Received: 27 August 2019 | Revised: 13 December 2019 | Accepted: 15 December 2019
DOI: 10.1111/aab.12565

MINOR REVIEW

Annals of Applied Biology An international journal of the aab
WILEY

# The incidence of turnip yellows virus in oilseed rape crops (*Brassica napus* L.) in three different regions of England over three consecutive growing seasons and the relationship with the abundance of flying *Myzus persicae*

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**Funding information**
Biotechnology and Biological Sciences Research Council, Grant/Award Numbers: BB/I017410/1, BBS/E/C/000J0200; Ghana Educational Trust Fund

## Abstract

Turnip yellows virus (TuYV) is the most important virus infecting oilseed rape in the United Kingdom. The incidence and spatial distribution of TuYV in winter oilseed rape (WOSR) crops in three regions of England were determined over three growing seasons. Leaf samples were collected from three fields in each region, in autumn (November–December) and spring (April) of the three crop seasons and tested for virus presence by enzyme-linked immunosorbent assay. Infection was detected in all fields except one. Higher TuYV incidences were recorded in 2007–2008 (≤89%) and 2009–2010 (≤100%) crop seasons than in 2008–2009 (≤24%). Highest incidences were recorded in Lincolnshire (≤100%), followed by Warwickshire (≤88%), with lowest incidences in Yorkshire (1–74%). There was a significant increase in incidence detected between autumn and spring sampling in eight fields, a significant decrease in one field and no significant change in 18 fields. Rothamsted Insect Survey suction trap data for the aphid *Myzus persicae* in Lincolnshire, Warwickshire and Yorkshire revealed two peaks of flight activity in most years (2007–2009). The second peak (September–November) coincided with emergence of WOSR. The highest cumulative (August–November) trap catches in the three regions during the three crop seasons occurred in Lincolnshire and the lowest in Yorkshire; catches in autumn 2009 were highest and lowest in autumn 2008. Regression analysis revealed a highly significant association between the cumulative numbers of *M. persicae* caught in the suction traps closest to the crops between August and November each year and the incidence of TuYV detected in the WOSR crops in the autumn of each year. Results are discussed in the light of factors affecting the spread of TuYV and future possibilities for control.

KEYWORDS
aphids, *Brassica napus* (oilseed rape), *Myzus persicae* abundance, turnip yellows virus incidence

  

## 1 | INTRODUCTION

*Turnip yellows virus* (TuYV, syn. *Beet western yellows virus*), a species in the *Polerovirus* genus of the *Luteoviridae* family is the most common virus infecting oilseed rape in the United Kingdom (Hardwick, Davies, & Wright, 1994; Stevens, McGrann, & Clark, 2008). It has a wide host range and infects more than 150 species in 23 dicotyledonous families, including economically important crops such as lettuce, spinach, field beans, radish, cabbage and oilseed rape (Graichen, 1996).

TuYV infection of oilseed rape crops in England was first reported in 1980 (Gilligan, Pechan, Day, & Hill, 1980) but the widespread incidence of the virus in the United Kingdom was first reported by Smith and Hinckes (1985). Results from a UK survey in 1983, covering 80 autumn-sown oilseed rape crops from Aberdeenshire to Essex showed that 97% were extensively infected with TuYV (Smith & Hinckes, 1985). Varying incidences of TuYV infection in oilseed rape crops have since been reported in the United Kingdom, ranging from less than 10 to 85% (Hardwick et al., 1994; Hill, Lane, & Hardwick, 1989; Jay, Rossall, & Smith, 1999; Walsh, Perrin, Miller, & Laycock, 1989). A survey conducted in 2009 covering oilseed rape crops on 80 farms from the south coast of England to Scotland showed TuYV infection of up to 70% (Clark & Stevens, 2009). Infection of oilseed rape crops by TuYV has also been reported in other countries including Germany (Schröder, 1994), France (Kerlan, 1991), the Czech Republic (Polak & Majkowa, 1992), Austria (Graichen, Rabeinstein, & Kurtz, 2000), Iran (Shahraeen, Farzadfar, & Lesemann, 2003), Serbia (Jasnic & Bagi, 2007; Milošević et al., 2015) and Australia (Coutts, Hawkes, & Jones, 2006). The virus has also been reported in lettuce in the United Kingdom (Walkey & Pink, 1990) and faba bean in Egypt and Morocco (Abraham, Varrelmann, & Vetten, 2008).

TuYV, like other members of the Luteoviridae is mostly restricted to the phloem tissue of host plants and is transmitted by aphid vectors from plant to plant in a persistent (acquisition times range from 30 min to hours, the vector cannot immediately transmit the virus and retains its ability to transmit through the moult and often for the remainder of its life), circulative (passes from the insect gut to the salivary glands via the haemolymph for transmission) and non-propagative (does not replicate in vector tissues) manner. The green peach aphid, *Myzus persicae* (Sulzer) is the principal vector in Europe (Schliephake, Graichen, & Rabenstein, 2000) with a transmission efficiency of about 90% (Schliephake et al., 2000). Enzyme-linked immunosorbent assay (ELISA) on samples of *M. persicae* caught in yellow water traps and Rothamsted Insect Survey suction traps have shown that 2–72% of *M. persicae* were carrying TuYV (Stevens et al., 2008).

TuYV infection is thought to be one of the major reasons why oilseed rape crops do not attain their potential yield in England (Stevens et al., 2008), estimated at 6.5 t $ha^{-1}$ (Berry & Spink, 2006), compared to the current yield of 3.4 t $ha^{-1}$ Department for Environment Food and Rural Affairs (2018). TuYV infection seriously affects all components of yield, including the number of pods per plant, number of seeds per pod and the oil content per seed. Plants infected with TuYV also have a reduced leaf area per plant and produce fewer primary branches (Jay et al., 1999). The effect of TuYV on the yield of oilseed rape depends on the incidence of virus infection and the crop variety (Walsh et al., 1989). One estimate of yield losses due to TuYV infection is up to 30% (Home-Grown Cereals Authority, 2009). Experimental plots of oilseed rape with 100% TuYV- infection yielded approximately 10% less seed and 13.4% less oil than plots with 18% virus infection (Smith & Hinckes, 1985). Plot experiments in Australia on spring oilseed rape, showed that a site with 96% infection suffered a yield loss of up to 46% (Jones, Coutts, & Hawkes, 2007) and in Germany, plots of winter oilseed rape with 90–100% TuYV infection yielded between 12 and 34% lower than plots that were almost virus-free (Graichen & Schliephake, 1999). When oilseed rape plants were co-infected with a mix of TuYV, cauliflower mosaic virus (CaMV) and turnip mosaic virus (TuMV), the yields of plants with severe virus symptoms were reduced by an estimated 70–79% (Hardwick et al., 1994).

Effective control of TuYV in oilseed rape is necessary to improve yields. However, for the most part, farmers growing oilseed rape in the United Kingdom seem not to be aware of the presence, let alone the incidence of TuYV in their crops. For this reason and as an important prerequisite for developing effective approaches to controlling the disease it is important to investigate the incidence of TuYV infection of oilseed rape crops at various locations, in different years and the type of disease pattern and spread in the fields. The quantitative relationship between the flight activities of the aphid vectors is also important for the timing and development of control strategies.

Here the incidence and distribution of TuYV in fields of winter oilseed rape in three regions of England in the autumn and spring of three consecutive crop seasons are described. It has been said that the spread of brassica viruses is related to the abundance and movement of aphid vectors (Walsh & Tomlinson, 1985). In Germany, high levels of TuYV infection were detected in winter oilseed rape crops during 1995–1996 following high levels of flight activity of aphids during the autumn of 1995 (Graichen & Schliephake, 1999). We have investigated these relationships in the context of *M. persicae* (said to be the most important vector of TuYV in Europe) and quantified them by relating the number of flying *M. persicae* caught in the Rothamsted Insect Survey suction traps located nearest to sampling sites to the incidences of TuYV at the sampling sites in the three regions, over the three consecutive growing seasons.

## 2 | MATERIALS AND METHODS

### 2.1 | Surveys of winter oilseed rape crops

Using a line transect sampling method (Buckland et al., 2001), upper leaves from 100 plants were sampled from three crop fields in each of three oilseed rape-growing regions of England, Eastern (Lincolnshire), Northern (Yorkshire) and Midlands (Warwickshire) in autumn (November–December; 2–6 true leaves) and the following spring (April; starting to flower) during the 2007–2008, 2008–2009 and

2009–2010 crop seasons (27 fields in all). Aphids were very rarely seen on the sampled plants, consequently no records were taken. Samples from each plant were placed in separate polythene bags to register sampling positions within fields. The Lincolnshire fields were near Long Sutton, the Warwickshire fields were near Gaydon, and the Yorkshire sites were near Allerton, Little Ouseburn, Aberford, Green Hammerton and Whixley. The locations of the fields were determined using a Global Positioning System (Garmin E-Trex HGPS Receiver, Garmin Corporation, Olathe, Kansas) (Table S1).

The sampling procedure involved estimating the length and breadth of each field in order to divide the field into 10 equally spaced transects with 10 equally spaced samples collected per transect. Where fields were exceptionally large, only a proportion of the fields were sampled. The mean field size was 20.8 ha (range from 4.3 to 40.0 ha).

### 2.2 | Sampling sites

Farms sampled rotate oilseed rape crops every 3–6 years with crops such as wheat, potato, sugar beet, peas and may also practice land fallowing. Winter oilseed rape is normally sown in England between late August and early September, overwinters, flowers in the spring (April–May) and is harvested in July/August. Seed sowing in field three in Warwickshire during the 2008–2009 crop season was delayed by the prevailing weather conditions until late September. Where the information was available, the cultivars in the fields sampled are given in Table S1.

### 2.3 | Detection of TuYV in the samples

The presence of TuYV was tested in all sampled plants by standard triple antibody sandwich ELISA using paired wells in microtitre plates (96-well Nunc Maxisorp; Nunc, Roskilde, Denmark) as described by Hunter, Jones, and Walsh (2002).

Absorbance values ($A_{405\ nm}$) were measured with a Biochrom Anthos 2010 microplate reader (Biochrom Ltd., Cambridge, UK). Values for 10 uninfected leaf samples were also measured. A sample was deemed to be positive when the absorbance was greater than the mean absorbance of 10 healthy samples on each ELISA plate, plus 2.262 × standard deviation of the mean of the 10 healthy samples (where 2.262 = inverse of Student's $t$ distribution at 5% probability level with 9 degrees of freedom).

### 2.4 | Data analysis

TuYV incidence data were analysed using a generalised linear model (GLM) (Nelder & Wedderburn, 1972). Differences between county and crop season means and their interactions were compared using the approximate least significant difference (LSD) calculated from the analyses.

A two-sample binomial test (Armitage & Berry, 1994) was used to determine whether there was a significant change in TuYV incidences in each field between autumn and spring. The overall correlation between autumn and spring incidences of TuYV infections was assessed using the Pearson correlation coefficient. All statistical analyses were carried out using GenStat (GenStat Release version 12.1) (Payne, Murray, Harding, Baird, & Soutar, 2009).

The cumulative numbers of *M. persicae* caught monthly in the Rothamsted Insect Survey suction traps closest to the sampling sites (Kirton in Lincolnshire [22–26 km from fields sampled], Askham Bryan in Yorkshire [13–17 km from fields sampled] and Wellesbourne in Warwickshire [10–11 km from fields sampled]) were determined from the weekly suction trap aphid catches obtained between August (crop sowing) and November for each year. A nonlinear regression analysis fitting an exponential function was used to explore the relationship between mean TuYV incidences in autumn and the cumulative aphid counts.

A Black–White (BW) join-count statistic (Cliff & Ord, 1969) was calculated using GenStat to assess spatial autocorrelation within each field for each sampling occasion, comparing a null hypothesis of random distribution of infected samples with an alternative hypothesis of spatial clustering. The statistic measures the number of neighbour pairs containing both an infected and a healthy plant, where neighbours were defined here to be adjacent samples in vertical or horizontal directions (each non-edge sample has four neighbours, that is, "rook case"). The significance of the join-count statistic is achieved by computing a standard normal deviate, called a $Z$-score which is given by the formula:

$$Z(\mathrm{BW}) = \frac{\mathrm{Observed}\,(\mathrm{BW}) - \mathrm{Expected}\,(\mathrm{BW})}{\sigma_{\mathrm{BW}}},$$

where $\sigma_{BW}$ is the standard deviation for BW joins. The expected number of BW neighbours is calculated based on the overall proportion of infected plants and represents the likely pattern under a random distribution. As the aim was to detect evidence of clustering, a one-sided test for negative values of the BW join-count statistic was appropriate, negative values indicating a positive spatial autocorrelation between infected plants and probability levels of $p \le .05$ indicating significant spatial autocorrelation.

## 3 | RESULTS

### 3.1 | Incidence of TuYV infection in winter oilseed rape crops

The overall mean TuYV incidences recorded in the autumns of 2007 (36.67 ± 4.56%) and 2009 (48.67 ± 3.62%) were not significantly different from each other but were significantly higher ($p < .001$) than recorded in the autumn of 2008 (6.11 ± 2.33%) (Table 1). Highly significant differences ($p < .001$) in the mean percentage autumn virus incidences were found between the counties (Table 1). Lincolnshire

**TABLE 1** Mean autumn percentage incidence of turnip yellows virus (TuYV) in winter oilseed rape crops in Lincolnshire, Warwickshire and Yorkshire in the 2007–2008, 2008–2009 and 2009–2010 crop seasons

| | Mean TuYV incidence (%) in autumn of crop season | | | |
|---|---|---|---|---|
| Region | 2007–2008 | 2008–2009 | 2009–2010 | Means[a] |
| Lincolnshire | 58.00 ± 8.51 b[b,c] | 13.00 ± 5.80 d, e | 94.00 ± 4.08 a | 55.00 ± 3.69 a |
| Warwickshire | 27.33 ± 7.69 c, d | 3.00 ± 2.94 e | 41.00 ± 8.48 b, c | 23.78 ± 3.94 b |
| Yorkshire | 24.67 ± 7.43 c, d | 2.33 ± 2.60 e | 11.00 ± 5.40 d, e | 12.67 ± 3.18 c |
| Means[d] | 36.67 ± 4.56 a | 6.11 ± 2.33 b | 48.67 ± 3.62 a | |

*Note:* Analysis of the TuYV incidence data was carried out using a generalised linear model.
[a]Means in the same column followed by different letters are significantly different from each other ($p < .001$).
[b]Mean and standard error (mean ± *SE*).
[c]Region–crop season incidence interaction means followed by different letters are significantly different from each other ($p < .05$).
[d]Means in the same row followed by different letters are significantly different from each other ($p < .001$).

**TABLE 2** Mean spring percentage incidence of turnip yellows virus (TuYV) in winter oilseed rape crops in Lincolnshire, Warwickshire and Yorkshire in the 2007–2008, 2008–2009 and 2009–2010 crop seasons

| | Mean TuYV incidence (%) in spring of crop season | | | |
|---|---|---|---|---|
| Region | 2007–2008 | 2008–2009 | 2009–2010 | Means[a] |
| Lincolnshire | 66.00 ± 12.08[b,c] | 10.00 ± 7.65 | 94.00 ± 6.04 | 56.67 ± 5.17 a |
| Warwickshire | 68.33 ± 11.86 | 12.33 ± 8.38 | 45.33 ± 12.69 | 42.00 ± 6.43 a |
| Yorkshire | 32.67 ± 11.96 | 3.67 ± 4.79 | 22.00 ± 10.56 | 19.44 ± 5.55 b |
| Means[d] | 55.67 ± 6.91 a | 8.67 ± 4.11 b | 53.78 ± 5.86 a | |

*Note:* Analysis of the TuYV incidence data was carried out using a generalised linear model.
[a]Means in the same column followed by different letters are significantly different from each other ($p = .002$).
[b]Mean and standard error (mean ± *SE*).
[c]The interaction effect between county and crop season is not significant ($p = .163$).
[d]Means in the same row followed by different letters are significantly different from each other ($p < .001$).

had the highest mean TuYV incidence (55.00 ± 3.69%), followed by Warwickshire (23.78 ± 3.94%) while Yorkshire had the lowest (12.67 ± 3.18%) (Table 1; Figure 2b). The interaction effects between the counties and crop seasons for autumn virus incidences were significant ($p < .05$). The highest mean incidence (94.00 ± 4.08%) was recorded in Lincolnshire during the autumn of 2009, while the lowest (2.33 ± 2.60%) was recorded in Yorkshire during the autumn of 2008.

The highest overall mean TuYV incidence in spring was recorded in the 2007–2008 crop (55.67 ± 6.91%), followed by the 2009–2010 crop (53.78 ± 5.86%); the 2008–2009 crop had the lowest (8.67 ± 4.11%) (Table 2). Lincolnshire had the highest overall mean spring incidence (56.67 ± 5.17%), followed by Warwickshire (42.00 ± 6.43%) and Yorkshire had the lowest (19.44 ± 5.55%). The GLM analysis did not indicate a significant interaction between the regions and crop seasons for the spring incidences of TuYV ($p = .163$). However, the highest mean incidence (94.00 ± 6.04%) was recorded in Lincolnshire in spring of the 2009–2010 crop, while the lowest mean incidence (3.67 ± 4.79%) was recorded in Yorkshire during 2008–2009 crop season (Table 2).

The comparisons of autumn and spring incidences of TuYV in the individual 27 fields in the three regions over the three crop seasons using the two-sample binomial test are shown in Table S1. Large differences in the incidences of TuYV in the various fields, counties and crop seasons surveyed, ranging from 0% (recorded in autumn and spring in Warwickshire in 2008–2009) to 100% (recorded in Lincolnshire in the autumn of 2009) were found. There were significant ($p < .05$) changes in the proportions of plants infected with TuYV between autumn and spring in five of the nine fields in 2007–2008 (all three fields in Warwickshire and one each in Lincolnshire and Yorkshire), three fields in 2008–2009 (two in Lincolnshire and one in Warwickshire) and only one field in 2009–2010 (Yorkshire) (Table S1). With the exception of one of the fields in Lincolnshire in 2008–2009, all significant changes involved an increase in TuYV incidence. Overall, there was a significantly high correlation ($r = .89$, $p < .001$, $df = 25$) between autumn and spring incidences of TuYV in the oilseed rape crops surveyed.

## 3.2 | Within field virus distribution

The results of the analysis of spatial distribution of TuYV-infected plants are given in Table S1. Where possible, BW join-count statistics were calculated for each of the 27 fields surveyed in the three crop seasons and then tested as standard normal deviates (*Z*-scores). Most of the fields (17 of the 25 analysed) showed positive, but non-significant spatial autocorrelation (negative *Z*-scores, $p > .05$) when sampled in autumn, indicating that most of the infected plants showed a slightly aggregated pattern of distribution. For a one-sided test at a probability of .05, values less than −1.645 (large negative *Z*-score) indicated that the number of observed join-counts was significantly less than expected, an indication of clustering of the infected plants. Lincolnshire Field 1 was the only field showing significant positive autocorrelation ($Z = -1.922$, $p < .05$) between the infected plants in autumn (2007), indicating significant clustering (Figure 1a). Spring sampling revealed a slightly more random pattern with half of the fields (13 of the 26 analysed) showing negative spatial autocorrelation (positive $Z$-scores) (e.g., Warwickshire Field 2 in spring 2010, $Z = 0.561$, $p = .288$; Figure 1b). Warwickshire Field 1 showed a significant positive autocorrelation ($Z = -2.177$, $p < .05$) between the infected plants in spring 2008, indicating clustering.

## 3.3 | Numbers of *Myzus persicae* caught in Rothamsted Insect Survey suction traps

Rothamsted Insect Survey suction trap catches showed two peaks of flight activity of *M. persicae* in Lincolnshire, Warwickshire and Yorkshire in most years (2007–2009; Figure 2a). The first peak occurred between June and July and the second occurred between September and November in each year, the latter coinciding with the emergence of oilseed rape crops. Crops were sown in August or September. The highest cumulative (August–November) trap catches of *M. persicae* during the three crop seasons occurred in Lincolnshire and the lowest in Yorkshire; catches in autumn 2009 were highest and those in autumn 2008 were lowest.

## 3.4 | Relationship between flying *Myzus persicae* and TuYV incidence

There was a clear relationship between TuYV incidence and aphid numbers (Figure 2). Regression analysis revealed a highly significant association between the numbers of *M. persicae* caught in the Rothamsted Insect Survey suction traps closest to the crops between August and November each year and the incidence of TuYV in the oilseed rape crops ($df = 2, 8$; $F = 24.2$; $p < .001$) in autumn of each year (Figure 3).

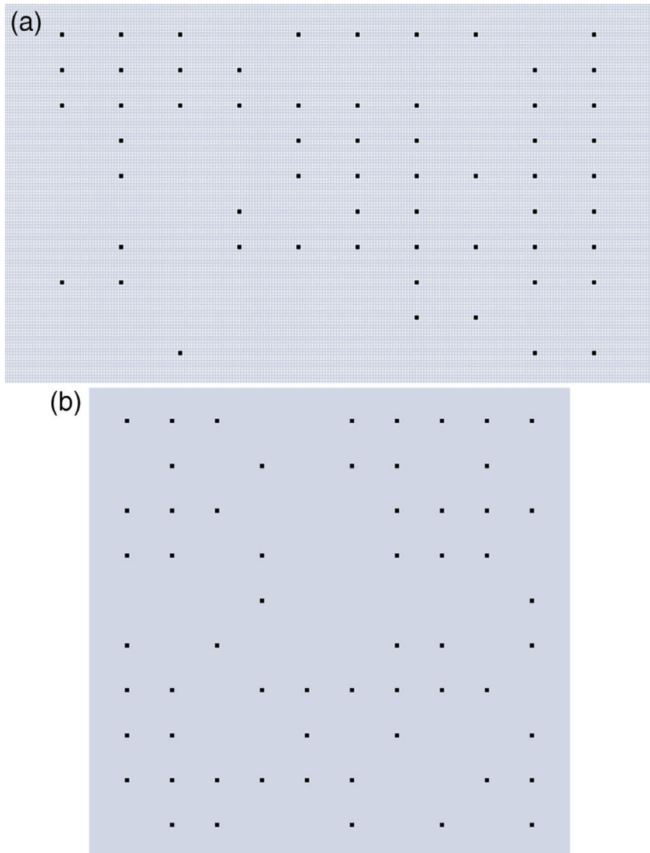


**FIGURE 1** (a) Spatial distribution of turnip yellows virus-infected plants in oilseed rape Field 1 in Lincolnshire in autumn of the 2007–2008 crop season showing significant clustering (Rook's case connection of Black–White join-count statistic was used to test for the spatial autocorrelation of the TuYV-infected plants. In this field, $Z = -1.922$, $p < .05$). (b) Spatial distribution of turnip yellows virus-infected plants in oilseed rape Field 2 in Warwickshire in spring of the 2009–2010 crop season showing random distribution (Rook's case connection of Black–White join-count statistic was used to test for the spatial autocorrelation of the TuYV-infected plants. In this field, $Z = 0.561$, $p = .288$)

## 4 | DISCUSSION

In this study, TuYV was prevalent in winter oilseed rape fields in three regions of England over a 3-year period with incidences within individual fields ranging from 0–100%. The virus was detected in 26 of the 27 oilseed rape fields sampled from three regions (Lincolnshire, Warwickshire and Yorkshire). This finding corroborates the previous reports of widespread occurrence of TuYV in oilseed rape crops in the United Kingdom (Hardwick et al., 1994; Hill et al., 1989; Jay et al., 1999; Smith & Hinckes, 1985; Stevens et al., 2008; Walsh et al., 1989) where incidences of 0–100% were also reported. The only field where no infection was recorded (Warwickshire field three in the 2008–2009 crop season) was sown late (September 27, 2008) relative to the other two Warwickshire fields (sown August 26–27, 2008) and the very few plants that had emerged were very small when sampled on December 15, 2008. It is clear from Figure 2a that aphid numbers in Warwickshire were very low by late September 2008 and this, combined with the late planting date and the sparsity of plants, is very likely to be the reason for the lack of infection. We have not done any detailed assessments of TuYV incidence in winter oilseed rape in the United Kingdom since 2010, however, the limited testing of commercial oilseed rape crops that we have done, has revealed incidences of 0–100% in the 2018–2019 crop, as for the 2007–2010 study reported here. That said, many crops tested early in 2019 had incidences of 100%, reflecting the very high numbers of *M. persicae* caught in Rothamsted Insect Survey suction traps between August and November 2018.

The analysis of the autumn incidences of TuYV in the oilseed rape crops in the different regions sampled were clearly associated with the cumulative numbers of *M. persicae* caught in the suction traps in

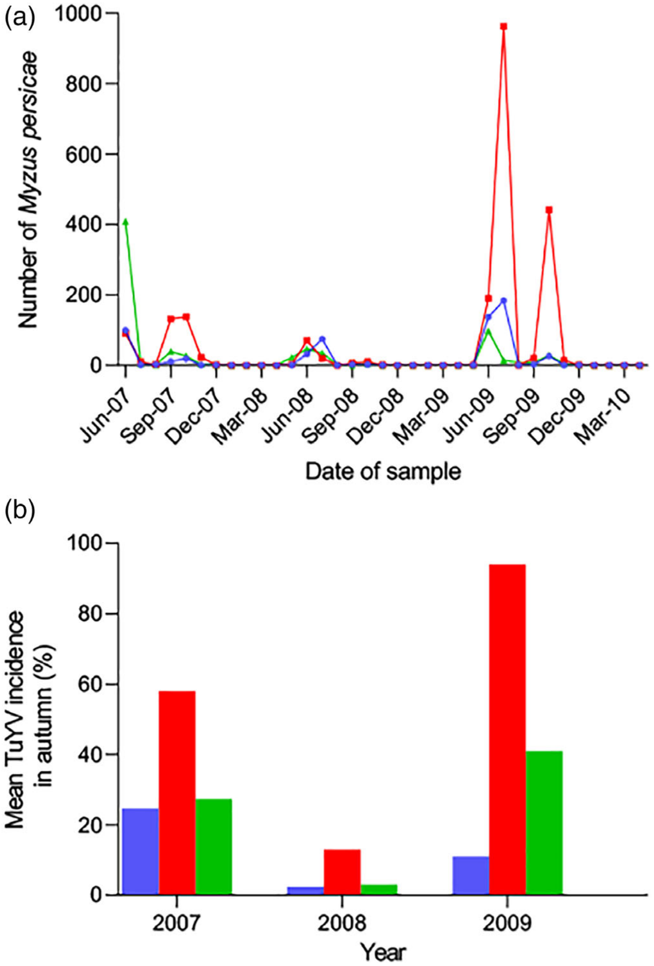


**FIGURE 2** (a) Rothamsted Insect Survey catches of *Myzus persicae* in suction traps located in Lincolnshire, Warwickshire and Yorkshire between June 2007 and April 2010 (Source: Aphid Bulletin, Rothamsted Insect Survey, Rothamsted Research, UK). (b) Mean incidences of turnip yellows virus from three fields in each of Lincolnshire, Warwickshire and Yorkshire in the autumns of 2007, 2008 and 2009

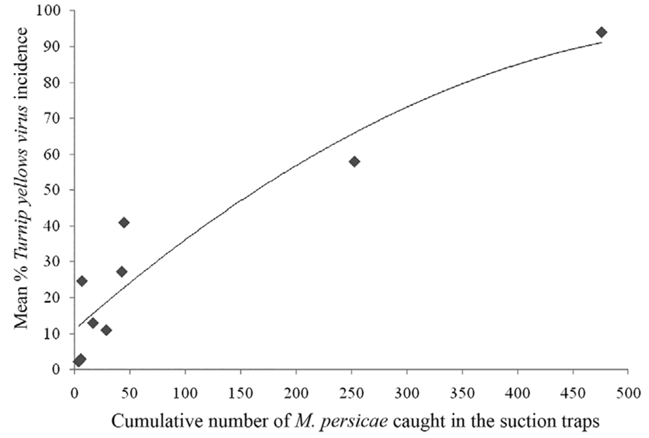


**FIGURE 3** Relationship between cumulative numbers of *Myzus persicae* caught in the Rothamsted Insect Survey suction traps located in Lincolnshire, Warwickshire and Yorkshire between August and November in 2007, 2008 and 2009 and mean percentage turnip yellows virus incidence in oilseed rape crops in the autumn of each year in the three regions ($df$ = 2, 8; $F$ = 24.2; $p$ < .001)

these regions between August and November. This indicates that the significantly higher incidences of TuYV recorded in the 2007–2008 and 2009–2010 crops compared with those in the 2008–2009 crops were due to the increased flight activity of *M. persicae* between August and November in 2007 and 2009, relative to 2008 (Figure 2). Graichen and Schliephake (1999) also demonstrated that a high incidence of TuYV in winter oilseed rape appeared to be closely related to the flight activity of *M. persicae* vectors in Germany. Clark and Stevens (2011) indicated a close correlation between aphid numbers caught in the autumn and the amount of virus present in oilseed rape in the United Kingdom. The timing and intensity of the spring and summer *M. persicae* aphid flights in the Columbia basin in the United States were associated with heat unit accumulation (day degrees) (Thomas, Pike, & Reed, 1997). The differences between the accumulated day degrees in the first part (January–May) of 2007, 2008 and 2009 for the site of the Warwickshire Rothamsted Insect Survey suction trap do not appear to account for the abundance of *M. persicae* caught in this suction trap between August and November in these years and hence the incidence of TuYV. It is possible that the accumulated day degrees later in these years might account for the differences; however other factors including rainfall, predation, parasites, pathogens, availability of suitable host plants etc. are also likely to have an effect. Mild autumn conditions favour the development of the aphid vectors and encourage TuYV spread (Stevens et al., 2008). The low numbers of aphids in 2008 accounting for the low incidence of TuYV, were said to be due to wet and windy weather and an abundance of natural enemies.

In general, the incidence of TuYV within oilseed rape crops is considered to increase from initial autumn infection to a maximum level in the following spring (Stevens et al., 2008). Our data showed significant increases in the incidence of TuYV in eight fields between autumn and spring, but no significant change in 18 fields and a significant decrease in only one field. Most of the increases in incidence between autumn and spring occurred in the 2007/2008 crop. All the fields in Warwickshire showed a significant increase in TuYV incidence between autumn 2007 and spring 2008 and the cumulative day degrees at our site in Warwickshire (10–11 km from the Warwickshire fields sampled) were greater between January and May 2007 than for the same months in 2008 and 2009. This indicates that in warmer winters, there could be yield/financial benefits from applying control measures such as effective insecticides at some point between November and April, depending up on regulations (numbers of spray and spray intervals permitted) and costs.

The significant regional differences in TuYV incidence, where highest levels of infection were observed in Lincolnshire and lowest in Yorkshire are likely to be attributable to a number of factors. There was much increased flight activity of *M. persicae* in Lincolnshire in the autumns of 2007 and 2009 relative to Yorkshire and Warwickshire. Also, the large area of vegetable brassicas grown in Lincolnshire is likely to be a reservoir of TuYV and source for aphids over the summer months, when no oilseed rape crops are present. Between 1986 and 1989, surveys in England and Wales detected lower TuYV incidences in the north and east (Hill et al., 1989). In 1992 and 1993, the incidence of TuYV was higher in Wales and the midlands, western and south western regions of England than in the eastern, south eastern or northern regions of England (Hardwick et al., 1994). Our data over 3 years and that of others (Blake, 2009; Clark & Stevens, 2009) suggest that there has been a change in prevalence, in that the highest levels of TuYV have been in Lincolnshire, close to the Wash and on the south coast.

The spatial autocorrelation analysis revealed that TuYV-infected oilseed rape plants showed either random or slightly aggregated pattern of distribution within individual fields, with most fields showing slightly aggregated patterns during autumn. This finding agrees with that of Bourdon (1987) who reported that crop plants infected with viruses can show random or aggregated distributions, with aggregated distributions more common in vector-borne viruses. There is very little data on the spatial incidence of TuYV, however Raybould, Maskell, Edwards, Cooper, and Gray (1999) also reported plants infected by TuYV and other viruses (CaMV, TuMV and turnip yellow mosaic virus) were distributed randomly or were very weakly aggregated within wild populations of *Brassica oleracea*. Most of the oilseed crops showed positive autocorrelation (slight aggregated pattern) during autumn but a more random pattern during the following spring. Data on a non-persistently transmitted virus showed that aggregation of infected plants appears where there is limited spread of the virus from the initial (primary) foci of infection (Eckel & Lampert, 1993). This suggests that autumn infection (tending towards aggregation) is mostly due to primary infection with some, probably limited, secondary infection. The reduction in aggregation between autumn (18 out of 25 had negative *Z*-scores and only seven had positive *Z*-scores) and the following spring (13 out of 26 had negative *Z* scores and 13 had positive *Z*-scores) indicates that the infection of plants between the autumn sampling dates and May of the following years was mostly due to secondary spread of the virus within the fields, rather than further primary infection coming from outside the fields. This is consistent with the lack of flying aphid vectors caught in suction traps during this period (Anon., 2011) and the characteristic spatial spread of persistently transmitted viruses (Thresh, 1976). All the crops we sampled were in arable crop growing vicinities and the most common crops surrounding the fields sampled were winter wheat and winter barley, neither of which is known to be an important host for TuYV.

Oilseed rape is not reaching its full yield potential in the United Kingdom. No doubt there are a number of reasons for this, however, there is compelling evidence for TuYV being a major contributor to the shortfalls. TuYV is probably the most widespread and common disease of oilseed rape in the United Kingdom. The high levels of infection found, in years where there have been wet and not particularly warm summers and autumns, indicates that in warmer, drier years predicted under climate change scenarios (Parry, 1990), TuYV is likely to be an even greater problem. Higher incidences of TuYV were recorded for the major OSR growing countries of Europe (Poland, Germany and France; Newbert, 2016), than those outlined here for a 3-year period in England. This indicates that losses across parts of mainland Europe must be much higher than in the United Kingdom and control measures are needed. The most effective insecticides for *M. persicae* control, the neonicotinoids, are now banned in the EU due to adverse effects on pollinating insects (Dewar, 2017). Varieties of oilseed rape with partial resistance to TuYV are now available, however, all varieties possess the same resistance source. This has created high selection pressure for resistance-breaking strains of TuYV. A further alternative source of resistance has been reported recently (Hackenberg et al., 2019).

## ACKNOWLEDGEMENTS

The authors wish to thank Dick Evenden and Simon Carr for the help in identifying fields to sample, David Brightman and Adrian Howell for allowing us to sample their crops. We also thank Philippa Hallsworth, Sue Parker, Richard Harrington, Jinhua Mu, Shujiang Zhang and Rosemary Collier for their help. This work was supported by the Government of Ghana Educational Trust Fund and Biotechnology and Biological Sciences Research Council, Crop Improvement Research Club (CIRC) Project BB/I017410/1. We are grateful to collaborators and staff who have contributed data from the Rothamsted Insect Survey, a National Capability, is funded by the Biotechnology and Biological Sciences Research Council under the Core Capability Grant BBS/E/C/000J0200.

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**How to cite this article:** Asare-Bediako E, Jones JE, Hambidge AJ, et al. The incidence of turnip yellows virus in oilseed rape crops (*Brassica napus* L.) in three different regions of England over three consecutive growing seasons and the relationship with the abundance of flying *Myzus persicae*. *Ann Appl Biol*. 2020;176:130–137. https://doi.org/10.1111/aab.12565