Evaluation of Onion Cultivars for Resistance to Onion Thrips (Thysanoptera: Thripidae) and Iris Yellow Spot Virus

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ABSTRACT Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), a worldwide pest of onion, *Allium cepa* L., can reduce onion yield by >50% and be even more problematic when it transmits Iris yellow spot virus (family *Bunyaviridae*, genus *Tospovirus*, IYSV). Because *T. tabaci* is difficult to control with insecticides and other strategies, field studies on onion, *Allium cepa* L., resistance to *T. tabaci* and IYSV were conducted in 2007 and 2008 in two locations in New York state. Forty-nine cultivars were evaluated for resistance by counting the number of larvae weekly and recording leaf damage. In another experiment, the impact of *T. tabaci* and IYSV on plant growth and yield was examined by spraying half of the plants with an insecticide. Eleven of the 49 cultivars had very little leaf damage and were considered resistant to *T. tabaci*. Visual assessment indicated that all resistant cultivars had yellow-green–colored foliage, whereas the other 38 had blue-green–colored foliage. The visual assessment of color agreed with data on color taken with a HunterLab Ultra Scan XE colorimeter. The onions 'Colorado 6' and 'NMSU 03-52-1' had the lowest numbers of *T. tabaci*, suggesting strong antibiosis and/or antixenosis. The other nine cultivars had variable numbers of *T. tabaci*, indicating a possible combination of categories of resistance. In the nonprotected treatments there were significant reductions in plant height and plant weight in most of the resistant cultivars, but there were reductions in bulb weight only in a few of them. The average of plants infected with IYSV was 10% in 2007 and 60% in 2008. Our findings indicate potential for developing onion resistance to *T. tabaci* as part of an overall integrated pest management strategy but suggest difficulties in identifying resistance to IYSV.

RESUMEN El trips de la cebolla, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), una plaga a nivel mundial de la cebolla, *Allium cepa* L., causa pérdidas en rendimiento (>50%) y puede ser aun mas problemática cuando transmite Iris yellow spot virus (familia *Bunyaviridae*, genero *Tospovirus*, IYSV) causante de la mancha amarilla. Debido a que *T. tabaci* es difícil de controlar con insecticidas y otros métodos, estudios en campo sobre resistencia de la cebolla a *T. tabaci* se llevaron a cabo en 2007 y 2008 en dos lugares en el estado de Nueva York. Cuarenta y nueve genotipos fueron evaluados por medio de conteos de numero de larvas y evaluaciones del daño a la hoja. En otro experimento, se estimo el impacto de *T. tabaci* y el virus en el crecimiento de la planta y el rendimiento aplicando insecticida en la mitad de las plantas. Once de los 49 genotipos presentaron poco daño y fueron considerados resistentes a *T. tabaci*. Observaciones visuales indicaron que los genotipos resistentes tuvieron hojas de color verde-amarillo y los otros tuvieron hojas de color verde-azul, esto coincide con medidas de color tomadas con el "HunterLab Ultra Scan XE colorimeter." 'Colorado 6' y 'NMSU 03-52-1' tuvieron los números mas bajos de *T. tabaci*, sugiriendo un alto nivel de antibiosis y/o antixenosis. Los otros nueve genotipos presentaron números variables de *T. tabaci* indicando una posible combinación de categorías de resistencia. Se observaron reducciones significativas en altura y peso de la planta en la mayoría de los genotipos resistentes, pero solo en unos pocos genotipos en el peso del bulbo. El promedio de plantas infectadas con IYSV fue del 10% en el 2007 y del 60% en el 2008. Estos resultados indican un desarrollo potencial de resistencia de la cebolla a *T. tabaci* como táctica para el manejo integrado de esta plaga, pero revelan dificultades para identificar resistencia a IYSV.

KEY WORDS *Thrips tabaci*, *Allium cepa*, onion resistance, Iris yellow spot virus

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Onion thrips, *Thrips tabaci* Lindeman (Thysanoptera: Thripidae), is a cosmopolitan and polyphagous pest, which probably originated from the eastern Mediterranean region, the center of origin for its most important host plant, onion (*Allium cepa* L.) (Mound 1997). *T. tabaci* is the main insect pest of onion in many parts of the world, including New York state where a total of 4,290 ha was planted in 2008 (NASS 2009). Several factors contribute to the high pest status of *T. tabaci*, including a rapid development time from egg to adult on onion, with reports ranging from 14.2 d (Arrieche et al. 2006) to 15.5 d (Murai 2000) at 23°C and 10.6 d at 30°C (Murai 2000). Its short generation time, coupled with its high reproductive capacity, frequently leads to population outbreaks, especially in hot, dry weather. *T. tabaci* feeding causes silvery leaf spots that turn into white blotches and silvery patches along the leaves, which reduces photosynthesis (Childers 1997). Its feeding can reduce onion bulb weight (Kendall and Capinera 1987, Rueda et al. 2007) resulting in yield losses of nearly 50% (Fournier et al. 1995) and 60% (Waiganjo et al. 2008).

In addition, *T. tabaci* transmits Iris yellow spot virus (family *Bunyaviridae*, genus *Tospovirus*, IYSV). IYSV was first identified on onions in southern Brazil in 1981, before its first confirmation in the United States in 1989 in the Pacific Northwest (Gent et al. 2006). IYSV spread to several important onion producing states, including New York where it was confirmed in the summer of 2006 (Hoepting et al. 2007). IYSV symptoms on leaves appear as straw-colored to white, dry, and sometimes as elongate lesions along the edges (Gent et al. 2006). Studies conducted in Colorado (Gent et al. 2004) indicate that IYSV reduces bulb size. Thus, besides the losses caused by direct feeding by *T. tabaci*, this virus poses a serious additional threat to onion production worldwide.

On onion, the main tactic used to manage *T. tabaci* infestations is the frequent use of foliar insecticides. This strategy is not sustainable for two main reasons. First, *T. tabaci* is difficult to control because insects are found mainly in the narrow spaces between the inner leaves (Shelton et al. 1987) where coverage with conventional foliar-applied insecticides is difficult. Second, some populations of *T. tabaci* have developed resistance to pyrethroid and organophosphate insecticides in New York (Shelton et al. 2003, 2006) and Canada (MacIntyre Allen et al. 2005), as well as many other regions of the world (Martin et al. 2003, Herron et al. 2008, Morishita 2008).

Three categories of resistance describe the effects of host plant resistance (HPR) on insects: antibiosis, which adversely affects the biology of the insect; antixenosis, in which the plant is a poor host to the insect and affects its behavior; and tolerance, or ability of a plant to withstand or recover from insect damage (Smith 2005). HPR may offer a long-term solution to *T. tabaci* and IYSV control. This is especially true if adults avoid colonizing the plant because IYSV is acquired when early instars feed on infected plants and can be transmitted in a persistent fashion by second instars and adults (Gent et al. 2006). Plant characteristics that reduce plant attractiveness to *T. tabaci* adults may inhibit oviposition resulting in less larval feeding and development, and could play a vital role in reducing infection by IYSV.

The use of onion cultivars resistant to *T. tabaci* and IYSV would reduce insecticide use, which would reduce environmental hazards and minimize the evolution of resistance to insecticides. Some studies on onion resistance to *T. tabaci* and IYSV have been conducted. Jones et al. (1935) compared *T. tabaci* populations on 46 onion cultivars. All cultivars tested had significantly higher numbers of *T. tabaci* than the resistant variety 'White Persian', which has thick, light green leaves and an open type of canopy. Coudriet et al. (1979) observed a similar type of leaf structure in the variety 'Nebuka', which had less *T. tabaci* compared with three other onion cultivars. Loges et al. (2004) associated the low number of larvae found on the variety 'Duquesa' with the lowest number of leaves and largest angle between the central leaves, compared with seven other onion cultivars. In another study six of 61 genotypes screened for resistance sustained fewer *T. tabaci* than the other cultivars (Brar et al. 1993). For IYSV, du Toit and Pelter (2005) determined the response of 46 onion cultivars to IYSV and showed that all of them were susceptible to the virus with infection rates ranging from 58 to 97%.

Although some progress has been made on HPR to *T. tabaci* and IYSV, more detailed studies are needed, especially because both pests are increasing in status worldwide (Gent et al. 2006). HPR is an important foundation of integrated pest management (IPM) (Panda and Khush 1995, Kennedy 2008). Evaluating a wide range of onion germplasm for resistance to *T. tabaci* and IYSV is critical for advancing the potential of using host plant resistance in onion IPM. The major objective of our study was to find new sources of resistance to both *T. tabaci* and IYSV by screening existing commercial lines and advanced breeding lines. Onion cultivars were evaluated in replicated field experiments in which *T. tabaci* populations and IYSV incidence were recorded over time. In addition, the impact that *T. tabaci* and/or IYSV had on growth and bulb yield was determined.

Materials and Methods

Plant Material. In this study, 49 dry bulb onion cultivars in total (Table 1) were used. Cultivars were selected based on their suspected resistance or susceptibility to *T. tabaci.* In addition, cultivars popular with New York and Northeast growers were included. This information was obtained by personal communication with New York extension educators, onion researchers at Colorado State University, New Mexico State University, University of Wisconsin, and onion seed companies. Nebula onions were used as the susceptible check in all the experiments not only for its susceptibility to *T. tabaci* but also for being one of the most popular onion cultivars grown in New York. Information on days to maturity and bulb

Table 1. List of onion cultivars used in this study

Cultivar	Leaf color[a]	Hunter b values (mean ± SE)[b]	Response to *T. tabaci*[c]	Days to maturity	Seed company
OLYS05N5[1]	Yellow-green	18.4 ± 1.5a	Resistant	120	Crookham
Tioga[1]	Yellow-green	18.4 ± 1.3a	Resistant	118	Seminis
Peso[1]	Yellow-green	17.8 ± 2.2ab	Resistant	115	Bejo
Calibra[1]	Yellow-green	17.7 ± 2.3ab	Resistant	115	Bejo
Damascus[1]	Blue-green	17.6 ± 3.2ab	Susceptible	112	Seminis
Vaquero[1]	Yellow-green	16.9 ± 2.0abc	Resistant	118	Nunhems
Candy[1]	Blue-green	16.8 ± 2.5abc	Susceptible	95	Seminis
Cometa[2]	Yellow-green	16.4 ± 1.8abcd	Resistant	120	Nunhems
Medeo[1]	Yellow-green	16.4 ± 3.6abcd	Resistant	106	Bejo
SYN-G2[1]	Blue-green	16.3 ± 2.1abcde	Susceptible	N.A.	—[d]
NMSU 03-52-1[1]	Yellow-green	16.1 ± 1.1abcdef	Resistant	120	—[e]
Delgado[1]	Yellow-green	15.2 ± 2.3abcdef	Resistant	116	Bejo
Festival[1]	Blue-green	15.1 ± 2.0abcdefg	Susceptible	108	Bejo
T-433[1]	Yellow-green	15.1 ± 1.7abcdefg	Resistant	117	Takii
Colorado 6[1]	Yellow-green	15.0 ± 2.4abcdefg	Resistant	120	Crookham
602-1[1]	Blue-green	14.7 ± 1.2abcdefg	Susceptible	N.A.	—[f]
Yankee[1]	Blue-green	14.4 ± 2.2abcdefg	Susceptible	108	Bejo
601-1[1]	Blue-green	14.2 ± 3.3abcdefg	Susceptible	N.A.	—[f]
Verrazano[1]	Blue-green	14.1 ± 3.1abcdefg	Susceptible	110	Seminis
606-1[1]	Blue-green	13.8 ± 2.0abcdefg	Susceptible	N.A.	—[f]
SYN-H10[1]	Blue-green	13.8 ± 2.8abcdefg	Susceptible	N.A.	—[d]
Red Bull[3]	Blue-green	13.7 ± 2.2abcdefg	Susceptible	117	Bejo
Red Zeppelin[3]	Blue-green	13.6 ± 1.9abcdefg	Susceptible	115	Seminis
SYN-G1[1]	Blue-green	13.6 ± 3.1abcdefg	Susceptible	N.A.	—[d]
406–1[1]	Blue-green	13.4 ± 1.3abcdefg	Susceptible	N.A.	—[f]
Bastille[1]	Blue-green	13.1 ± 1.4abcdefg	Susceptible	100	Stokes
SYN-H7[1]	Blue-green	13.1 ± 0.9abcdefg	Susceptible	N.A.	—[d]
Santana[1]	Blue-green	12.9 ± 1.5bcdefg	Susceptible	115	Bejo
Barrage[1]	Blue-green	12.7 ± 2.8bcdefg	Susceptible	100	Stokes
Frontier[1]	Blue-green	12.7 ± 1.5bcdefg	Susceptible	100	Takii
Sherman[1]	Blue-green	12.6 ± 1.9bcdefg	Susceptible	100	Bejo
Corona[1]	Blue-green	12.5 ± 2.3bcdefg	Susceptible	100	Bejo
Milestone[1]	Blue-green	12.2 ± 2.1cdefg	Susceptible	110	Takii
Nicolet[1]	Blue-green	12.1 ± 1.8cdefg	Susceptible	112	Seminis
Joliet[1]	Blue-green	12.0 ± 1.3cdefg	Susceptible	105	Seminis
Mountaineer[1]	Blue-green	12.0 ± 1.1cdefg	Susceptible	100	Takii
Nebula[1]	Blue-green	11.8 ± 2.4cdefg	Susceptible	100	Nunhems
Red Wing[3]	Blue-green	11.8 ± 1.4cdefg	Susceptible	118	Bejo
Ruby Ring[3]	Blue-green	11.7 ± 1.8cdefg	Susceptible	112	Takii
Infinity[1]	Blue-green	11.6 ± 2.5cdefg	Susceptible	105	Nunhems
Tahoe[1]	Blue-green	11.6 ± 2.4cdefg	Susceptible	102	Bejo
Red Beauty[3]	Blue-green	11.3 ± 2.2defg	Susceptible	105	Bejo
Mars[3]	Blue-green	11.1 ± 0.7defg	Susceptible	108	Seminis
Trailblazer[1]	Blue-green	10.9 ± 1.7efg	Susceptible	100	Takii
Alonso[1]	Blue-green	10.8 ± 2.2fg	Susceptible	106	Bejo
Prince[1]	Blue-green	9.8 ± 1.5g	Susceptible	105	Bejo
Bunker[1]	Blue-green	N.A.	Susceptible	120	Seminis
Fortress[1]	Blue-green	N.A.	Susceptible	110	Seminis
Millennium[1]	Blue-green	N.A.	Susceptible	105	Nunhems

Within a column, means followed by different letters are significantly different ($P < 0.05$; Tukey's test). Under Cultivar, superscript 1, 2, and 3 represent bulb color: 1, yellow; 2, white; and 3, red. N.A., not applicable.

[a] Leaf color obtained by personal observation.

[b] Leaf color taken by using a HunterLab Ultra Scan XE colorimeter.

[c] Onion cultivars confirmed or found as resistant or susceptible in this study.

[d] Onion lines developed in the program of M. A. Mutschler, Department of Plant Breeding and Genetics, Cornell University, Ithaca, NY.

[e] Onion line developed in the program of C. S. Cramer, Department of Plant and Environmental Science, New Mexico State University, Las Cruces, NM.

[f] Onion lines developed in the program of M. Havey, USDA–ARS and Department of Horticulture, University of Wisconsin, Madison, WI.

color was obtained from the respective companies or the breeder.

Screening Cultivars for *T. tabaci* Populations and Their Damage on Plant Leaves. In 2007 and 2008, 22 and 46 onion cultivars, respectively, were evaluated for resistance to *T. tabaci*, or *T. tabaci*/IYSV by using *T. tabaci* counts, and plant damage ratings. Plants were seeded into 200 cell 4.5-cm plug trays with one seed per cell filled with Cornell mix soil (Boodley and Sheldrake 1977), and then grown under greenhouse conditions at 20–30°C and 20–40% RH with supplemental lights set for a photoperiod of 14:10 (L:D) h. After 8 wk in the greenhouse, onion plants were transplanted into a commercial field in 2007 (Potter, NY) and two commercial fields in 2008 (Potter, NY and Elba, NY) in a randomized complete block design consisting of four blocks, each block with 20 plants per cultivar in a row. Distance between plant rows was 30 cm, and distance between plants within rows was 5 cm.

The number of *T. tabaci* larvae was counted in a nondestructive manner from seven randomly selected plants per cultivar in each block. Counts started after the first *T. tabaci* were observed (31-VII-2007 and 14-VII-2008, respectively) and continued every 7 d until plants reached maturity or until one of the cultivars was completely damaged so it could no longer serve as a host.

A visual rating for leaf damage caused by *T. tabaci* was taken once during the season using a scale ranging from 1 to 9. Similar scales (9-point) have been used to measure damage caused by different insects pests on different crops (Coudriet et al. 1979, Smith 2005). In this study, rating was defined as follows: 1, no damage; 3, 25% of the leaves white or with blotches; 5, 50% of leaves white or with blotches; 7, 75% of leaves white or with blotches; and 9, complete damage (100% leaves white). J.D.-M. estimated the ratings visually.

Information on leaf color was obtained by unpublished data on 49 onion cultivars. Leaf color also was measured on 46 onion cultivars using the HunterLab Ultra Scan XE colorimeter (Hunter Associates Laboratory, Reston, VA). The HunterLab colorimeter responded to spectral distributions of light in the same manner as the human eye. It takes direct readings of a, b, and L. The L measures from black (0) to white (100), +b measures yellow, −b blue, +a red, and −a green color (Ameny and Wilson 1997). Only Hunter b values were taken into account for this study because the leaf color of the onion cultivars evaluated varied from blue-green to yellow-green (+b indicates yellow, −b indicates blue). Five outer leaves per plant were selected in the field, and measurements were taken on the outside and inside middle section of each leaf and the mean of the two measurements was used.

Impact of *T. tabaci* Populations on Leaves, Plant Growth, and Bulb Yield. The impact of *T. tabaci* and *T. tabaci*/IYSV on onion plant growth (2007) and bulb yield (2008) was evaluated with seven and 12 onion cultivars, respectively. Plants were grown in the greenhouse as described above. After 8 wk in the greenhouse, the cultivars were transplanted into a field in 2007 (Potter, NY) and three field locations in 2008 (Potter, Elba I, and Elba II) in a split plot design with four blocks, and two treatments per block, one protected (P) with insecticide and the other nonprotected (NP). There were 20 plants per cultivar in each treatment per block. Distance between plant rows was 30 cm, and distance between plants within rows was 5 cm.

The number of *T. tabaci* larvae was counted weekly, as in the screening experiment, from 10 randomly selected plants per replicate. The insecticide spinetoram (Radiant SC, Dow AgroSciences, Indianapolis, IN) was sprayed in the protected treatment immediately after every count using a backpack CO_2 sprayer with four nozzles, two inside (XR8004VS) and two outside (XR11004VS), at 2.7 atmospheres. The rate of the insecticide was 0.58 liter/ha and the volume was 746.0 liters/ha. Visual ratings for leaf damage caused by *T. tabaci* were recorded using the scale described above.

In 2007, height and fresh weight of plants were measured on eight plants per cultivar in each replicate. In 2008, plant height and weight of bulbs at harvest were taken on five and seven plants, respectively, per cultivar in each replicate. Weight of bulbs in 2007 was not taken because onions were transplanted into the field late (end of June), which did not allow the bulbs to fully mature.

IYSV Infection Assessment. Onions infected with IYSV may or may not express symptoms (B.A.N., personal observation). Therefore, onion plants infected with IYSV were diagnosed using double antibody sandwich enzyme-linked immunosorbent assays (DAS-ELISAs) (Clark and Adams 1977) and commercially available antibodies, as well as positive and negative controls for IYSV (Agdia Inc., Elkhart, IN). At the end of the 2007 season, all the plants in the field were taken to the laboratory and tested for IYSV. Plants were tested individually; a section of leaf tissue from the middle section of the plant was used where preliminary studies have shown a greater probability of detecting the virus (B.A.N., unpublished data). All samples and controls were tested in duplicate wells on 96-well microtiter plates, and the mean of the two readings was used for data analysis. At the end of the 2008 season, seven plants per cultivar per replicate were taken to the laboratory to determine the presence of IYSV by DAS-ELISA. In some cases, there were less than seven plants per cultivar available due to dryness or early maturation. Plants in Elba II were not tested.

Statistical Analyses. Analysis of variance (ANOVA) for *T. tabaci* populations, leaf damage ratings, plant height, plant fresh weight, bulb weight, and color data among cultivars was conducted by using PROC GLM and controlled for blocks. Multiple comparisons were computed by using Tukey's studentized range test ($P < 0.05$) (SAS Institute 2003). For the experiments with P and NP treatments, each cultivar was analyzed separately because our interest was to compare *T. tabaci* populations, leaf damage ratings, plant height, plant fresh weight, and bulb weight between these treatments. Data were then analyzed as a randomized complete block design using PROC GLM. Subsequently, separate analyses were conducted to compare responses of cultivars to these factors within P and NP treatments, also using a randomized complete block design.

A logistic regression model for IYSV infection rates was performed by using PROC GENMOD and controlled for blocks (SAS Institute 2003). In the experiments with P and NP treatments, each cultivar was analyzed separately because the interest was to compare IYSV infection rates between the two treatments.

Analysis of regression was done (PROC REG) with days to maturity, Hunter b values and cumulative number of *T. tabaci* larvae as predictors of onion leaf damage caused by *T. tabaci* (Y_{damage} = days to maturity + Hunter b values + cumulative number of *T. tabaci* larvae) and as well as predictors of IYSV

(Y_{IYSV} = days to maturity + Hunter b values + cumulative number of *T. tabaci* larvae) (SAS Institute 2003). Correlation coefficients (r) were calculated by examining the relationship between *T. tabaci* populations, damage, days to maturity, and IYSV percentage of plants infected in the screening experiments.

Results

Screening Cultivars for *T. tabaci* Populations and Their Damage on Plant Leaves. *Damage on Plant Leaves.* In 2007, visual rating for *T. tabaci* leaf damage was done at 89 d after transplanting (DAT). There were significant differences among cultivars (F = 12.45; df = 21, 63; $P < 0.001$) (Table 2). Of the 22 cultivars, 14 had damage ratings between 3.4 and 4.4, with 30 and 43% of their leaf tissue damaged by *T. tabaci.* 'OLYS05N5' had the lowest damage (<10% leaf damage) and was significantly less damaged than many of the popular commercial cultivars (e.g., 'Infinity', 'Red Wing', Nebula, 'Red Bull', 'Red Beauty') and had similar ratings to 'Peso', 'Colorado 6', 'Cometa', 'Tioga', 'Delgado', 'Calibra', and 'Medeo' (Table 2). In 2008, *T. tabaci* caused limited leaf damage in Potter with only ≈20% in the most susceptible cultivars (Table 2). In Elba, leaf damage was evaluated at 87 DAT and was ≈70% in the susceptible Infinity onions. The reaction of the resistant onions OLYS05N5, Colorado 6, 'T-433', NMSU 03-52-1, Delgado, Peso, Tioga, Cometa, Medeo, Calibra, and 'Vaquero' was significantly (F = 10.09; df = 45, 135; $P < 0.001$) different from Infinity (Table 2).

T. tabaci Populations. In 2007, the first count of *T. tabaci* larvae was done at 34 DAT and then every seven d until 105 DAT for a total of 11 counts. Figure 1 illustrates the cumulative number of larvae on the eight cultivars that had the lowest damage rating (Table 2). Onions Nebula and 'Yankee' were used as susceptible checks. There were significant differences in the cumulative number of larvae among cultivars at 90 DAT (F = 15.06; df = 9, 267; $P < 0.001$) and 105 DAT (F = 20.41; df = 9, 267; $P < 0.001$) (Fig. 1). Colorado 6 had the lowest number of larvae but was not significantly different from OLYS05N5, Cometa, or Tioga at 90 DAT and 105 DAT (Fig. 1).

In 2008, the first count of *T. tabaci* larvae was done at 44 DAT and then every seven d until 86 DAT for a total of seven counts. Populations of *T. tabaci* in Potter were very low (data not shown), but *T. tabaci* larvae populations in Elba were higher (data not shown) causing leaf damage >70%, as explained above.

IYSV Infection Assessment. In 2007, all the plants present at the end of the experiment were collected; there were between 23 and 43 plants per cultivar for a total of 678 onion plants. Only 11% of the plants were infected with IYSV. The percentage of plants infected ranged from 3 to 31% (Table 3), and there were no significant (χ^2 = 27.67, df = 21, P = 0.1498) differences in infection levels among the cultivars tested. The eight cultivars that had the lowest leaf rating damage (Table 2) had infection rates below or close to 10%, except for Delgado, which had an IYSV infection rate of 19%. Infinity, which had one of the highest damage ratings and numbers of larvae, had only one infected plant (3%) (Table 3).

In 2008, 20–28 plants were tested per cultivar in Potter, making a total of 1,135 plants (Table 3). Percentages of plants infected with IYSV varied from 16 to 75%, and there were significant differences (χ^2 = 118.37, df = 40, $P < 0.001$) in infection rates among cultivars. 'Santana' onions had the highest infection

Table 2. Ratings of onion leaf damage (mean ± SE) due to *T. tabaci* (screening experiments) in Potter, (2007 (22 onion cultivars) at 89 DAT; Potter, 2008 (46 cultivars) at 87 DAT; and Elba, 2008 (46 cultivars) at 87 DAT

Cultivar	Potter (2007)[a]	Potter (2008)[a]	Elba (2008)[a]
OLYS05N5	1.6 ± 0.5e	1.0 ± 0.0c	1.0 ± 0.0g
Colorado 6	2.0 ± 0.4e	1.0 ± 0.0c	1.1 ± 0.3g
T-433		1.0 ± 0.0c	1.6 ± 0.3fg
NMSU 03-52-1		1.1 ± 0.3bc	1.6 ± 0.6fg
Delgado	2.4 ± 0.5cde	1.0 ± 0.0c	1.8 ± 0.3fg
Peso	1.9 ± 0.3e	1.0 ± 0.0c	1.9 ± 0.3defg
Tioga	2.4 ± 0.5cde	1.1 ± 0.3bc	1.9 ± 0.5defg
Cometa	2.3 ± 0.6de	1.0 ± 0.0c	2.1 ± 0.9cdefg
Medeo	2.8 ± 0.3bcde	1.0 ± 0.0c	2.3 ± 0.5bcdefg
Calibra	2.4 ± 0.6cde	1.1 ± 0.3bc	2.3 ± 0.5bcdefg
Vaquero		1.0 ± 0.0c	2.3 ± 1.0bcdefg
Mountaineer		1.9 ± 0.3ab	3.6 ± 0.5abcdefg
Ruby Ring		2.0 ± 0.4a	3.6 ± 0.5abcdefg
SYN-G2		2.0 ± 0.0a	4.0 ± 0.8abcdef
Trailblazer		2.1 ± 0.3a	4.1 ± 1.9abcdef
SYN-G1		2.1 ± 0.3a	4.3 ± 0.6abcdef
406-1		1.9 ± 0.3ab	4.3 ± 1.3abcdef
Damascus		1.8 ± 0.3abc	4.3 ± 1.4abcdef
Verrazano		2.3 ± 0.5a	4.4 ± 1.3abcdef
602-1		1.8 ± 0.3abc	4.4 ± 1.8abcdef
Candy		2.3 ± 0.3a	4.5 ± 0.6abcde
Frontier		2.3 ± 0.2a	4.5 ± 1.0abcde
Alonso	4.0 ± 0.4ab	2.1 ± 0.3a	4.5 ± 1.7abcde
Mars		2.1 ± 0.3a	4.6 ± 1.3abcd
601-1		2.4 ± 0.5a	4.6 ± 1.7abcd
Nicolet		2.1 ± 0.3a	4.8 ± 1.0abc
Red Zeppelin		2.3 ± 0.6a	4.8 ± 1.3abc
SYN-H10		2.1 ± 0.3a	4.8 ± 1.3abc
Milestone	3.9 ± 0.9ab	2.0 ± 0.4a	5.0 ± 0.7ab
Sherman		2.0 ± 0.4a	5.0 ± 1.4ab
SYN-H7	3.5 ± 0.4abcd	1.9 ± 0.3ab	5.0 ± 1.6ab
Barrage		2.1 ± 0.3a	5.1 ± 1.8a
606-1	3.4 ± 0.5abcd	2.1 ± 0.3a	5.1 ± 2.2a
Joliet		2.0 ± 0.0a	5.3 ± 1.7a
Yankee	4.1 ± 0.9a	2.1 ± 0.6a	5.4 ± 0.5a
Red Beauty	4.4 ± 0.5a	1.9 ± 0.3ab	5.4 ± 1.1a
Santana	4.0 ± 0.4ab	2.1 ± 0.3a	5.5 ± 1.0a
Festival		2.1 ± 0.3a	5.5 ± 1.3a
Prince		2.1 ± 0.3a	5.5 ± 1.3a
Red Bull	4.0 ± 1.1ab	1.9 ± 0.3ab	5.8 ± 1.0a
Bastille		1.9 ± 0.3ab	5.9 ± 0.3a
Tahoe		2.1 ± 0.3a	5.9 ± 0.3a
Corona		2.3 ± 0.3a	6.0 ± 0.8a
Nebula	3.9 ± 0.8ab	2.3 ± 0.5a	6.0 ± 0.8a
Red Wing	4.1 ± 0.5a	2.3 ± 0.3a	6.1 ± 0.6a
Infinity	4.0 ± 0.7ab	2.1 ± 0.5a	6.3 ± 1.0a
Bunker	3.5 ± 0.0abcd		
Fortress	3.8 ± 0.3ab		
Millenium	3.6 ± 0.3abc		

Within a column, means followed by different letters are significantly different ($P < 0.05$; Tukey's test).

[a] Visual rating for *T. tabaci* leaf damage on a scale ranging from 1 to 9. 1, no damage; 3, 25% of the leaves white or with blotches; 5, 50% of leaves white or with blotches; 7, 75% of leaves white or with blotches; and 9, complete damage (100% leaves white).

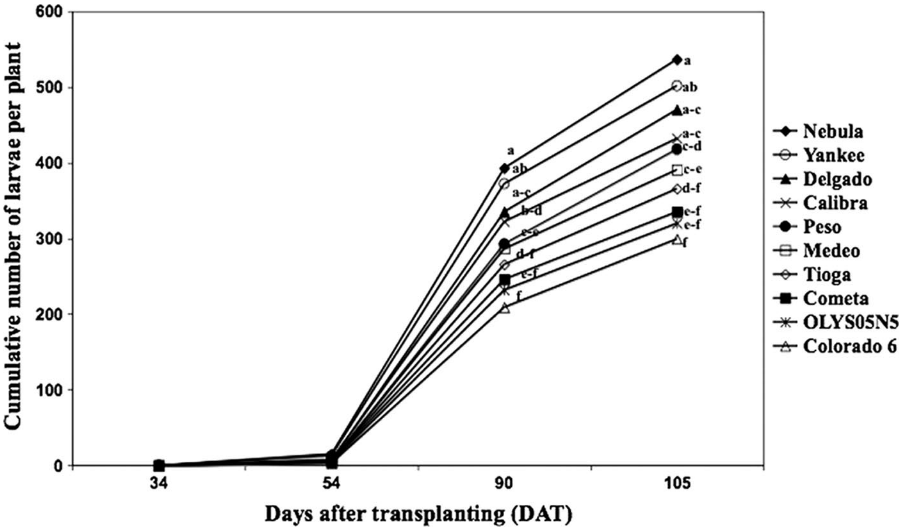

Fig. 1. Cumulative number of larvae per plant on 10 onion cultivars (screening experiment, 2007). Lines with different letters are significantly different ($P < 0.05$; Tukey's test).

rate (75%) and was not significantly different from the 'Red Zeppelin', Red Wing, 'Sherman', Red Bull, Calibra, SYN-H10, Medeo, and Nicolet (Table 3). In Elba, 1,099 plants in total were tested and most of the cultivars listed had 28 plants tested except for Nebula, SYN-H10, 'Barrage', '406-1', '601-1', Red Wing, 'Damascus', 'Bastille', and 'Vaquero' that had between 23 and 27 plants. The number of plants tested on 'Mountaineer', 'Corona', 'Festival', Santana, 'Frontier', and '606-1' ranged from 13 to 19. Percentages of plants infected varied from 15 to 79% and there were significant ($\chi^2 = 93.21$, df = 42, $P < 0.001$) differences in infection levels among cultivars (Table 3). The highest infection percentage in Red Zeppelin (79%) was not different from Santana, Calibra, Red Bull, Infinity, 406-1, and Delgado (Table 3).

Measurement of Onion Leaf Color. Leaf color was visually assessed and there were two colors observed among the different cultivars, yellow-green and blue-green (Table 1). All the Hunter b values were positive indicating a dominance of yellow color over blue color (Table 1). Only the cultivars that showed resistance to *T. tabaci* had yellow-green leaf color (Table 1) and along with the other four cultivars had the highest b values (Table 1). Figure 2A clearly shows that the resistant varieties on the upper-left corner were the only ones with both, low damage and high b values.

Relationship Between Damage on Plant Leaves, T. tabaci Populations, IYSV, Days to Maturity, and Hunter b Values. The *r* values between damage and cumulative number of larvae were not very strong in the screening experiments in Potter (2007), Potter (2008), and Elba (2008), with values of 0.57, 0.72, and 0.70, respectively (Table 4). However, correlation between damage ratings within the different locations was very strong, with values of 0.93 (Potter 2007 and 2008), 0.96 (Potter 2007 and Elba 2008), and 0.89 (Potter 2008 and Elba 2008). There was very low correlation between IYSV percentage of plants infected and damage ratings in Potter 2007, Potter 2008, and Elba 2008 (0.15, 0.08, and 0.13, respectively); between IYSV percentage of plants infected and cumulative number of larvae in Potter 2007, Potter 2008, and Elba 2008 (0.27, 0.05, and 0.05, respectively); and between IYSV percentage of plants infected within the different locations, 0.15 (Potter 2007 and 2008), −0.14 (Potter 2007 and Elba 2008), and 0.60 (Potter 2008 and Elba 2008) (Table 4). The correlation between days to maturity and plant leaf damage was not very strong in Potter (2007), Potter (2008), and Elba (2008), −0.57, −0.65, and −0.60, respectively. Correlation was low between days to maturity and cumulative number of larvae in Potter (2007), Potter (2008), and Elba (2008), −0.65, −0.43, and −0.44, respectively. The correlation between days to maturity and IYSV percentage of plants infected was very low in Potter (2007), Potter (2008), and Elba (2008), −0.03, 0.15, and 0.14, respectively (Table 4).

Days to maturity, Hunter b values, and cumulative number of *T. tabaci* were used to predict leaf damage caused by *T. tabaci* and IYSV infection in the screening experiment in 2008. Hunter b values ($F = 9.62$, df = 37, $P < 0.0039$) (Fig. 2A) and cumulative number of *T. tabaci* ($F = 15.87$, df = 37, $P < 0.0003$) (Fig. 2B) were significant predictors of leaf damage. Days to maturity approached significance ($F = 3.93$, df = 37, $P < 0.0556$) as a predictor of damage (Fig. 2C). However, Hunter b values ($F = 1.26$, df = 34, $P < 0.2707$), cumulative number of *T. tabaci* ($F = 0.49$, df = 34, $P < 0.4905$) and days to maturity ($F = 2.91$, df = 34, $P < 0.0979$) were not significant predictors of IYSV percentage of plants infected.

Impact of T. tabaci Populations on Leaves, Plant Growth, and Bulb Yield. *Damage on Plant Leaves.* In 2007, the leaf damage evaluation was done at 89 DAT.

Table 3. IYSV incidence on onion plants, as shown by DAS-ELISA, in the screening experiments in Potter, 2007 (22 onion cultivars); Potter, 2008 (41 cultivars); and Elba, 2008 (43 cultivars)

Cultivar	Potter 2007, % plants infected (mean ± SE)	Potter 2008, % plants infected (mean ± SE)	Elba 2008, % plants infected (mean ± SE)
Vaquero		50.0 ± 24.7bcde	14.8 ± 11.2h
606-1	31.0 ± 53.2a	17.9 ± 27.0hi	15.8 ± 18.7gh
Yankee	16.7 ± 19.2a	21.5 ± 8.3ghi	21.5 ± 7.6gh
Bastille		39.3 ± 29.4cdefgh	24.0 ± 25.7gh
SYN-G2		35.7 ± 37.8cdefgh	25.0 ± 12.7fgh
OLYS05N5	8.8 ± 17.7a	25.0 ± 24.4fghi	25.0 ± 16.7fgh
Damascus		42.9 ± 35.0bcdefg	25.0 ± 19.9fgh
Milestone	3.2 ± 6.5a	46.4 ± 24.4bcdef	28.6 ± 10.8efgh
SYN-H7	15.4 ± 21.8a	39.3 ± 18.0cdefgh	28.6 ± 10.8efgh
Corona		42.9 ± 23.3bcdefg	28.6 ± 30.5efgh
Mountaineer			30.8 ± 23.2efgh
T-433		28.6 ± 26.1defghi	32.2 ± 12.7efgh
Sherman		60.7 ± 29.4abc	32.2 ± 16.6efgh
Cometa	2.7 ± 5.4a	17.9 ± 18.0hi	32.2 ± 22.6efgh
Barrage		25.0 ± 24.4fghi	34.8 ± 26.3defgh
Mars		17.9 ± 13.7hi	35.7 ± 22.9defgh
Colorado 6	10.7 ± 21.5a	32.2 ± 21.4defghi	35.7 ± 25.3defgh
Verrazano		25.0 ± 13.7fghi	35.7 ± 31.5defgh
Alonso	11.1 ± 22.2a	25.0 ± 24.4fghi	35.8 ± 7.6defgh
SYN-G1		28.6 ± 11.7defghi	36.0 ± 25.3defgh
Frontier			36.9 ± 43.2defgh
Tahoe		25.6 ± 31.4efghi	37.0 ± 13.7defgh
601-1			38.5 ± 24.6cdefgh
Ruby Ring		27.0 ± 30.8dfghi	39.3 ± 22.6cdefg
Festival		39.3 ± 21.4cdefgh	41.2 ± 32.7bcdefg
Joliet		32.1 ± 29.4defghi	42.3 ± 31.6bcdefg
Prince		39.3 ± 13.6cdefgh	42.9 ± 10.8bcdefg
Tioga	4.4 ± 8.7a	25.0 ± 21.5fghi	42.9 ± 10.8bcdefg
NMSU 03-52-1		39.3 ± 21.4cdefgh	42.9 ± 15.2bcdefg
602-1		32.2 ± 13.7defghi	42.9 ± 20.2bcdefg
Peso	8.3 ± 5.6a	35.7 ± 18.4cdefgh	42.9 ± 28.6bcdefg
Medeo	8.0 ± 16.0a	53.6 ± 7.1abcd	46.4 ± 12.6bcdefg
SYN-H10		53.6 ± 13.6abcd	47.9 ± 15.4bcdefg
Nebula	11.6 ± 14.0a	28.6 ± 30.8defghi	47.9 ± 20.3bcdef
Nicolet		53.6 ± 13.6abcd	50.0 ± 13.2bcdef
Red Wing	13.8 ± 19.5a	67.9 ± 27.0ab	52.0 ± 22.2bcde
Delgado	18.6 ± 15.2a	46.5 ± 17.9bcdef	53.6 ± 16.6abcde
406-1		46.4 ± 24.4bcdef	60.0 ± 32.8abcd
Infinity	3.0 ± 6.1a	35.7 ± 24.7cdefgh	60.7 ± 29.3abcd
Red Bull	19.3 ± 19.4a	60.7 ± 18.0abc	64.3 ± 17.1abc
Calibra	9.7 ± 12.4a	53.6 ± 29.4abcd	67.8 ± 12.7ab
Santana	12.9 ± 14.9a	75.0 ± 24.4a	72.2 ± 19.7ab
Red Zeppelin		67.9 ± 21.4ab	78.6 ± 17.1a
Red Beauty	5.9 ± 6.8a	16.1 ± 23.6i	
Bunker	12.0 ± 24.0a		
Fortress	8.0 ± 9.2a		
Millenium	19.3 ± 14.7a		
No. plants tested	678	1,135	1,099
Avg. % infected	10.8	38.4	41.1

Within a column, means followed by different letters are significantly different ($\alpha = 0.05$; logistic regression model using PROC GENMOD).

There were significant ($F = 28.84$; df = 6, 18; $P < 0.001$) differences in leaf damage ratings among cultivars in the NP treatment (Table 5). As in the screening experiment, OLYS05N5 had the lowest damage rating in the NP treatment but was not significantly different from Colorado 6 or Peso (Table 5); and the leaf damage observed in the Delgado was not significantly different from Colorado 6′ or Peso. As expected, the insecticide used was very effective and kept *T. tabaci* populations extremely low throughout the experiment with the cultivars in the P treatment having 0% (damage rating of 1) leaf damage (Table 5).

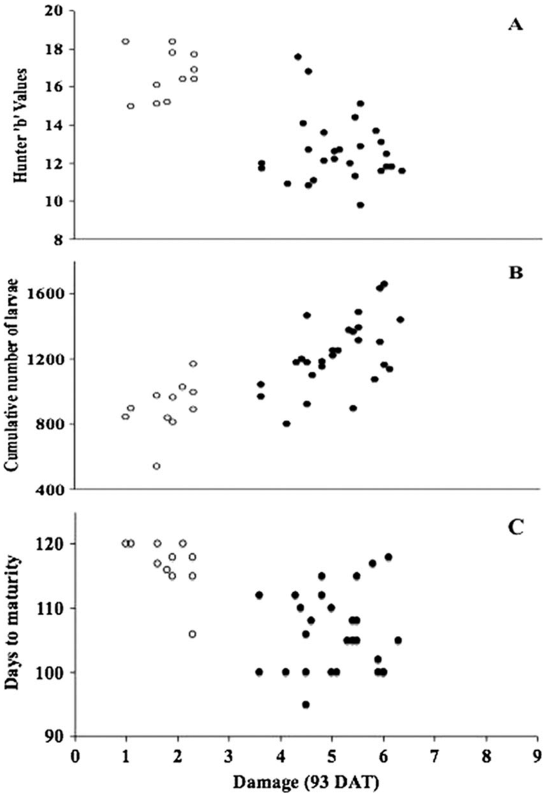

Fig. 2. Hunter b values, cumulative number of larvae, and days to maturity as predictors of leaf damage (yield loss experiment, 2008). (A) Damage versus Hunter b values. (B) Damage versus cumulative number of larvae. (C) Damage versus days to maturity. Hunter b values ($P < 0.0039$) and cumulative number of *T. tabaci* ($P < 0.0003$) were significant predictors of leaf damage. Days to maturity approached significance ($P < 0.0556$) as a predictor of damage ($P < 0.05$, regression analyses using PROC REG). Unfilled circles represent the 11 onion cultivars found resistant to *T. tabaci*.

In 2008, populations of *T. tabaci* larvae in Elba I were higher than in the other two locations and the damage in the susceptible check Nebula was ≈70% in the NP treatment (Table 5). The damage in Cometa, Vaquero, Colorado 6, OLYS05N5, T-433, and ‘NMSU 03-52-1 was not significantly different between the treatments (Table 5). For the Elba II site, data are not shown because *T. tabaci* populations and damage were very low, and there were no significant differences ($P > 0.05$) between the damage of NP and P treatments, regardless of the cultivars. In Potter, populations of *T. tabaci* were somewhat higher (data not shown), but again there were no significant ($P > 0.05$) differences in the damage between NP and P treatments, except for Nebula (susceptible check) with damage in the NP treatment of only 10% (data not shown).

T. tabaci Populations. Counts of larvae were done on the same dates as in the screening experiment. In

Table 4. Correlation coefficients [*r*] between leaf damage ratings, cumulative number of *T. tabaci* larvae, IYSV percentage of plants infected, and days to maturity in the screening experiments

Damage rating	Potter 2007			Potter 2008			Elba 2008		
	Damage rating	Cumulative no. larvae	IYSV (%)	Damage rating	Cumulative no. larvae	IYSV (%)	Damage rating	Cumulative no. larvae	IYSV (%)
(Potter 2007)		0.57 (22)	0.15 (19)	0.93 (19)			0.96 (19)		
Damage rating (Potter 2008)					0.72 (46)	0.08 (41)	0.89 (46)		
Damage rating (Elba 2008)								0.70 (46)	0.13 (43)
IYSV (%) (Potter 2007)		0.27 (19)				0.15 (19)			−0.14 (18)
IYSV (%) (Potter 2008)					0.05 (41)				0.60 (40)
IYSV (%) (Elba 2008)								0.05 (43)	
Days to maturity	−0.57 (20)	−0.65 (20)	−0.03 (20)	−0.65 (38)	−0.43 (38)	0.15 (33)	−0.60 (38)	−0.44 (38)	0.14 (33)

The value in parentheses indicates the number of different onion cultivars used for each correlation.

2007 in the NP treatment, the susceptible check Nebula had the highest cumulative number of larvae and was significantly different ($F = 95.99$, df = 6, $P < 0.001$) from all the other cultivars (Fig. 3). OLYSO5N5 had the lowest number of cumulative larvae and was not significantly different from Colorado 6 at 105 DAT. Peso had an intermediate number of larvae (Fig. 3). The cumulative number of larvae on the susceptible Yankee and Delgado was not significantly different (Fig. 3); however, the damage found on Yankee in the NP treatment was significantly higher (Table 5).

Figure 4 illustrates the cumulative number of *T. tabaci* larvae per plant at 87 DAT and leaf damage at 93 DAT in the NP treatment in 2008. Leaf damage ($F = 52.02$; df = 11, 3; $P < 0.001$) and *T. tabaci* populations ($F = 42.60$; df = 11; $P < 0.001$) were significantly higher in the susceptible Nebula, compared with the other cultivars. NMSU 03-52-1 and 'Colorado 6' had the lowest populations and damage. Medeo, even with high *T. tabaci* populations, sustained little damage. The other cultivars, with intermediate *T. tabaci* populations, did not show significant differences in the cumulative number of larvae among them and sustained little damage (Fig. 4).

Table 5. Ratings of onion leaf damage (mean ± SE) due to *T. tabaci* (impact on plant growth and yield loss experiments) in Potter, 2007 (seven onion cultivars) at 89 DAT and in Elba, 2008 (12 cultivars) at 93 DAT

Cultivar	Potter (2007)[a]		Elba (2008)[a]	
	NP	P	NP	P
NMSU 03-52-1			1.1 ± 0.3aB	1.0 ± 0.0aA
Colorado 6	1.9 ± 0.5aBC	1.0 ± 0.0bA	1.4 ± 0.3aB	1.0 ± 0.0aA
OLYS05N5	1.6 ± 0.3aC	1.0 ± 0.0bA	1.4 ± 0.3aB	1.0 ± 0.0aA
T-433			1.4 ± 0.3aB	1.0 ± 0.0aA
Cometa			1.5 ± 0.0aB	1.0 ± 0.0aA
Vaquero			1.5 ± 0.4aB	1.0 ± 0.0aA
Delgado	2.8 ± 0.3aB	1.0 ± 0.0bA	1.8 ± 0.3aB	1.0 ± 0.0bA
Peso	2.0 ± 0.4aBC	1.0 ± 0.0bA	1.8 ± 0.3aB	1.0 ± 0.0bA
Calibra			1.8 ± 0.5aB	1.0 ± 0.0bA
Tioga			1.9 ± 0.3aB	1.0 ± 0.0bA
Medeo			2.1 ± 0.6aB	1.0 ± 0.0bA
Nebula	4.1 ± 0.3aA	1.0 ± 0.0bA	6.6 ± 0.8aA	2.1 ± 0.6bA
Yankee	3.8 ± 0.6aA	1.0 ± 0.0bA		
Millenium	4.3 ± 0.7aA	1.0 ± 0.0bA		
Avg.	2.9	1.0	2.0	1.1

Means followed by different lowercase letters within a row or different capital letters within a column are significantly different ($P < 0.05$; Tukey's test).

[a] Visual rating for *T. tabaci* leaf damage on a scale ranging from 1 to 9: 1, no damage; 3, 25% of the leaves white or with blotches; 5, 50% of leaves white or with blotches; 7, 75% of leaves white or with blotches; and 9, complete damage (100% leaves white).

Plant Height. In 2007, plant height was measured at 91 DAT and for each cultivar there was a significant ($P < 0.05$) decrease in plant height in the nonprotected treatment (data not shown). The percentage reduction in plant height varied between 15 and 23%, but these differences were not significant ($F = 0.36$; df = 6, 3; $P = 0.8949$) (data not shown).

In 2008, there was a significant decrease in plant height in the NP treatment at 93 DAT in the susceptible check Nebula and in the other cultivars, except for Colorado 6, T-433, and Calibra (Table 6). Percentages of height reduction varied from 2 to 31%. Nebula had the highest percentage and was significantly ($F = 3.64$; df = 11, 3; $P = 0.0019$) different from Cometa, Delgado, Calibra, T-433, and Colorado 6 (Table 6).

Plant Weight. In 2007, at the end of the season, the fresh weight of plants was taken and there were significant ($P < 0.05$) decreases in weight in all the cultivars in the NP treatment, except for Colorado 6 (data not shown). Plant weight reductions for cultivars ranged from 17 to 43.5% but did not differ significantly from each other ($F = 0.75$; df = 6, 3; $P = 0.6196$) (data not shown).

Bulb Weight. Most of the cultivars did not show significant ($P > 0.05$) differences in bulb weight in the NP treatment except for the susceptible Nebula and the onions OLYS05N5, Cometa, and NMSU 03-52-1 (Table 6). Bulb weight reductions ranged from 1 to 54%. Nebula had the highest reduction and was significantly ($F = 9.92$; df = 11, 3; $P < 0.001$) different from all the other cultivars.

IYSV Infection Assessment. In 2007, 578 onion plants in total from the experiment on the impact of *T. tabaci* on plant growth were tested for IYSV (Table 7). The number of plants tested per cultivar ranged from 37 to 44. Surprisingly, the percentages of IYSV-infected plants in the P and NP treatments were not different, 7.8 and 7.4%, respectively, although plants in the NP

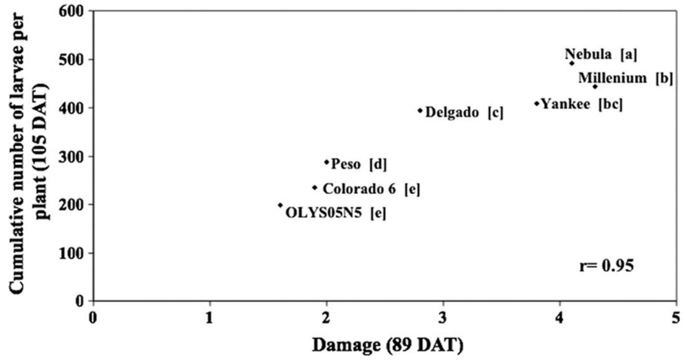

Fig. 3. Cumulative number of larvae per plant versus Damage on seven onion cultivars in the NP treatment (impact on plant growth experiment, 2007). Cultivars with different letters have significantly different cumulative number of larvae ($P <$ 0.05; Tukey's test).

treatment had more *T. tabaci.* For Peso and 'Millenium', the percentage of plants infected with IYSV was even higher in the P treatment compared with the NP treatment (Table 7). There were no significant ($P >$ 0.05) differences in infection levels between P and NP treatments for any of the cultivars.

In 2008, 672 (28 plants per cultivar) and 642 (22 and 28 plants per cultivar except for NMSU 03-52-1, which had 16 plants in the P treatment) onion plants in total were tested in Potter and Elba, respectively (Table 7). Surprisingly, the level of infection found was higher for plants in the P treatment in almost every cultivar. In Potter, the percentages of infected plants in the NP and P treatments were 31.0 and 45.8%, respectively. There were significant ($P < 0.05$) differences between P and NP treatments in Nebula ($\chi^2 = 4.90$, df = 1, $P =$ 0.0269), OLYS05N5 ($\chi^2 = 6.68$, df = 1, $P = 0.0098$), Tioga ($\chi^2 = 7.36$, df = 1, $P = 0.0067$), and Cometa ($\chi^2 = 5.26$, df = 1, $P = 0.0218$). In Elba, percentages in the NP and P treatments were 37.1 and 58.6%, respectively. There were significant ($P < 0.05$) differences between P and NP treatments in OLYS05N5 ($\chi^2 =$ 6.17, df = 1, $P = 0.0130$), Colorado 6 ($\chi^2 = 8.74$, df = 1, $P = 0.0031$), and Tioga ($\chi^2 = 12.66$, df = 1, $P =$ 0.0004).

Discussion

Eleven onion cultivars in total were found to be resistant to *T. tabaci.* In the screening experiment in Potter (2007), eight cultivars (OLYS05N5, Colorado 6, Delgado, Tioga, Peso, Cometa, Calibra, and Medeo) had the lowest damage ratings, and there were no significant differences among them. Colorado 6, OLYS05N5, Cometa, and Tioga had the lowest cumulative number of *T. tabaci* larvae. This suggests that these four cultivars may possess antibiosis or Antixenosis, or both, as a category of resistance against *T. tabaci.* Medeo and Peso had an intermediate cumulative number of larvae, whereas Calibra and Delgado had cumulative numbers of larvae comparable with the populations observed in the susceptible checks, suggesting that the latter two cultivars may be tolerant to *T. tabaci* populations. In the yield loss experiment in Elba (2008), the same eight cultivars had the lowest *T. tabaci* feeding damage along with Vaquero, NMSU 03-52-1, and T-433 that were included in 2008 experiments. NMSU 03-52-1 had the lowest number of *T. tabaci*, indicating strong antibiosis or antixenosis or both, but additional tests will need to be undertaken to determine the resistance category. Vaquero and

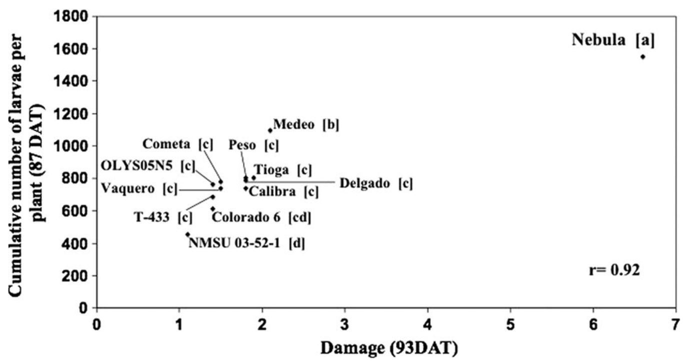

Fig. 4. Cumulative number of larvae per plant versus Damage on 12 onion cultivars in the NP treatment (yield loss experiment, 2008). Cultivars with different letters have significantly different cumulative number of larvae ($P < 0.05$; Tukey's test).

Table 6. Onion plant ht (mean ± SE) at 93 DAT and bulb weights (mean ± SE) (Yield loss exp-Elba, 2008) on 12 onion cultivars

Cultivar	Plant ht (cm)[a]			Bulb wt (g)[b]		
	P	NP	% reduction	P	NP	% reduction
Delgado	64.2 ± 7.0a	58.3 ± 7.1b	8.9 ± 12.0B	54.9 ± 40.5a	54.4 ± 31.6a	0.9 ± 0.6E
Colorado 6	61.7 ± 7.1a	60.1 ± 8.0a	2.3 ± 9.2B	15.7 ± 11.7a	15.2 ± 18.0a	3.2 ± 2.3DE
Peso	66.6 ± 4.8a	59.5 ± 6.1b	10.5 ± 7.0AB	44.5 ± 31.9a	41.4 ± 20.0a	7.0 ± 1.7CDE
T-433	57.0 ± 4.1a	55.3 ± 6.7a	3.2 ± 4.6B	51.2 ± 27.5a	44.5 ± 22.7a	13.1 ± 6.5BCDE
Tioga	63.5 ± 5.5a	53.9 ± 5.7b	15.0 ± 6.5AB	45.6 ± 35.0a	39.5 ± 22.7a	13.5 ± 0.7BCDE
Calibra	58.2 ± 7.9a	55.0 ± 4.7a	4.1 ± 16.4B	44.9 ± 29.2a	38.3 ± 27.5a	14.7 ± 8.0BCDE
Medeo	62.6 ± 5.9a	48.3 ± 4.7b	22.7 ± 6.9AB	51.0 ± 25.9a	40.9 ± 30.0a	20.0 ± 13.8BCDE
Vaquero	64.2 ± 6.8a	58.0 ± 6.1b	9.4 ± 8.3AB	63.0 ± 39.0a	46.5 ± 32.7a	26.1 ± 8.4BCD
NMSU 03-52-1	59.2 ± 6.3a	49.1 ± 6.1b	17.0 ± 7.8AB	40.8 ± 20.9a	30.0 ± 15.7b	26.5 ± 11.7BC
Cometa	64.6 ± 6.5a	58.6 ± 4.4b	9.1 ± 6.1B	24.8 ± 14.2a	18.0 ± 9.4b	27.5 ± 4.3BC
OLYS05N5	72.8 ± 8.4a	64.5 ± 6.5b	11.3 ± 2.6AB	34.6 ± 12.8a	23.8 ± 10.8b	31.1 ± 2.2B
Nebula	57.8 ± 5.0a	40.0 ± 6.3b	30.8 ± 6.1A	74.7 ± 18.5a	34.4 ± 20.1b	54.0 ± 21.3A
Avg.	62.7	55.0		45.5	35.6	

Means followed by different lowercase letters within a row or different capital letters within a column are significantly different ($P < 0.05$; Tukey's test).

[a] Average of 5 plants per cultivar in four replicates.

[b] Average of 7 plants per cultivar in four replicates.

T-433 had intermediate levels of *T. tabaci,* which may indicate a combination of categories of resistance.

The *r* values between *T. tabaci* feeding damage and cumulative number of larvae were not very strong in the screening experiments due to the presence of tolerant cultivars that showed low damage, but supported *T. tabaci* populations similar to the most susceptible cultivars and vice versa where very susceptible cultivars had high damage ratings but low *T. tabaci* populations. However, the regression analyses indicated that *T. tabaci* populations were a significant predictor of leaf damage. Nevertheless, correlation coefficients between *T. tabaci* feeding damage ratings within the different locations were very strong. This illustrates a consistent response of *T. tabaci* feeding damage across years and locations. Most of the cultivars that showed resistance to *T. tabaci* are considered late maturing. However, late maturity was not the

Table 7. IYSV incidence on onion plants, as shown by DAS-ELISA, in the impact on plant growth in Potter, 2007 (seven onion cultivars) and in the yield losses experiments in Potter, 2008 (12 cultivars) and Elba, 2008 (12 cultivars)

Cultivar	Treatment	Potter 2007, % plants infected (mean ± SE)	Potter 2008, % plants infected (mean ± SE)	Elba 2008, % plants infected (mean ± SE)
Medeo	NP		53.6 ± 7.1	37.0 ± 19.1
	P		46.4 ± 29.4	53.6 ± 21.4
Peso	NP	6.8 ± 4.6	21.4 ± 27.3	35.7 ± 18.4
	P	12.2 ± 14.6	39.3 ± 13.6	50.0 ± 14.3
Delgado	NP	2.4 ± 4.8	60.7 ± 18.0	46.4 ± 13.7
	P	2.2 ± 4.4	53.6 ± 24.4	60.7 ± 27.0
OLYS05N5	NP	9.5 ± 11.0	14.3 ± 11.7*	32.1 ± 29.5*
	P	10.3 ± 14.5	46.4 ± 24.4	64.3 ± 14.3
Colorado 6	NP	12.5 ± 5.0	25.0 ± 24.4	39.3 ± 13.7*
	P	9.3 ± 13.2	39.3 ± 21.4	78.6 ± 24.7
Tioga	NP		21.5 ± 18.5*	28.6 ± 0.0*
	P		57.2 ± 26.1	78.6 ± 27.4
Cometa	NP		7.2 ± 8.3*	17.9 ± 18.0
	P		32.2 ± 31.7	35.7 ± 8.2
Calibra	NP		57.2 ± 20.2	55.6 ± 18.6
	P		71.4 ± 20.2	60.7 ± 27.0
NMSU 03-52-1	NP		35.7 ± 24.7	27.3 ± 23.5
	P		39.3 ± 18.0	50.0 ± 0.0
Vaquero	NP		28.6 ± 11.7	42.9 ± 20.2
	P		39.3 ± 29.4	50.0 ± 31.7
T-433	NP		25.0 ± 18.0	46.4 ± 13.7
	P		35.8 ± 8.3	60.7 ± 21.4
Nebula	NP	7.5 ± 9.6	21.5 ± 18.5*	36.0 ± 15.3
	P	2.5 ± 5.0	50.0 ± 14.3	60.9 ± 30.1
Yankee	NP	4.6 ± 5.3		
	P	4.7 ± 5.4		
Millenium	NP	5.4 ± 6.2		
	P	13.5 ± 10.3		
Total plants tested		578	672	642
Avg. % infected (NP/P)		7.4/7.8	31.0/45.8	37.1/58.6

* Significantly differences between P and NP treatment per each cultivar ($\alpha = 0.05$; logistic regression model using PROC GENMOD).

single best indicator of resistance because susceptible cultivars also matured late (Fig. 2C). This was confirmed by the correlations between days to maturity with *T. tabaci* populations and their feeding damage ratings and by the regression analyses that showed that days to maturity was not a significant ($P > 0.05$) predictor of leaf damage.

Although some cultivars had low populations of *T. tabaci* and showed little feeding damage, there were significant reductions in plant height across all cultivars in the NP treatments in 2007. Also, there were significant reductions in fresh plant weight in all the cultivars, except Colorado 6. This indicates that even low populations that cause low levels of leaf damage could have an impact on growth even on resistant cultivars. These results confirm findings from other field studies, showing the need for lower thresholds than previously proposed (Rueda et al. 2007). In 2008, when populations and damage were somewhat higher, significant reductions in height were observed for nine of the 12 cultivars studied, but significant reductions in bulb weights were observed in only four of the cultivars. This suggests that, at least in some cultivars, height reduction is not necessarily associated with bulb weight reduction.

Percentages of plants infected with IYSV varied from 15 to 79% in the screening experiments in 2008. There was no clear pattern of infection from year to year or from location to location; cultivars that sustained low numbers of *T. tabaci* and showed low leaf damage had high infection rates or vice versa. For example, Vaquero had one of the highest infection rates in Potter (50%) but the lowest in Elba (14.8%). Susceptible cultivars to *T. tabaci,* such as Red Zeppelin, Santana, and Red Bull, showed high infection rates in both locations; but other susceptible cultivars such as 606-1 and Yankee had low infection rates.

Cultivars that showed resistance to *T. tabaci* also had infection rates that ranged from 15 to 68%. These results suggest that cultivars resistant to *T. tabaci* are not necessarily resistant to the virus and vice versa. This was confirmed by the very low correlations between IYSV percentage of plants infected and damage ratings and between IYSV percentage of plants infected and cumulative number of larvae in the different screening experiments and by the regression analyses that showed that *T. tabaci* populations were not a significant predictor of IYSV infection. Also, IYSV percentage of plants infected in the different cultivars varied with field location, as confirmed by the low correlations between IYSV percentage of plants infected in Potter 2007, 2008 and Elba 2008. Surprisingly, onion plants in the P treatments in both places had the highest rates of IYSV infection in both locations in 2008. Joost and Riley (2005), using the electrical penetration graph technique, showed that *Frankliniella occidentalis* (Pergande) probed longer and more frequently on tomato plants treated with imidacloprid compared with untreated plants; it is possible that *T. tabaci* probed more frequently with longer durations in onions protected with spinetoram. This insecticide acts more slowly and may permit longer probing durations before *T. tabaci* mortality occurs; however, this needs to be further studied. Another possible explanation for this is that *T. tabaci* adults migrated from the adjacent, maturing commercial onion field into the P treatments, where onion plants were larger, healthier looking, and greener than those in the NP treatments. Thus, selective movement of *T. tabaci* adults into the P treatments could have resulted in an increased likelihood of IYSV transmission in the P treatments. Hsu et al. (2010) recently reported a positive correlation between high numbers of *T. tabaci* adults sampled in onion fields at the end of the season and high levels of IYSV. They suggested that late in the season viruliferous adults were likely migrating from harvested onion fields into nearby unharvested onion fields, where they transmitted IYSV.

HPR has been successfully deployed for several hundred years to control some insect pests in several important field crops, but its use in vegetables has been limited (Stoner 1992, Smith 2005). This has been attributed to several causes, including the difficulty in developing the high levels of resistance necessary to meet the high cosmetic standards required for vegetable crops, as well as the higher market value of vegetable crops that justifies the use of costly insecticides (Stoner 1992). However, there are examples of commercialized or advanced breeding lines developed for host plant resistance in vegetable crops, including the following: tomatoes *Lycopersicon esculentum* Mill, resistance to *Tetranychus telarius* (L.) (Gilbert et al. 1974); cucumber, *Cucumis sativus* L., resistance to *Acalymma* sp. and *Diabrotica* sp. (Peterson et al. 1982); potato, *Solanum tuberosum* L., resistance to *Leptinotarsa decemlineata* (Say) (Plaisted et al. 1992); carrot, *Daucus carota* L., resistance to *Psila rosae* (F.) (Ellis 1999); and cabbage, *Brassica oleracea* L. variety *capitata,* resistance to *Trichoplusia ni* (Hübner), *Pieris rapae* (L.), *Plutella xylostella* (L.) (Dickson et al. 1984) and to *T. tabaci* (Shelton et al. 1983, 1998). Although our studies identified useful germplasm for HPR in onions to *T. tabaci,* and suggest a strong link between color and resistance, more detailed behavioral studies are needed, so that breeding for HPR can be advanced more quickly. Some studies have suggested that *T. tabaci* avoids onion leaves with light green color (Jones et al. 1935, Coudriet et al. 1979). In the current study, only cultivars that were resistant to *T. tabaci* had a visual yellow-green color and these observations were corroborated with Hunter b values measured on 46 onion cultivars, where the b values on the resistant cultivars were among the 15 highest values, which indicates a stronger yellow color on them compared with the other cultivars (Table 1). The regression analyses indicated that leaf color (Hunter b values) was a significant predictor of *T. tabaci* feeding damage. Our findings strengthened the hypothesis that leaf color may be a key factor associated with resistance and/or susceptibility of onion cultivars to *T. tabaci.*

Differentiating between yield losses caused by *T. tabaci* and IYSV in open field studies is difficult. IYSV was detected for the first time in the summer of 2006 in New York, and it seems the virus is not yet affecting onion yields. In our studies, symptoms of IYSV were mild to absent and appeared late in the season in a scattered pattern, suggesting that reductions in plant size and bulb weight were due to *T. tabaci* feeding rather than IYSV. The overall average percentage of IYSV-infected plants was 10 and 60% in some of the experiments in 2007 and 2008, respectively. This increase should be of concern to onion growers in New York and other areas of recent infection because IYSV incidence increased almost 50% in just 1 yr. If IYSV infects onion plants early in the growing season, the losses may be devastating. Unfortunately, we were not able to identify germplasm resistant to IYSV. However, identifying varieties that have a strong antixenotic effect to the vector might be promising because this trait should mitigate the likelihood of transmission of IYSV.

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