosphorus and potassium and onion lodging rate and final yield presented for main effects (year, rotation, and fertilizer) and significant interactions. Upper case letters designate LSMeans comparisons and lower case letters Bonferroni adjusted means comparisons. All statistics are presented when treatment effects were significant ($P < 0.05$).

Effect	Olsen P mg kg^{-1} soil	Olsen K mg kg^{-1} soil	Lodging rate[a]	Final yield Mg ha^{-1}
Year				
2009	31.5	362$^{A.a}$	4.02$^{A.a}$	36.0$^{A.a}$
2010	30.9	290$^{B\ b}$	0.833$^{B\ b}$	10.8$^{B\ b}$
Rotation				
Wheat	34.0	352$^{A.a}$	2.27	23.1
Corn	28.3	300$^{B\ b}$	2.58	23.7
Fertilizer				
Standard	34.6	339	3.03$^{A.a}$	25.6$^{A.a}$
Reduced	29.3	325	2.13$^{B\ b}$	21.5$^{B.ab}$
Biostimulant	29.5	314	2.13$^{B\ b}$	23.1$^{B\ b}$
*Year*Rotation*				
2009 Corn	24.2$^{B\ b}$	–	–	
2009 Wheat	38.8$^{A.a}$	–	–	
2010 Corn	32.4$^{A.ab}$	–	–	
2010 Wheat	29.3$^{AB.ab}$	–	–	
ANOVA p values				
Year (Y)	0.863	0.0003	<0.0001	<0.0001
Month (M)	N/A	N/A	<0.0001	N/A
Rotation (R)	0.069	0.006	0.099	0.250
Fertilizer (F)	0.336	0.635	0.0002	0.005
$Y \times R$	0.009	0.100	0.911	0.061

[a] Lodging rate was measured on a visual rating scale of 1 to 5 which represented percentage of plant lodged at 25%, 50%, 60%, 80% or 90%

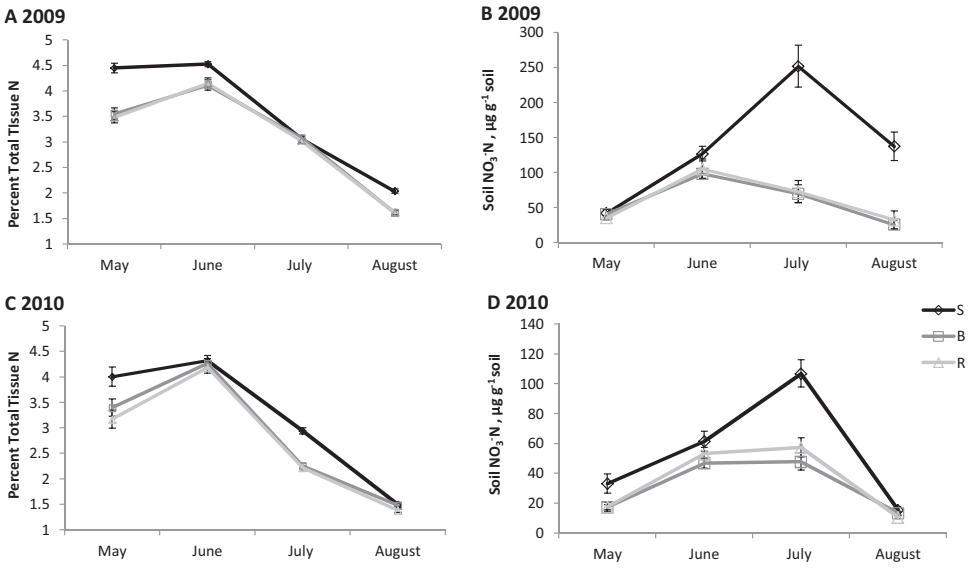

Fig. 1. The interaction of year × fertilizer × month for the percentage of plant dry weight total tissue N and soil NO_3^- N in 2009 (panels A and B, respectively) and 2010 (panels C and D, respectively). Differences in treatment means are fully described in Table 2. *S* = standard fertilizer rate, *B* = biostimulant + reduced fertilizer rate, *R* = reduced fertilizer rate.

onions planted after wheat had more adult thrips than after corn in mid June ($P = 0.036$) and early July ($P = 0.002$) (Fig. 3A). In 2010, there was no effect of rotation on adult thrips densities until mid August when more occurred in wheat than corn ($P = 0.040$) (Fig. 3C). There was a nearly significant year × rotation × month interaction for larval OT densities (Table 4 and Fig. 3). If this interaction is considered, then in August 2009, there were significantly ($P = 0.001$) fewer OT larvae after corn. There was no other significant effect of rotation on OT larvae in either year (Fig. 3B and D).

Densities of thrips eggs within onion leaves and larvae hatched from eggs were not affected by year, crop rotation, or fertilizer treatment; however, there was a significant ($P < 0.0001$) year × month effect for both numbers of eggs and hatched larvae. The peak of both thrips eggs and hatched larvae was early July in 2009 and mid-August in 2010 (data not shown), following similar trends for adult and larval thrips populations on plants (Fig. 3).

Similar to OT, the number of adult *Frankliniella occidentalis* (Pergande), western flower thrips, were greater in 2010 than 2009 ($P = 0.0012$) (data not shown). Neither fertilizer treatment nor crop rotation significantly affected populations of western flower thrips (data not shown).

Onion samples collected in 2009 for DAS-ELISA testing were not analyzed due to sample quality problems. In 2010, neither crop rotation nor fertilizer treatment influenced the incidence of onion plants that tested positive for IYSV (data not shown); however, virus incidence rates were low. In August, onions positive for IYSV ranged from 0 to 6% of tested samples whereas by September, the incidence rate was 0 to 20%.

3.3. Soil chemistry

Soil chemical properties were affected by fertilizer treatment and crop rotation (Tables 2 and 3). Total soil N was strongly influenced by year ($P < 0.0001$) and rotation, with total soil N significantly greater after wheat ($P = 0.006$) than corn (data not shown). Extractable soil NO_3^- N was over two times greater in 2009 than 2010 and was also strongly influenced by fertilizer treatment (Table 2). A highly significant year × fertilizer × month interaction showed soil NO_3^- N peaked in July in both years (Fig. 1). However, NO_3^- N was lowest in May 2009 but in 2010, it was lowest in August. Within each month, soil NO_3^- N was significantly greater in *S* treatments in July and August 2009 ($P < 0.0001$ for all 2009 pairwise comparisons) while in 2010 soil NO_3^- N was greater in *S* than *R* or *B* treatments only in May ($P = 0.004$ and $P = 0.002$) and July ($P < 0.001$ and $P = 0.003$). In June of each year, the *B* treatment was significantly lower in soil NO_3^- N than *S* treatment ($P = 0.044$ and $P = 0.043$) while *R* was intermediary. There were no treatment differences in May 2009 or August 2010. A significant year × rotation interaction indicated more soil NO_3^- N in onion following wheat than corn in 2009, but not in 2010. A rotation × month interaction indicated soil NO_3^-–N was greatest in June and July of both years and greater following wheat than corn in all months. Differences in soil NH_4^+ (data not shown) were noted only in the months of June and July of each year, following fertilizer applications of

Table 4
Means ($n = 4$) for numbers of onion thrips adults and larvae per plant, and number of eggs per leaf presented for main effects (year, rotation, and fertilizer) and significant interactions. Upper case letters designate LSMeans comparisons and lower case letters Bonferroni adjusted means comparisons. All statistics are presented when treatment effects were significant ($P < 0.05$).

Effect	Adults	Larvae	Eggs	Hatched larvae
Year				
2009	$5.70^{B\ b}$	$33.4^{B\ b}$	136	$37.3^{B\ b}$
2010	$18.3^{A\ a}$	$132^{A\ a}$	159	$66.9^{A\ a}$
Rotation				
Wheat	12.8	88.3	144	51.3
Corn	11.2	76.8	151	52.9
Fertilizer				
Standard	$6.25^{A\ a}$	$43.3^{A\ a}$	149	50.2
Reduced	$4.76^{B\ b}$	$34.7^{B\ b}$	144	45.5
Biostimulant	$6.92^{A\ a}$	$45.6^{AB\ ab}$	151	60.6
Year × Rotation				
2009 Corn	$1.94^{C\ c}$	–	–	–
2009 Wheat	$3.76^{B\ b}$	–	–	–
2010 Corn	$9.29^{A\ a}$	–	–	–
2010 Wheat	$9.00^{A\ a}$	–	–	–
ANOVA P values				
Year (*Y*)	<0.0001	<0.0001	0.4006	0.0032
Month (*M*)	<0.0001	<0.0001	<0.0001	<0.0001
Rotation (*R*)	0.053	0.189	0.553	0.762
Fertilizer (*F*)	0.009	0.042	0.484	0.170
Y × *R*	0.017	0.199	0.131	0.277
Y × *R* × *M*	0.036	0.061	0.327	0.475

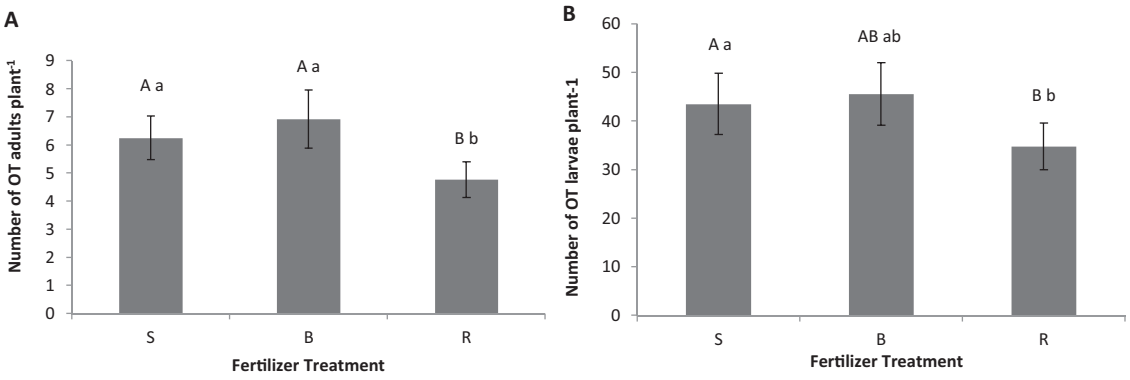

Fig. 2. Effect of fertilizer treatment on densities of onion thrips (OT) adults (A) and larvae (B) per onion plant averaged over the two years and all sample months. Treatment means ($n = 4$) designated by different letters are significant at $P \leq 0.05$. Upper case letters designate LSMeans comparisons and lower case letters Bonferroni adjusted means comparisons. *S* = standard fertilizer rate, *B* = biostimulant + reduced fertilizer rate, *R* = reduced fertilizer rate.

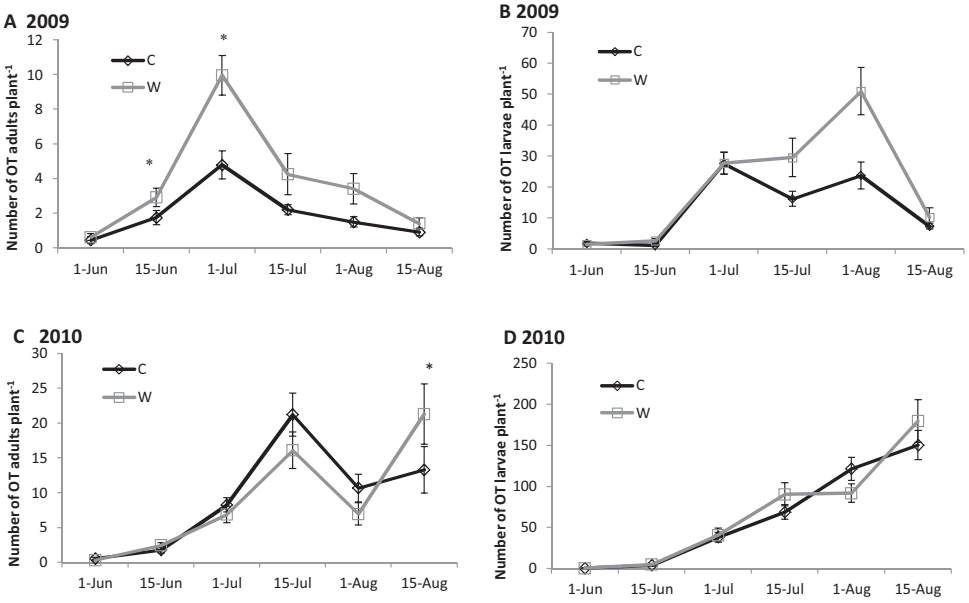

Fig. 3. Effect of crop rotation on densities of onion thrips (OT) adults and larvae per onion plant in 2009 (panels A and B, respectively) and 2010 (panels C and D, respectively). Treatment means ($n = 4$) designated with an asterisk are significantly different at $P \leq 0.05$ using a LS Means comparison. No significant differences were observed with a Bonferroni means correction. C = corn rotation and W = wheat rotation planted prior to onion crop.

Table 5
Means ($n = 4$) for cumulative soil nitrate collected in lysimeters at 0.6 and 1.2 m depth from the months of April through June in 2009 and soil nitrate extracted from soil chores at 0–0.3 m, 0.3–0.6 m and 0.6–0.9 m depth in October 2009 and March 2010 presented for main effects (year, rotation, and fertilizer) and significant interactions. Upper case letters designate LSMeans comparisons and lower case letters Bonferroni adjusted means comparisons. All statistics are presented when treatment effects were significant ($P < 0.05$).

Effect	NO_3^- N μg mL^{-1} 0–0.6 m	NO_3^- N μg mL^{-1} 0–1.2 m	NO_3^- N mg kg^{-1} soil[C] 0–0.3 m	NO_3^- N mg kg^{-1} soil 0.3–0.6 m	NO_3^- N mg kg^{-1} soil 0.6–0.9 m
Year					
Spring	–	–	3.77$^{B\ b}$	2.69$^{B\ b}$	3.38$^{B\ b}$
Fall	–	–	19.9$^{A\ a}$	15.6$^{A\ a}$	12.1$^{A\ a}$
Rotation					
Wheat	6.79	12.4	9.30	8.44	9.26$^{A\ a}$
Corn	5.74	12.4	14.4	9.86	6.21$^{B\ b}$
Fertilizer					
Standard	6.40	11.1	16.8	13.1$^{A\ a}$	10.6$^{A\ a}$
Reduced	6.28	13.2	9.14	7.55$^{B\ ab}$	6.09$^{B\ b}$
Biostimulant	6.13	12.8	9.60	6.84$^{B\ b}$	6.52$^{B\ b}$
ANOVA P values					
Year (*Y*)	–	–	<0.0001	<0.0001	<0.0001
Rotation (*R*)	0.224	0.982	0.253	0.907	0.015
Fertilizer (*F*)	0.918	0.804	0.073	0.020	0.002
$Y \times R$	–	–	0.048	0.343	0.513

ammonium sulfate ($(NH_4)^2SO_4$) in early June. The *S* treatments had greater extractable NH_4^+ than both *R* and *B* in June 2009 ($P = 0.001$ and $P < 0.0001$), June 2010 ($P = 0.001$ and $P = 0.023$) and July 2010 ($P = 0.001$ and $P = 0.003$). In July 2009, NH_4^+ was greater in *S* than *B* treatments ($P = 0.030$), but not in the *R* treatment. Soil P and K levels were not affected by fertilizer treatment; however, K was greater ($P < 0.001$) in 2009 than 2010 and also following wheat ($P = 0.006$) than corn (Table 3). Soil P had a significant year by rotation interaction with wheat greater ($P = 0.002$) than corn in 2009, but no rotation differences in 2010. There were no other significant rotational or fertilizer effects on soil chemical properties.

The movement of excess NO_3^- through the soil profile was captured at three different times during the course of the experiment: during early to mid 2009 and 2010 with suction lysimeters, following the 2009 field season after spring snowmelt, and finally in the fall following harvest in 2010. In-season cumulative NO_3^- leachate (Table 5) collected in lysimeters at 0.6 and 1.2 m depths from May through July, 2009 was not significantly affected by crop rotation or fertilizer treatment; however, treatment differences were observed in extractable soil NO_3^- following harvest (Table 5). In 2010, immediately after harvest, there was significantly more NO_3^- at all three sampling depths (0–0.3, 0.3–0.6, 0.6–0.9 m) than in 2009 after snow melt. Soil NO_3^- was greatest in the *S* treatment at 0.3–0.6 and 0.6–0.9 m and greater after wheat than corn at 0.6–0.9 m. There was a significant year × rotation interaction for soil NO_3^- at 0–0.3 m depth only. At this depth, soil NO_3^- was greater ($P = 0.029$) after corn than wheat in 2010 with no difference between rotations in 2009.

3.4. Soil microbial activity

Soil microbial parameters were also influenced by year, fertilizer, and crop rotation. Dehydrogenase activity (Table 6) was significantly greater ($P = 0.001$) in 2010 than 2009, as well as greater ($P < 0.0001$) after wheat than corn. Dehydrogenase activity was greatest in May and August, and lowest in July in both years. In August, *R* and *B* treatments were greater than *S* ($P = 0.021$ and $P = 0.008$, respectively). Dehydrogenase activity was also greater in the *B* treatment in July compared to the *S* ($P = 0.032$). Dehydrogenase activity was greater after wheat than corn in all months with the greatest activity observed in May and the lowest in June. Both soil respiration and minC (Tables 6 and 7) were also greater in 2010 than 2009 and greater after wheat than corn. There was a significant fertilizer × month interaction on soil respiration with soil respiration significantly greater in the *S* treatment than *B* and *R* in May ($P = 0.043$ and $P = 0.004$, respectively), but not different in July. Microbial biomass was greater in 2009 than 2010 with a significant year × rotation interaction (Table 7). There was no difference in response to rotation in 2009; however in 2010, microbial biomass was greater after wheat than corn. Soil microbial biomass was also greater in the *B* than *S* treatment with *R* intermediate.

3.5. Results of the Bonferroni correction for multiple comparisons

Employing a Bonferroni correction for multiple comparisons had little effect on the interpretation of main effects, but did influence interpretation of interaction effects. As described above, there was a significant year × fertilizer × month interaction for tissue N, but a delay in peak N uptake could not be discerned in 2010. Unlike in 2009, in August 2010, tissue N was greater in *S* than *R* treatments only, with *B* intermediary. The corrected means separations for total onion yield showed a significant difference between *S* and *B* only ($P = 0.004$) with *R* intermediary. Total weight and number of jumbo-sized onion bulbs in 2010 were greater in *S* than *B* ($P = 0.011$ and $P = 0.008$) with no difference in *R*.

Table 6
Means ($n = 4$) for soil biological properties presented for main effects (year, rotation, and fertilizer) and significant interactions. Upper case letters designate LSMeans comparisons and lower case letters Bonferroni adjusted means comparisons. All statistics are presented when treatment effects were significant ($P < 0.05$).

Effect	Dehydrogenase mg TPF kg^{-1} soil	Soil respiration mg kg^{-1} soil h^{-1}
Year		
2009	$1.23^{B\ b}$	$231^{B\ b}$
2010	$1.50^{A\ a}$	$265^{A\ a}$
Rotation		
Wheat	$1.56^{A\ a}$	$262^{A\ a}$
Corn	$1.17^{B\ b}$	$234^{B\ b}$
Fertilizer		
Standard	1.31	254
Reduced	1.42	242
Biostimulant	1.37	248
Rotation × Month		
Wheat May	$1.93^{A\ a}$	–
Corn May	$1.34^{C\ b}$	–
Wheat June	$1.23^{CD\ bc}$	–
Corn June	$0.94^{E\ c}$	–
Wheat July	$1.31^{C\ b}$	–
Corn July	$1.11^{D\ bc}$	–
Wheat August	$1.77^{B\ a}$	–
Corn August	$1.28^{C\ b}$	–
Fertilizer × Month		
Standard May	$1.70^{A\ a}$	$257^{A\ ab}$
Reduced May	$1.57^{A\ abc}$	$232^{C\ b}$
Biostimulant May	$1.65^{A\ ab}$	$240^{BC\ ab}$
Standard June	$1.10^{BC\ d}$	–
Reduced June	$1.08^{C\ d}$	–
Biostimulant June	$1.07^{C\ d}$	–
Standard July	$1.12^{C\ d}$	$252^{AB\ ab}$
Reduced July	$1.21^{BC\ d}$	$252^{AB\ a}$
Biostimulant July	$1.30^{B\ cd}$	$257^{A\ ab}$
Standard August	$1.32^{BC\ bcd}$	–
Reduced August	$1.59^{A\ abc}$	–
Biostimulant August	$1.65^{A\ ab}$	–
ANOVA P values		
Year (*Y*)	0.0006	<0.0001
Month (*M*)	<0.0001	0.004
Rotation (*R*)	<0.0001	0.0004
Fertilizer (*F*)	0.452	0.377
R × *M*	0.003	0.426
F × *M*	0.052	0.006

Table 7
Means ($n = 4$) for soil biological properties presented for main effects (year, rotation, and fertilizer) and significant interactions. Upper case letters designate LSMeans comparisons and lower case letters Bonferroni adjusted means comparisons. All statistics are presented when treatment effects were significant ($P < 0.05$).

Effect	Mineralizable C mg kg^{-1} soil	Microbial biomass mg kg^{-1} soil	
Year			
2009	$8.94^{B\ b}$	$1.29^{A\ a}$	
2010	$13.4^{A\ a}$	$1.15^{B\ b}$	
Rotation		*2009*	*2010*
Wheat	12.3^{Aa}	$1.29^{A\ a}$	$1.22^{A\ a}$
Corn	10.1^{Bb}	$1.30^{A\ a}$	$1.08^{B\ b}$
Fertilizer			
Standard	11.5	$1.17^{B\ b}$	
Reduced	11.7	$1.24^{AB\ a}$	
Biostimulant	11.7	$1.26^{A\ a}$	
ANOVA P values			
Year (*Y*)	<0.0001	<0.0001	
Month (*M*)	0.0065	<0.0001	
Rotation (*R*)	0.006	0.046	
Fertilizer (*F*)	0.222	0.054	
Y × *R*	0.308	0.023	

Fertilizer effects were unchanged by a Bonferroni correction on adult thrips means separations. However, the greater adult populations in wheat were no longer significantly different from corn. The corrected means comparisons showed a difference in fertilizer effects on larvae, where there were more larvae in *S* than *R* treatments ($P = 0.038$), but *B* treatment did not differ from *R* or *S*.

Corrected means comparisons for soil NO_3^- N were still significantly greater under *S* fertilizer in July and August of 2009 ($P < 0.0001$ for all pairwise comparisons). In July of 2010, *S* treatments were greater in soil NO_3^- N than *B* ($P = 0.029$) but not *R*. While soil NO_3^- was greater under wheat than corn in 2009, only the months of May ($P = 0.008$) and August ($P = 0.005$) were significantly different when corrections for multiple comparisons were made. No other differences in interactions for soil NO_3^- N were observed. Soil leaching at 0.3–0.6 m was still greater ($P = 0.026$) under *S* than *B* treatments, but *R* did not differ from either. Microbial biomass was lower ($P < 0.0001$) in *S* than both *R* and *B* (Table 7). Soil respiration showed no fertilizer × month interaction. There were also no significant fertilizer × month interaction effects for dehydrogenase activity while dehydrogenase activity was significantly greater after wheat than corn in May and August only. There were no other significant differences between Bonferroni corrected and LSMeans means separations.

4. Discussion

4.1. Onion growth and yield

For the sake of capturing all potential soil, plant and pest interactions and minimizing Type II error in our systems analysis, we have presented significance levels for multiple comparisons and mean separations based on non-adjusted LSMeans. It must be emphasized however, that this approach increases type I error and so the nature of our findings presented as such are considered exploratory in nature. In order to better demonstrate the degree of certainty surrounding our findings, we also report means separations based on a Bonferroni correction for multiple comparisons. Using the most liberal as well as conservative approaches to the problem of multiple comparisons provides a useful bracket within which the degree of certainty of any given result can be assessed. Employing a Bonferroni correction had little effect on the interpretation of main effects, demonstrating that our key findings are robust. Two- and three-way interactions are often complex and challenging to interpret in a biological sense. Less robust findings will need to be confirmed through future targeted research.

The difference in response variables between years can be primarily attributed to weather pattern differences between the two years of the study. In 2010, an unusually cold and wet spring caused late planting and reduced crop growth in all treatments compared to 2009. In 2010, the average high for the month of May was 17 °C, as compared with 24 °C in 2009. Total rainfall for the months of March through June in 2010 was 298.6 mm, which was more than two fold greater than the rainfall in 2009 for the same time period (Utah Climate Center, 2011), and nearly two times greater than the 30 year average rainfall (NOAA, 2011). These rainfall and temperature differences played a role in not only onion growth and yield, but also soil nutrient status and leaching potential in 2010. In 2009, plants were larger and reducing N fertilizer had no significant impact on yield which was in line with county averages collected in a two year field survey (Reeve et al., unpublished). In 2010, a later planting date coupled with high rainfall and low spring temperatures produced smaller plants, and the higher nitrogen application rate resulted in improved yields (while the year × fertilizer interaction was not significant, it is noteworthy that there was a greater yield response to fertilizer in the wet year).

Although we did not measure soil nutrients prior to the application of treatments, management history and soil type were similar. Similar to onion growth, soil K levels were also lower in 2010 than 2009; however, K availability was sufficient in all treatments (Hamson, 1993). Soil N varied greatly between years, with early season NO_3^- almost twofold greater in 2009 indicating significant N loss in the wet spring of 2010. Reduced-rate fertilizer treatments (*R* and *B*) in 2010, while still supplying adequate amounts of P and K, may not have provided sufficient N to allow for adequate growth before onions reached genetic physiological long-day triggers in the mid-season. Onion dry weight and leaf area were strongly affected by reductions in fertilizer rate in 2010 (data not shown). In long day onions, the number of leaves initiated prior to the day length and degree day triggers have a direct effect on final bulb size (Lancaster et al., 1996). Further research is needed to determine whether a well-timed fertilizer schedule can indeed produce optimum onion growth with much reduced fertilizer inputs under both favorable and challenging growing conditions. Drost and Koenig (2002) previously demonstrated the benefits of a reduced input fertilizer management plan for onions using a slow release fertilizer. It is interesting that the *B* treatment may have increased yield over the *R* treatment, however, this finding needs to be confirmed as the means separation showed no significant advantage over the *R* treatment. Russo and Berlyn (1990) found improved root growth and better resistance to environmental stress with an organic biostimulant; however, other studies have proved inconclusive (Chen et al., 2002).

Differences in late season onion growth patterns among fertility treatments were observed in both years, but were more pronounced in 2010. When *R* and *B* treatments were continuing to initiate leaves and increase bulb size in August, onions treated with the *S* rate were already starting to senesce. Since bulbing response involves a complex interaction of photoperiod, degree days, number of leaves initiated, and fertilizer inputs (Lancaster et al., 1996), the delayed maturation observed in *R* and *B* treatments is probably due to the slower growth rate. While our results indicated a longer time to maturity for *R* and *B* treatments, plant growth data were only collected through 15 August. Harvest dates were approximately one month after final lodging assessments were recorded. A period of rapid growth in the *R* and *B* treatments occurred in September in 2009 resulting in similar total yield and bulb size between all treatments at harvest. This was not observed in 2010, however. All treatments were harvested on the same date in respective years, using similar timing to local commercial onion production.

4.2. Thrips and Iris yellow spot virus

Despite substantial differences in onion growth and yield between the two years of the study, we found a consistent preference of adult OT for onions treated with higher rates of N fertilizer, likely due to higher tissue N in those treatments. These results are in agreement with Malik et al. (2009) who found over 70% increase in thrips numbers at high levels of N (200 and 250 kg ha^{-1}) when compared to moderate and low N inputs (0, 50, 100, or 150 kg ha^{-1}). Our results also support the findings of a recent meta-analysis on the effects of fertilizers on sucking insects (Butler et al., 2012). Adult thrips populations were greater (without Bonferonni correction) following wheat than corn, particularly in 2009 where the impact of prior crop had a more pronounced effect on soil NO_3^-. We speculate that greater depletion of N levels in soils following growth of corn resulted in lower populations of thrips on onions the following season.

In 2010, adult thrips were less affected by rotation, and soil NO_3^- was approximately two times lower than the previous year, regardless of rotation. Increased numbers of both adult and immature thrips on onions treated with biostimulants suggest similar increased plant apparency as with higher rates of N. There were no changes detected in leaf chlorophyll content (data not shown) between fertilizer treatments that could explain possible differences in visual attraction. One study showed vegetation grown in the area prior to leek production affected population patterns of thrips even after the undersown crop was removed (den Belder et al., 2000). The authors suggested the previously undersown clover caused a change in the chemical volatiles of leeks, and that these changes in leek volatiles persisted even after the clover was removed (den Belder et al., 2000). Perhaps pre-and early season applications of biostimulants evoke a similar shift in plant volatiles. While the previous crop in an onion rotation has been suggested as an important factor for overwintering sites for onion thrips (Larentzaki et al., 2007), thrips response to crop rotation, onion tissue N, and soil nutrient status, has not been previously reported.

The timing of the increase in immature thrips within standard fertilizer (*S*) rate plots follows a reasonable timeline after observed increase in adult densities, supporting a carry-over effect of early adult colonization preferences. Generation time in summer months can range from 20 to 40 days (Jones, 2005). Alternatively, the larval populations may also benefit from greater fecundity or survival in higher fertilizer rate treatments (*S*). Both thrips fecundity and time to maturity have been linked to quality of diet (Milne and Walter, 1998), and there was significantly more total tissue nitrogen in *S* plants in both years. Surprisingly, we found no effects of fertilizer treatment or crop rotation on the numbers of thrips eggs laid and hatched, providing a lack of evidence for greater thrips fecundity and egg viability. Since immature thrips have limited motility, and movement between plants is unlikely, increased adult colonization combined with shorter development time are the most likely explanations for greater larval densities on onions treated with the higher N rate. Higher N may also lower defense compounds in plants (Brandt et al., 2011; Koricheva et al., 1998; Stamp, 2003) making the plants a more attractive or digestible food source for insects.

Although OT feeding damage alone may hamper yield by reducing available nutrients during the onion bulbing stage (Kendall and Capinera, 1987), virus transmission remains the largest threat to sustainable onion production in the U.S. (Gent et al., 2006, 2004). While our study revealed no treatment effects on IYSV infection rates in the one year where we gathered good quality IYSV data, overall presence of the disease was low in both years of the study based on visual observations. Recent variety trials conducted in Oregon reported 'Vaquero' (the variety used in this trial) as low to moderately susceptible to IYSV damage with 1–25% of plants with foliar symptoms in low disease seasons and 26–50% in high disease seasons (Shock et al., 2008).

Early season thrips infestations in onion fields may allow a longer timeline for virus transmission. In a model described by Mo et al. (2009), thrips typically have an initial invasion into onion fields, followed by a gradual season-long build-up of populations, with multiple population peaks in which maximum thrips populations can be reduced most effectively by strategies that delay the initial infestation date. The results of this study suggest a reduced fertilizer rate may delay the initial thrips infestation, hence a season-long reduction in populations and possibly IYSV incidence. Hsu et al. (2010) suggest late-season vulnerability to IYSV transmission increases with migrating thrips from neighboring fields that have been harvested. That study indicates the density of late-season thrips was more predictive of IYSV levels than early season thrips densities (Hsu et al., 2010). Although plants may have escaped early season colonization by thrips, onions treated with lower rates of fertilizer required more time to mature in this study, and therefore may increase the plant's susceptibility to late-season thrips infestations in areas where late season migration is significant.

4.3. Soil microbial characteristics and N leaching potential

An increasing number of growers are interested in the use of biostimulants to increase nutrient cycling and improve soil and crop health. The beneficial effects of organic matter additions such as composts and manures are well known; however, these are bulky and expensive to apply (Endelman et al., 2010). Biostimulants are usually applied in liquid form and contain proprietary formulations of humic acids, sugars, and trace elements. They are marketed as a cost-effective way to increase microbial activity, nutrient cycling, and crop health. In this study, the biostimulant amendment had no impact on within-season onion growth, soil microbial characteristics or soil fertility, but may have had a slight positive effect on yield. Although there were few significant biostimulant effects on soil chemical and biological properties, plots receiving biostimulant had higher populations of onion thrips.

The relative size and activity of the microbial biomass in response to management is an important indicator of soil nutrient cycling potential and soil health. Microbial biomass, MinC, and basal respiration were mostly affected by sampling time and rotation and not fertilizer treatment; however, microbial biomass was significantly greater in biostimulant (*B*) than standard (*S*) treatments (*R* treatment was intermediary), and soil respiration was stimulated by *S* treatments in May. Increased size and activity of soil microbial populations following a wheat rotation is likely a result of greater MinC likely due to the lower C:N ratio of wheat than corn (Hines et al., 2006). These results are similar to those of Moore et al. (2000) who found increased microbial biomass in more complex rotations, but little effect of fertilizer rate. In contrast, microbial activity as measured by dehydrogenase was affected by rotation and also possibly by fertilizer. High-N rate (*S*) resulted in the lowest microbial activity at the end of the season in both years. This may indicate microbial populations in the high fertilizer treatments were increasingly C limited (Schimel and Weintraub, 2003). Previous research has shown a possible link between mineral N additions and a period of reduced activity of microbial populations measured as soil respiration and microbial biomass (Gunapala and Scow, 1998). A negative correlation between dehydrogenase activity and amount of N applied has also been previously demonstrated (Shen et al., 2010). Increased microbial biomass and enzyme activities in response to management can be an indicator of both greater microbial numbers and diversity (Reeve et al., 2010). Although not measured in this study, microbial diversity has been shown to decrease with increasing N rates (Doran and Zeiss, 2000; Shen et al., 2010). The formulation of mineral N fertilizers may also contribute to reductions in microbial activity levels (Bremner and Tabatabai, 1973). Tabatabai (1994) notes that the inhibition of dehydrogenase activity by NO_3^-, may not reflect changes in microbial activity per second, but the action of these compounds as alternative electron acceptors. As such, further research is needed to confirm potential effects of high rates of N fertilizer on microbial populations.

Contamination of surface and ground waters as a result of excessive fertilizer use has been well documented and associated with significant health risks and environmental impacts (Doran and Zeiss, 2000). The results of this study confirm that, in general, commonly utilized fertilizer rates for onion are in excess of crop needs and can pose a significant threat of leaching into the external environment. While the levels of extractable NH^{4+} were only greater in *S* treatments immediately following the second fertilizer application of $(NH_4)^2SO_4$, the data clearly shows an increase of soil NO_3^- with increased fertilizer input over the course of the

season. The movement of NO_3^- through the soil profile was also affected by fertility treatment. We did not observe NO_3^- movement from May to August, in either year probably due to irrigation type and frequency. The lack of sufficient soil water to effectively sample from the suction cup lysimeters from July through October demonstrates no movement of water or nutrients at depths of 0.6 m or lower during this time period. However, the *S* fertilizer rate had significantly higher levels of residual NO_3^- in both the 0.3–0.6 and 0.6–0.9 m depths, as did the wheat at 0.6–0.9 m. These results suggest unrecoverable loss of NO_3^- from the cropping system with the subsequent potential for groundwater contamination. Although 2010 was considerably wetter than 2009, lysimeter data in the spring and summer of 2010 also did not show in-season NO_3^- movement through the soil profile (data not shown). Likely, denitrification as a result of wet and cold spring soil conditions coupled with the July application of the majority of N fertilizer would have avoided significant movement out of the root zone following spring precipitation events. In both 2009 and 2010, the reduced fertilizer rate resulted in significantly less nitrogen detected in the soil as NO_3^-, which could provide significant benefits to the environment by reducing NO_3^- leaching over the winter months.

5. Conclusions

The benefits of managing onions with split applications of reduced N are promising. There was little impact on total yield, bulb size or storage quality as a result of a reduced-N input, though the time to maturity may be slightly increased as a result of reduced fertilizer. Because bulb yield response to fertilizer rate was stronger in 2010 than in 2009, N loss due to moisture or denitrification likely contributed to reduced onion plant and bulb size in the less favorable season (2010), suggesting the need for a tailored fertility management plan based on seasonal field conditions.

Reduced N fertility treatments demonstrated other system-wide benefits. The reduced N plots showed a 24 and 31% reduction in adult thrips populations over the *S* and *B* treatments, respectively, which holds significant potential for reducing insecticide applications and concurrent benefits to non-target organisms and human health. Lower N rates led to lower residual soil NO_3^- which could reduce the risk of NO_3^- leaching, an environmental concern. Fertilizer inputs may have influenced the timing of peak microbial activity, for which the implications on nutrient cycling and N availability warrant further study. We found a small benefit to total yield due to addition of a soil biostimulant, but few effects on soil microbial populations or within-season onion growth. There was a trend of increased onion thrips densities in biostimulant treatments even though N rates were the same as the reduced rate (*R*) fertilizer treatment.

A standard crop rotation plan in Utah includes cropping wheat in the year prior to onions. Elevated levels of extractable NO_3^- as well as the possibility of increased adult OT populations after wheat suggests it may be preferable to plant corn prior to onion. Further investigation into the long-term impact of crop rotation on nutrient cycling in onion cropping systems is warranted.

Considering the relatively small size of plots and their close proximity to each other, significant differences in population densities of a motile insect like adult onion thrips have interesting implications in terms of adult behavior and host selection. Clearly, there are complex factors involved in the population dynamics and phenology of OT. Although consistent differences in thrips response to fertilizer treatments were observed in this study, it should be noted that thrips densities and IYSV disease incidence were relatively low in both years. The differences in thrips counts between treatments could not be fully explained by differences in onion growth, tissue N levels, or soil N values. More likely, there is a combination of factors such as visual cues and quality of food resources that impact the population size throughout the course of the season. Applications of reduced rates of nitrogen fertilizer may promote a period of lower thrips pressure; however, this may extend crop maturity and increase late season exposure to IYSV transmission. This late season exposure may be a more significant concern in production fields that are in close proximity to external sources of onion thrips from an early harvest, such as seeded fields planted in close proximity to transplanted fields. Further research on IYSV disease expression and the relationship between the time of disease transmission and impact on yield could help discern the most effective timing of thrips control to evade crop loss. Ultimately, a whole farm or systems approach to assessing the impacts of management decisions on pests could result in the development of management tools to assess cumulative risk. Such a tool could be used to develop more resilient farming systems, hence reducing the need for excess inputs and the potential for environmental contamination.

Acknowledgments

This research was supported by the Western Sustainable Agriculture Research and Education (WSARE) Program (Project No. SW08-076), the Utah Agricultural Experiment Station, and Utah State University, and approved as journal paper number 8354. Special thanks to local onion growers Morgan Reeder, Dan Norman and Wade Norman whose support and cooperation were integral to this project. The knowledge and assistance of Thor Lindstrom and Alicia Campbell in the field and laboratory as well as statistical guidance from Susan Durham and Dr. Eric Dyreson was greatly appreciated.

References

Altieri, M.A., 1999. The ecological role of biodiversity in agroecosystems. Agric. Ecosyst. Environ. 74, 19–31.
Anderson, J.P.E., Domsch, K.M., 1978. A physiological method for the quantitative measurement of microbial biomass in soil. Soil Biol. Biochem. 10, 215–221.
Bremner, J.M., Tabatabai, M.A., 1973. Effects of some inorganic substances on TTC assay of dehydrogenase activity in soils. Soil Biol. Biochem. 5, 385–386.
Bowling, C.C., 1979. The stylet sheath as an indicator of feeding activity of the rice stink bug. J. Econ. Entomol. 72 (2), 259–260.
Bulluck, L.R., Brosius, M., Evanylo, G.K., Ristaino, J.B., 2002. Organic and synthetic fertility amendments influence soil microbial, physical and chemical properties on organic and conventional farms. Appl. Soil Ecol. 19, 147–160.
Butler, J., Garratt, M.P.D., Leather, S.R., 2012. Fertilisers and insect herbivores: a meta-analysis. Ann. Appl. Biol. 161, 223–233.
Brandt, K., Leifert, C., Sanderson, R., Seal, C.J., 2011. Agroecosystem management and nutritional quality of plant foods: the case of organic fruits and vegetables. Crit. Rev. Plant Sci. 30, 177–197.
Chen, S., Subler, S., Edwards, C.A., 2002. Effects of agricultural biostimulants on soil microbial activity and nitrogen dynamics. Appl. Soil Ecol. 19, 249–259.
DeFrancesco, J., 2012. Pest management strategic plan for dry bulb storage onions in the United States. USDA NIFA, Washington, DC.
den Belder, E., Elderson, J., Vereijken, P.F.G., 2000. Effects of undersown clover on host-plant selection by *Thrips tabaci* adults in leek. Entomol. Exp. App. 94, 173–182.
Doran, J.W., Zeiss, M.R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Appl. Soil Ecol. 15 (1), 3–11.
Doré, T., Makowski, D., Malézieux, E., Munier-Jolain, N., Tchamitchian, M., Tittonell, P., 2011. Facing up to the paradigm of ecological intensification in agronomy: revisiting methods, concepts and knowledge. Eur. J. Agron. 34, 197–210.
Drinkwater, L.E., 2009. Ecological knowledge: foundation for sustainable organic agriculture. In: Francis, C. (Ed.), Organic Farming: The Ecological System. Agromony Mongraph 54. Soil Sci. Soc. Am., Madison, WI, pp. 9–43.
Drost, D., Koenig, R., 2002. Improving productivity and N use efficiency with a polymer coated nitrogen source. Hortic. Sci. 37 (2), 338–342.
Endelman, J.B., Reeve, J.R., Hole, D.J., 2010. Economically optimal compost rates for organic crop production. Agron. J. 102, 1283–1289.
Garcia, L.V., 2004. Escaping the Bonferroni iron claw in ecological studies. Oikos 105, 657–663.
Gavlak, R., Horneck, D., Miller, R.O., Kotuby-Amacher, J., 2003. Soil and Plant Reference Methods for the Western Region. Western Region Extension Publication. WREP 125.
Gent, D.H., du Toit, L.J., Fichtner, S.F., Mohan, S.K., Pappu, H.R., Schwartz, H.F., 2006. Iris yellow spot virus: an emerging threat to onion bulb and seed production. Plant Dis. 90, 1468–1480.

Gent, D.H., Schwartz, H.F., Khosla, R., 2004. Distribution and incidence of iris yellow spot virus in Colorado and its relation to onion plant population and yield. Plant Dis. 88, 446–452.
Gil-Sotres, F., Trasar-Cepeda, C., Leirós, M.C., Seoane, S., 2005. Different approaches to evaluating soil quality using biochemical properties. Soil Biol. Biochem. 37, 877–887.
Gunapala, N., Scow, K.M., 1998. Dynamics of soil microbial biomass and activity in conventional and organic farming systems. Soil Biol. Biochem. 30, 805–816.
Halvorson, A.D., Follett, R.F., Bartolo, M.E., Schweissing, F.C., 2002. Nitrogen fertilizer use efficiency of furrow-irrigated onion and corn. Agron. J. 94, 442–449.
Hamson, A.R., 1993. Utah Fertilizer Guide. Utah State University Extension, Utah, pp. 55–56.
Hines, J., Megonigal, J.P., Denno, R.F., 2006. Nutrient subsidies to belowground microbes impact aboveground food web interactions. Ecology 87, 1542–1555.
Hsu, C.L., Hoepting, C.A., Fuchs, M., Shelton, A.M., Nault, B.A., 2010. Temporal dynamics of iris yellow spot virus and its vector, *Thrips tabaci* (Thysanoptera: Thripidae), in seeded and transplanted onion fields. Environ. Entomol. 39, 266–277.
Jones, D., 2005. Plant viruses transmitted by thrips. Eur. J. Plant Pathol. 113, 119–157.
Kendall, D.M., Capinera, J.L., 1987. Susceptibility of onion growth stages to onion thrips (Thysanoptera: Thripidae) damage and mechanical defoliation. Environ. Entomol. 16, 859–863.
Koricheva, J., Larsson, S., Haukioja, E., Keinanen, M., 1998. Regulation of woody plant secondary metabolism by resource availability: hypothersis testing by means of meta-analysis. Oikos 83, 212–226.
Lancaster, J.E., Triggs, C.M., De Ruiter, J.M., Gandar, P.W., 1996. Bulbing in onions: photoperiod and temperature requirements and prediction of bulb size and maturity. Ann. Bot.—London 78, 423–430.
Larentzaki, E., Shelton, A.M., Musser, F.R., Nault, B.A., Plate, J., 2007. Overwintering locations and hosts for onion thrips (Thysanoptera: Thripidae) in the onion cropping ecosystem in New York. J. Econ. Entomol. 100, 1194–1200.
Larkin, R.P., 2008. Relative effects of biological amendments and crop rotations on soil microbial communities and soilborne diseases of potato [electronic resource]. Soil Biol. Biochem. 40, 1341–1351.
MacIntyre Allen, J.K., Scott-Dupree, C.D., Tolman, J.H., Ron Harris, C., 2005. Resistance of *Thrips tabaci* to pyrethroid and organophosphorus insecticides in Ontario, Canada. Pest Manage. Sci. 61, 809–815.
Malik, M.F., Nawaz, M., Ellington, J., Sanderson, R., El-Heneidy, A.H., 2009. Effect of different nitrogen regimes on onion thrips, *Thrips tabaci* Lindemann, on onions, *Allium cepa* L. Southwest. Entomol. 34, 219–225.
Milne, M., Walter, G.H., 1998. Significance of mite prey in the diet of the onion thrips *Thrips tabaci* Lindeman (Thysanoptera: Thripidae). Aust. J. Entomol. 37, 120–124.
Mo, J., Stevens, M., Liu, D.L., Herron, G., 2009. Investigating the effect of invasion characteristics on onion thrips (Thysanoptera: Thripidae) populations in onions with a temperature-driven process model. Environ. Entomol. 38, 1575–1584.
Moore, J.M., Klose, S., Tabatabai, M.A., 2000. Soil microbial biomass carbon and nitrogen as affected by cropping systems. Biol. Fertil. Soils 31, 200–210.
Moran, M.D., 2003. Arguments for rejecting the sequential Bonferroni in ecological studies. Oikos 100, 403–405.
National, 2006. National Agricultural Statisctics Survery (NASS). USDA.
NOAA. 2001. "Normals 1971–2000." Retrieved August 24, 2011 from http://www.ncdc.noaa.gov
Pappu, H.R., Jones, R.A.C., Jain, R.K., 2009. Global status of tospovirus epidemics in diverse cropping systems: successes achieved and challenges ahead. Virus Res. 141, 219–236.
Peters, R.D., Sturz, A.V., Carter, M.R., Sanderson, J.B., 2003. Developing disease-suppressive soils through crop rotation and tillage management practices. Soil Tillage Res. 72, 181–192.
Reeve, J.R., Schadt, C.W., Carpenter-Boggs, L., Kang, S., Zhou, J., Reganold, J.P., 2010. Effects of soil type and farm management on soil ecological functional genes and microbial activities. ISME J. 4, 1099–1107.
Russo, R.O., Berlyn, G.P., 1990. The use of organic biostimulants to help low input sustainable agriculture. J. Sustainable Agric. 1, 19–42.
Saxton, A.M., 1998. A macro for converting mean separation output to letter groupings in Proc Mixed. In: Proc. 23rd SAS Users Group Intl., SAS Institute, Cary, NC, pp. 1243–1246.
Schimel, J.P., Weintraub, M.N., 2003. The implications of exoenzyme activity on microbial carbon and nitrogen limitation in soil: a theoretical model. Soil Biol. Biochem. 35, 549–563.
Shen, W., Lin, X., Shi, W., Min, J., Gao, N., Zhang, H., Yin, R., He, X., 2010. Higher rates of nitrogen fertilization decrease soil enzyme activities, microbial functional diversity and nitrification capacity in a Chinese polytunnel greenhouse vegetable land. Plant Soil 337, 137–150.
Shock, C.C., Feibert, E., Jensen, L., Mohan, S.K., Saunders, L.D., 2008. Onion variety response to Iris yellow spot virus. Hortic. Technol. 18 (3), 539–544.
Soil Survey Staff, 2010. Web Soil Survey. Natural Resources Conservation Service, United States Department of Agriculture. Online www.websoilsurvery.nrcs.usda.gov. (accessed November17, 2010).
Stamp, N., 2003. Out of the quagmire of plant defense hypotheses. Q. Rev. Biol. 78, 23–55.
Tabatabai, M.A., 1994. Soil enzymes. In: Weaver, R.W., Angle, J.S., Bottomley, P.S. (Eds.), Methods of Soil Analysis, Part 2. Microbiologial and Biochemical Properties. SSA Book Series No. 5. Soil Sci. Soc. Am., Madison, WI, pp. 775–833.
USDA-AMS, 1995. "United States Standards for Grades of Onions (other than bermuda-granex-grano and creole type)". Retrieved August 22, 2011 from http://www.ams.usda.gov
Utah Climate Center. 2011. GIS Climate Search. Retrieved August 11, 2011, from http://www.climate.usurf.usu.edu
White, T.C.R., 1984. The abundance of invertebrate herbivores in relation to the availability of nitrogen in stressed food plants. Oecologia 63, 90–105.
Zitter, T.A., Simons, J.N., 1980. Management of viruses by alteration of vector efficiency and by cultural practices. Annu. Rev. Phytopathol. 18, 289–310.