Evaluation of a damage threshold for two-spotted spider mites, *Tetranychus urticae* Koch (Acari: Tetranychidae), in hop culture

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Summary

Damage caused by two-spotted spider mites (*Tetranychus urticae*) at harvest to yield, quality (measured in percentage α-acids content) and cone infestation was assessed on hop cvs Hallertauer Magnum, Hallertauer Tradition and Perle. Acaricide-untreated hop plants with known levels of *T. urticae* infestation were compared with neighbouring acaricide-treated plants. Although in 24 of the 36 experimental harvests the untreated hop plants had spider mite infestations of > 100 mites leaf^{-1}, yields and α-acids content from the untreated plants were significantly lower than the treated plants in only four instances. However, although mite infestation of cones from untreated hops were significantly higher than acaricide-treated plants in 27 of the 36 cases, in only one instance did that cause economic loss. Spider mite infestation levels of *c.* 90 mites leaf^{-1} are tolerable at harvest time with little or no risk of causing economic loss to hop growers.

Key words: Damage threshold, experimental harvest, hop, *Humulus lupulus*, *Tetranychus urticae*, two-spotted spider mite

Introduction

The dried cones, i.e. infructescences, of female hop plants (*Humulus lupulus* L.) are used by the brewing industry world-wide mainly to render a bitter taste and sometimes to provide a pronounced aroma to beer and related beverages. Originally, since the early Middle Ages, hop cones were added to beer for their preservative properties (Behre, 1999), but that role is now redundant.

Cultivated hop plants are regularly attacked by several arthropod pests. In Europe the most prevalent are the damson-hop aphid *Phorodon humuli* (Schrank) and the two-spotted spider mite *Tetranychus urticae* Koch. Without control measures, both pests are able to damage the quantity and quality of harvested cones. In some years they may completely destroy a crop (Neve, 1991).

Hop growers in Europe believe they have few options other than to apply acaricides in a preventive manner for the control of *T. urticae.* As an exception, in the hedge-like "dwarf hops" cropping system being developed in the UK, biological control of spider mites can be achieved by inoculative release of the allochthonous predatory mite *Phytoseiulus persimilis* Athias-Henriot (Campbell & Lilley, 1999; Lilley *et al.*, 1999; Barber *et al.*, 2003*b*). However, even in dwarf hops, an integrated approach combining the application of a selective acaricide followed by release of *P. persimilis* gave more effective control of *T. urticae* than did the predator alone (Lilley & Campbell, 1999). In conventional "tall hops", with trellis systems up to 7 m high, the success of predator-release strategies has been inconsistent and too unreliable for their exploitation by growers (e.g. Pruszynski & Cone, 1972; Hirschberger & Kremheller, 1993; Strong & Croft, 1995, 1996; Benker, 1999; Jones *et al.*, 2003).

In the Hallertau in Germany, the world's largest coherent hop-growing region, *T. urticae* is usually controlled by a prophylactic routine application of an acaricide. Approximately two thirds to three quarters of the area under cultivation are treated regularly once a year with acaricides. In 2003, an extremely hot season, second or third applications were necessary in many cases, as spider mites flourish especially well under hot and dry conditions (Neve, 1991). Growers' decisions to spray are personal and based on their previous experience with the pest. Therefore, the development of a dynamic threshold model for the control of *T. urticae* would provide them with a tool that would enable them to decide on objective grounds whether a prophylactic use of acaricides is necessary or not (Weihrauch, 2003).

A reliable field census method for *T. urticae* is an essential first module for the development of this control threshold model system, especially since this task would by necessity be undertaken by growers themselves. A new six-level pest index for *T. urticae* on hops devised by Weihrauch (2004) is summarised in Table 1. The mean scores from assessed leaves, which vary between 0.00 and 5.00, summarise the average severity of spider mite infestation levels at a site.

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Table 1. *Tabular representation of the pest index for two-spotted spider mites* Tetranychus urticae *Koch in hop culture*

Pest Index											
0		1		2		3		4		5	
mites	eggs	mites	eggs	mites	eggs	mites	eggs	mites	eggs	mites	eggs
0		0	x	0	xx	0	xxx				
		1-9									
		1-9	x	1-9	xx	1-9	xxx				
				10-49		10-49	xx				
				10-49	x	10-49	xxx				
						50-99					
						50-99	x				
						50-99	xx	50-99	xxx		
								100-999			
								100-999	x		
								100-999	xx	100-999	xxx
										> 1000	

Eggs: x = some, < 30; xx = many, 30 - 300; xxx = very many, > 300
Values shown are numbers per monitored leaf (taken from Weihrauch, 2004)

The second and most important module within this control threshold system is the economic injury threshold: how many spider mites are actually tolerable on hop plants at the end of the growing season without loss of yield or quality of the harvested cones? Wright & Cone (1999) noted that no empirically-derived economic injury level has been established for spider mites on hops, notwithstanding that Strong & Croft (1995) adopted a provisional action threshold of 5–10 spider mites leaf^{-1} for their studies. However, Strong & Croft's (1995) threshold was based on the damage they suspected may be caused in the absence of further control interventions, but the supporting evidence for that threshold were not published. Therefore, the principal aim of the present study was to evaluate the damage caused by *T. urticae* to hops at harvest in each of 3 years, and to use that information to establish an empirically-derived economic injury threshold. Three hop cultivars were included in order to ensure that findings were robust and representative of hop cultivation in the Hallertau.

Materials and Methods

Study area

The Hallertau is the world's largest contiguous hop-growing region. Although the land area under hops cultivation has declined steadily in the region since 1993, there were still 14 391 ha of hops grown in 2003, which represents about one quarter of world acreage. The Hallertau is situated south of the River Danube in the central part of Bavaria, Germany, and has an area totalling approximately 1500 km².

Experimental layout

The damage caused by *T. urticae* was assessed by harvesting acaricide-untreated hop plants with known levels of infestation on the day of the harvest, and comparing that with nearby acaricide-treated plants in the same garden. The latter plants were either uninfested, or with sufficiently low infestations that the grower could market them without financial loss according to hop market and personal standards. Neighbouring treated and untreated plants were chosen in order to minimise other factors, mainly soil-borne, that could potentially influence yield or quality.

The hop gardens chosen for this study were a subset from a large monitoring program for *T. urticae*, which was run from 1998 to 2000 in either 107 (1998) or 104 (1999/2000) gardens distributed evenly over the Hallertau growing region. All of these gardens had been regularly treated with acaricides in former years. Plots of 84 hop plants (six rows with 14 plants each; *c*. 300 m², representing average conditions of the field) were laid out in each garden in 1998. Three hop stems were grown up each of the two support wires at each plant, and that unit is hereinafter referred to as a 'bine'. The 84 plant plots were not treated with acaricides in any of the three years of investigations. Other pests and diseases were controlled in the plots using the respective grower's routine programme, except that the pesticides used were chosen to minimise any side-effects on spider mites. The pesticide treatments in the rest of the gardens were left completely to the farmer's decision.

Each garden was monitored shortly before the first application of an acaricide, usually in June, and finally a few days before harvest, which spanned the last 10 days of August to early September. Thus, the levels of spider mite infestations in each garden were well-known. Twelve of these gardens with a desired infestation level in the control plot were chosen annually for experimental harvests.

Spider mite monitoring

The monitoring procedure was conducted by the assessment of 20 leaves from different plants per sampling date and plot. Leaves were taken randomly from the lower part of the bines in June, and from the middle and upper regions of the bines in August and September. Leaves were examined using magnifying glasses (5×). Precise counts were made when numbers were low, but were estimated when they exceeded 100 *T. urticae* individuals in all postembryonic development stages, including legless quiescent stages (deutochrysalis and teliochrysalis). In addition, the density of spider mite eggs laid on the leaves was scored into one of four classes: no eggs, some eggs (< 30 leaf^{-1}), many eggs (30–300 leaf^{-1}) and very many eggs (> 300 leaf^{-1}). Spider mite numbers and egg densities of each leaf then were transformed to the corresponding pest index (Table 1).

Experimental harvests

In three field seasons from 1998 to 2000, 12 experimental harvests were conducted annually, thereby creating 36 data sets altogether. Four harvests were made from each of three cultivars, viz the bitter cv. Hallertauer Magnum (HM) and the aroma cvs Hallertauer Tradition (HT) and Perle (PE). Spider mite infestations on the untreated control plants and the treated plants selected for harvesting were monitored on the same day immediately prior to harvest. Four replicate samples of 10 untreated bines were compared with a similar number of acaricide-treated bines in each garden. Four rows of 10 bines each were marked for harvesting in the centre of the untreated control plot, leaving a gap of usually seven plants to the border of the treated plot (*c.* 9–11 m), where 10 treated bines were marked in each of the same four rows. All bines were first checked visually for normal growth; those with non-spider mite induced injuries or abnormalities were excluded from harvesting.

Field harvesting was conducted using the grower's own equipment. In this procedure, the bines were cut automatically just above ground level and their tops were pulled from the upper wires of the trellis system to fall on a self-loading trailer. Each harvested group of 10 bines was immediately separated on the trailer from the following replicate with a sheet of plastic film. The harvested bines were taken without delay to the stationary picking machine at the farmstead to separate cones from stems, leaves and other debris. The cones from each 10 bine sample were picked separately and bagged, and their fresh weights were recorded. A sub-sample of *c.* 3 kg fresh weight was taken from each replicate for further processing.

The sub-samples were immediately taken to the laboratory, weighed on an analytic scale, then dried overnight in an experimental kiln to a moisture content of *c.* 10–12%, and the exact dry weight was recorded once the sample had cooled. A further sub-sample of approximately 100 g of dried cones was taken from each sub-sample. The exact moisture content was determined, and the percentage α-acids was measured by conductimetric analysis according to EBC 7.4 (Anon., 1998).

Finally, 500 cones were taken from each sub-sample for evaluation of percentage spider mite infestation, and for weight determination. Infestation percentages were evaluated, according to German hop market standards, by visual assessment for spider mite traces on the cones, i.e. cone colour and puncture marks. In addition, the "weighted average" of infestation (ranging from 1.000 to 4.000, with 1.000 representing zero infestation) was determined according to the formula: [(number of uninfested cones) + 2 (number of cones with light infestation) + 3 (number of cones with middle infestation) +4 (number of cones with heavy infestation)] * (number of all assessed cones)$^{-1}$.

Statistical analysis

Data for yield, percentage α-acids content, percentage spider-mite infested cones and cone weight of the harvested hops were subjected to analysis of variance (ANOVA) using SAS software version 8.2. Significant differences between acaricide-treated and untreated plots in each of the data sets were determined by an F-test ($P < 0.05$, df = 1,6) during the PROC ANOVA procedure. Although the treatments were unreplicated at each site, any differences between adjacent plots could be associated with confidence to the differences in spider mite infestation levels between them as the plots were carefully selected for homogeneity beforehand.

Results

Yield

Significant differences in yield between acaricide-treated and -untreated plants were found in seven of the 36 harvests. In three instances, the untreated plants had 22.5%, 32.0% and 32.7% higher yields, respectively, than the acaricide-treated plants. The pest indices (with average spider mite numbers leaf^{-1} in parentheses) of the untreated plants were 1.60 (31), 3.27 (112) and 3.47 (254), respectively. In the other four harvests the untreated plants had of 11.8%, 14.8%, 17.7% and 22.6% lower yields than acaricide-treated plants and at those sites the pest indices (average spider mite numbers leaf^{-1}) were 2.30 (210), 2.87 (117), 2.23 (88) and 4.03 (414), respectively. For the remaining 29 harvests, no significant differences were recorded between sprayed and untreated hops, although the latter had infestation levels up to a pest index of 4.80, which is equivalent to 1077 spider mites leaf^{-1} (Table 2).

α-acids

Significant differences in α-acids between treated and untreated plants were observed in eight instances. In four instances, the untreated

Table 2. *Results of 36 experimental harvests 1998 – 2000 comparing yields and α-acids content from acaricide-treated and –untreated hops in the Hallertau relative to infestation by* Tetranychus urticae

Locality	Harvesting date	Cv.[a]	Pest index	*T. urticae* leaf^{-1}	Yield [dt ha^{-1}]			Yield untr.	α-acids [%]			α-acids untr.
					Untr.[b]	Acar.[c]	SEM[d]	Relative [%]	Untr.[b]	Acar.[c]	SEM[d]	Relative [%]
Holzhof	25 Aug 2000	PE	1.60	31	**14.45**	10.90	0.58	**132.7**	6.53	6.53	0.31	100.1
Ried	25 Aug 2000	PE	1.63	70	21.09	21.66	1.11	97.4	7.17	7.23	0.28	99.1
Unterempfenbach	24 Aug 1998	PE	1.67	22	14.35	15.14	0.83	94.8	**5.38**	4.63	0.17	**116.1**
Grafendorf	26 Aug 1999	HT	1.93	46	18.30	15.79	1.74	115.9	7.17	5.83	0.39	123.0
Unterempfenbach	24 Aug 1998	HT	2.00	50	15.07	14.45	1.05	104.3	5.02	5.28	0.29	95.1
Tegernbach	27 Aug 1999	HT	2.07	66	19.75	22.12	1.07	89.3	6.70	6.57	0.11	102.0
Attenbrunn	27 Aug 1998	PE	2.20	63	16.56	17.07	0.72	97.0	9.35	**10.19**	0.23	**91.8**
Engelbrechtsmünster	23 Aug 2000	HT	2.23	88	20.33	**24.71**	0.83	**82.3**	7.46	7.46	0.21	99.9
Lurz	02 Sep 1999	HM	2.30	210	15.02	**17.04**	0.46	**88.2**	14.78	14.44	0.27	102.4
Unterempfenbach	24 Aug 2000	HT	2.43	48	20.07	17.14	1.09	117.1	7.44	7.80	0.13	95.4
Larsbach	28 Aug 1998	HT	2.43	111	14.26	13.45	0.54	106.0	**5.66**	4.71	0.16	**120.3**
Unterempfenbach	26 Aug 1999	HT	2.57	56	15.92	12.20	1.12	130.5	**8.23**	7.38	0.17	**111.5**
Grafendorf	04 Sep 1998	HM	2.87	117	17.49	**20.51**	0.79	**85.2**	12.02	**13.04**	0.24	**92.2**
Eichelberg	14 Sep 1998	HM	2.97	227	20.21	18.45	1.42	109.5	14.97	15.23	0.46	98.3
Hüll	27 Aug 1999	PE	3.03	87	15.12	17.78	1.06	85.0	8.00	8.16	0.22	98.0
Engelbrechtsmünster	25 Aug 1998	HT	3.20	88	19.47	20.14	0.40	96.6	4.90	5.00	0.13	98.0
Hüll	26 Aug 1998	PE	3.27	112	**13.64**	10.33	0.49	**132.0**	5.03	4.83	0.22	104.1
Lurz	30 Aug 2000	HM	3.40	576	16.88	19.58	1.21	86.2	14.83	15.00	0.25	98.9
Oberempfenbach	30 Aug 1999	PE	3.47	254	**21.15**	17.27	0.71	**122.5**	**10.66**	8.43	0.29	**126.5**
Grünberg	04 Sep 2000	HM	3.57	728	15.70	15.20	1.59	103.3	14.79	14.59	0.27	101.4
Stadelhof	03 Sep 1999	HM	3.63	369	18.93	19.45	0.46	97.3	14.54	14.44	0.32	100.7
Grubwinn	25 Aug 2000	HT	3.67	190	24.99	24.63	0.68	101.4	7.69	7.69	0.33	100.0
Unterempfenbach	26 Aug 1999	HT	3.73	201	17.35	15.72	1.81	110.4	5.92	5.66	0.11	104.6
Buch	09 Sep 1998	HM	3.87	438	17.49	18.26	1.37	95.8	14.59	16.23	0.64	89.9
Martinszell	07 Sep 1998	HM	4.03	414	16.19	**20.92**	0.72	**77.4**	15.56	**16.50**	0.27	**94.3**
Engelbrechtsmünster	29 Aug 2000	HM	4.13	423	20.38	20.33	0.77	100.3	15.86	16.07	0.12	98.7
Hüll	26 Aug 1998	HT	4.17	233	14.97	15.89	0.71	94.2	5.12	4.74	0.13	108.1
Ilmendorf	30 Aug 1999	PE	4.23	377	13.71	15.05	2.68	91.1	7.11	6.96	0.25	102.2
Ronnweg	06 Sep 2000	HM	4.27	479	17.70	17.18	2.09	103.0	14.13	14.41	0.12	98.1
Hüll	26 Aug 1998	PE	4.27	483	16.81	18.58	1.42	90.5	7.51	7.39	0.08	101.7
Eichelberg	31 Aug 2000	PE	4.27	697	18.39	16.61	0.77	110.8	7.50	7.93	0.18	94.5
Oberempfenbach	06 Sep 1999	HM	4.30	551	16.89	17.72	1.30	95.3	15.71	15.33	0.36	102.5
Ilmendorf	02 Sep 1999	HM	4.33	653	13.44	16.20	2.22	83.0	13.16	12.81	0.46	102.7
Eichelberg	06 Sep 2000	HM	4.33	875	19.48	19.46	0.80	100.1	14.29	14.33	0.38	99.7
Stadelhof	29 Aug 2000	HT	4.53	664	21.07	24.77	1.33	85.0	7.70	**8.38**	0.14	**91.9**
Oberempfenbach	28 Aug 2000	PE	4.80	1077	21.94	20.81	0.80	105.5	9.64	9.48	0.25	101.7

Significantly higher values (ANOVA, $P < 0.05$, df = 1,6) are printed bold
[a] HM = Hallertauer Magnum, HT = Hallertauer Tradition, PE = Perle
[b] Acaricide-untreated
[c] Acaricide-treated
[d] Standard error of the mean

plants had 11.5%, 16.1%, 20.3% and 26.5% higher α-acids content than treated plants and the corresponding pest indices (average spider mite numbers leaf^{-1}) were 2.57 (56), 1.67 (22), 2.43 (111) and 3.47 (254), respectively. In the other four instances the untreated plants had 5.7%, 7.8%, 8.1% and 8.2% lower α-acids content than treated plants, with corresponding pest indices (average spider mite numbers leaf^{-1}) of 4.03 (414), 2.87 (117), 4.53 (664) and 2.20 (63), respectively. No significant differences were found between sprayed and untreated hops in the remaining 28 harvests (Table 2).

Cone infestation

Cones from untreated plants had significantly higher spider mite infestations than those from acaricide-treated ones in 27 of the 36 harvests.

Table 3. *Leaf and cone infestation by* Tetranychus urticae *and its effect on cone weights from acaricide-treated and –untreated hops in the Hallertau*

Locality	**Pest index**		***T. urticae* leaf^{-1}**		**Infested cones [%]**			**Weighted average**[a]		**Weight [g] (500 cones)**		
	Untr.[b]	**Acar.**[c]	**Untr.**[b]	**Acar.**[c]	**Untr.**[b]	**Acar.**[c]	**SEM**[d]	**Untr.**[b]	**Acar.**[c]	**Untr.**[b]	**Acar.**[c]	**SEM**[d]
Holzhof	1.60	0.00	31	0	**46.8**	12.5	1.69	1.760	1.147	48.4	49.9	1.90
Ried	1.63	0.20	70	1	**29.4**	10.2	3.55	1.397	1.110	52.8	52.5	1.37
Unterempfenbach	1.67	0.30	22	3	**14.8**	5.4	1.07	1.180	1.062	39.9	37.7	1.66
Grafendorf	1.93	0.00	46	0	5.2	2.2	0.96	1.084	1.031	67.0	54.1	4.33
Unterempfenbach	2.00	0.10	50	0	9.7	7.1	1.02	1.162	1.092	40.8	42.1	1.90
Tegernbach	2.07	0.00	66	0	41.6	35.8	3.59	1.618	1.446	62.5	**71.9**	2.59
Attenbrunn	2.20	2.10	63	33	9.6	12.3	1.11	1.120	1.177	53.8	49.0	2.09
Engelbrechtsmünster	2.23	0.10	88	0	**13.0**	6.6	0.83	1.143	1.067	41.5	**47.3**	0.70
Lurz	2.30	0.00	210	0	60.2	62.3	10.52	1.933	1.871	112.8	113.3	2.59
Unterempfenbach	2.43	0.80	48	1	**9.0**	4.5	0.85	1.106	1.047	46.5	47.5	1.53
Larsbach	2.43	0.50	111	1	12.9	8.9	2.78	1.176	1.116	**44.8**	40.0	1.27
Unterempfenbach	2.57	0.20	56	3	3.6	4.0	0.63	1.042	1.044	70.5	63.2	2.20
Grafendorf	2.87	0.00	117	0	**69.5**	12.3	3.35	2.354	1.172	95.6	105.1	3.30
Eichelberg	2.97	0.10	227	0	**18.6**	11.5	1.47	1.312	1.155	88.1	96.0	3.89
Hüll	3.03	0.20	87	1	**60.7**	45.8	2.71	2.024	1.669	52.9	52.9	2.91
Engelbrechtsmünster	3.20	0.00	88	0	**51.0**	4.4	3.58	1.772	1.051	34.1	35.4	1.40
Hüll	3.27	2.50	112	67	**28.8**	6.2	3.88	1.545	1.083	43.5	48.3	1.40
Lurz	3.40	0.00	576	0	**42.9**	29.9	2.70	1.482	1.333	119.5	113.3	3.67
Oberempfenbach	3.47	0.10	254	0	**45.8**	25.0	3.89	1.606	1.228	**51.3**	44.2	1.74
Grünberg	3.57	0.10	728	0	**55.8**	33.9	5.36	1.794	1.373	109.8	118.5	4.78
Stadelhof	3.63	0.10	369	0	45.8	45.8	2.19	1.588	1.625	130.3	129.4	1.83
Grubwinn	3.67	1.10	190	33	**83.9**	31.4	3.95	2.558	1.518	49.1	50.5	1.66
Unterempfenbach	3.73	0.70	201	3	**17.8**	4.1	2.65	1.244	1.049	63.7	59.2	3.09
Buch	3.87	0.10	438	1	**52.0**	13.0	6.63	2.001	1.200	102.0	114.7	3.83
Martinszell	4.03	1.30	414	16	**59.1**	18.6	3.01	2.032	1.271	104.6	**116.0**	1.94
Engelbrechtsmünster	4.13	0.20	423	0	**42.4**	10.5	4.63	1.712	1.113	132.1	130.0	3.47
Hüll	4.17	2.00	233	30	**64.4**	37.6	5.18	2.106	1.689	45.7	50.1	2.80
Ilmendorf	4.23	1.60	377	19	**72.4**	33.1	4.05	2.054	1.378	46.9	47.0	3.55
Ronnweg	4.27	0.00	479	0	**35.2**	18.8	4.10	1.570	1.245	124.4	125.6	3.67
Hüll	4.27	0.20	483	1	48.5	38.0	8.09	1.836	1.638	43.8	46.6	1.40
Eichelberg	4.27	0.30	697	1	**63.4**	26.6	2.35	2.191	1.452	42.6	48.3	1.90
Oberempfenbach	4.30	0.60	551	2	**22.6**	5.7	2.48	1.348	1.076	119.9	111.7	5.02
Ilmendorf	4.33	1.30	653	13	**38.0**	18.8	4.58	1.543	1.243	115.1	103.8	4.50
Eichelberg	4.33	0.30	875	1	**67.9**	24.1	2.60	1.991	1.296	125.8	131.8	2.12
Stadelhof	4.53	0.60	664	4	**45.2**	31.5	3.29	1.752	1.341	47.5	49.8	1.08
Oberempfenbach	4.80	1.70	1077	22	**96.0**	85.2	1.23	2.710	2.232	49.9	48.9	2.56

Significantly higher values (ANOVA, $P < 0.05$, df = 1,6) are printed bold. Site order as Table 2

[a] See text for calculation

[b] Acaricide-untreated

[c] Acaricide-treated

[d] Standard error of the mean

Using a "weighted average" of cone infestation, in all but three cases untreated plants had higher levels of infestation than the treated plants (Table 3). In addition, in most cases, the cone infestations on sprayed hops were remarkably high, although the corresponding spider mite numbers on leaves were often low and in 28 cases did not exceed a pest index of 0.80 or five spider mites leaf^{-1}. However, with the exception of Oberempfenbach, 28 August 2000 in which 85.2% of the cones from sprayed plants were infested (Table 3), such high levels of cone infestation did not precipitate economic loss for the growers as these high levels of infestation were not detected during the standard valuation of cones in the "neutral quality assessment" procedure.

A regression analysis was performed between the pest index of leaves and the "weighted average of infestation" of harvested cones from both untreated control plots and sprayed plants, in order to establish the relationship between leaf and cone infestation. In the control plots, a significant correlation between *T. urticae* infestation on leaves and cones was found (n = 36; r = 0.5550; r^2 = 0.3080; P < 0.01). However, as the coefficient of determination (r^2) explains only 30.8% of variance, that relationship is quite weak (Fig. 1). The correlation in the acaricide-treated plots was also significant (n = 36; r = 0.3909; r^2 = 0.1528; P < 0.05), but that relationship explained only 15.3% of the variance, so is even weaker (Fig. 2).

Cone weight

Significant differences in average cone weight between treated and untreated plants were recorded in five harvests. In two instances, the untreated plants had 12.0% and 16.1% heavier cones than those from treated plants, with corresponding pest indices (average spider mite numbers leaf^{-1}) of 2.43 (111) and 3.47 (254), respectively. The yield from untreated plants in the latter harvest (Oberempfenbach, 1999) was also significantly higher, whereas α-acids were significantly higher in both cases. In three instances the untreated plants had 9.8%, 12.3% and 13.1% lower cone weights than treated plants with corresponding pest indices (average spider mite numbers leaf^{-1}) of 4.03 (414), 2.23 (88) and 2.07 (66), respectively. At the first site (Engelbrechtsmünster, 2000), untreated plants also had a significantly lower yield and α-acids level than treated plants, whereas only yield was also lower at the second site (Martinszell, 1998). There was no corresponding significant difference in either yield or quality at the third site (Tegernbach, 1999) which had a pest index of 2.07 in the untreated plot. No significant differences were found in cone weight between sprayed hops and untreated plots in the other 31 harvests (Table 3).

Discussion

There are a number of factors that may influence yield and quality within a hop garden of the same cv. even between single plants, e.g. water supply, virus infestation, fungal diseases, arthropod pests, or mechanical injury from arthropods, moles, rabbits, deer, and by the grower himself during cultivation. Finally, the most prevalent factor affecting individual plant yields at a local level are soil-borne differences,

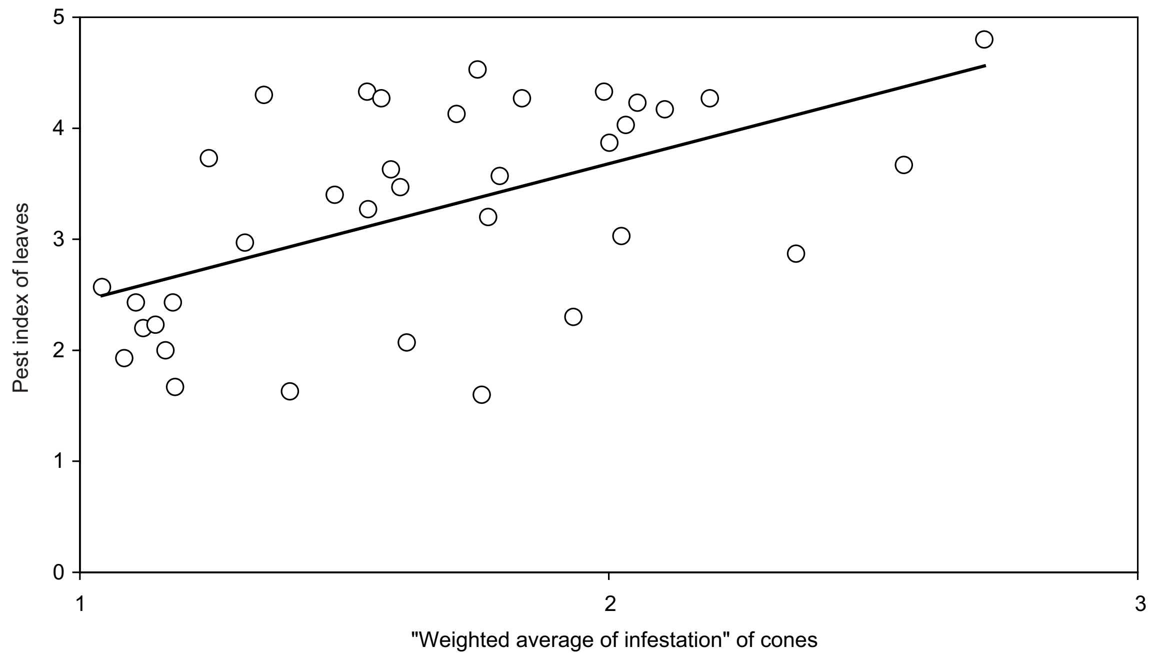

Fig.1. Relationship between pest index of leaves and cone infestation by *Tetranychus urticae* on acaricide-untreated hop plants. For details see text. The solid line represents the regression line fitted through all points (y = 1.2411x + 1.1979; n = 36; r^2 = 0.3080; P < 0.01).

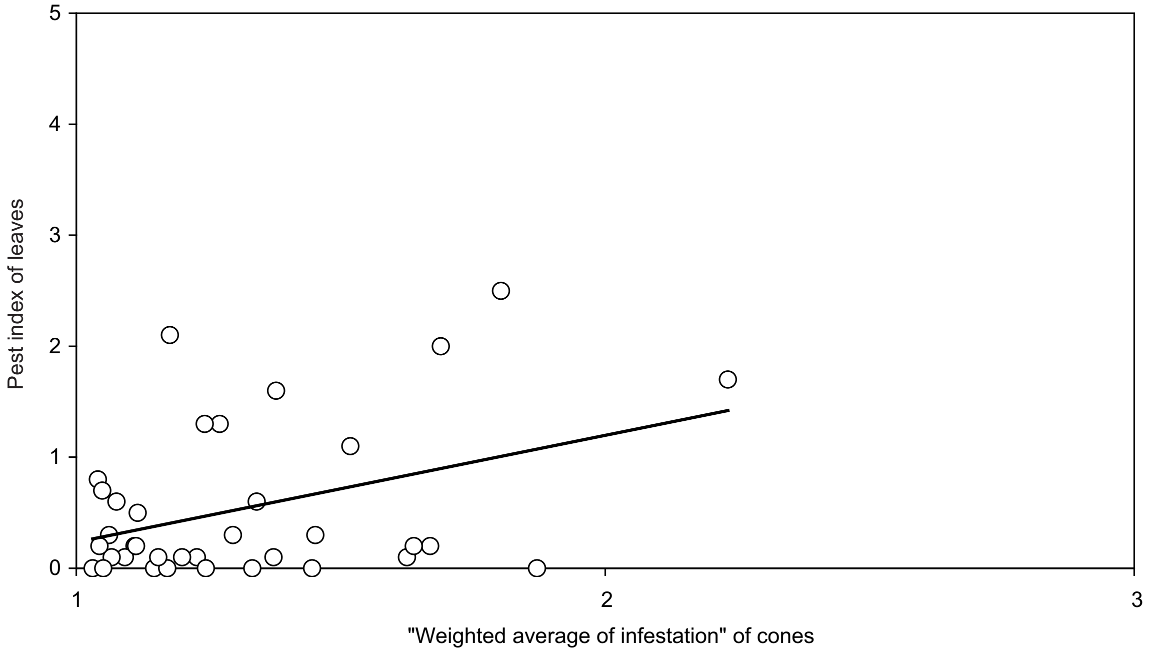

Fig.2. Relationship between pest index of leaves and cone infestation by *Tetranychus urticae* on acaricide-treated hop plants. For details see text. The solid line represents the regression line fitted through all points (y = 0.9616x – 0.726; n = 36; r^2 = 0.1528; $P < 0.05$).

which was clearly demonstrated at the end of the 19 century by Gross (1899) in fertiliser trials. During this study I minimised the impact of those factors by careful selection for uniformity among experimental plants and by comparing neighbouring groups of acaricide-treated and -untreated plants growing not more than 11 m away within the same row. However, the possibility cannot be excluded that small-scale differences of soils had some influence, especially on yield, in the experimental harvests.

Contrary to the effects of other hop diseases and pests on yield and quality of the harvested cones, e.g. viruses (Pethybridge *et al.*, 2002) or damson-hop aphid *Phorodon humuli* (Benker, 1999; Barber *et al.*, 2003*a*), the effect of *T. urticae* on hop yield and quality has attracted little attention in the scientific literature. Benker (1999) concluded from one experimental harvest, and without statistical analysis of the data, that an infestation level of 100–150 spider mites leaf^{-1} at harvest had no detrimental effect on yield and α-acids levels. Strong & Croft (1993) adopted a pre-harvest infestation of 10 spider mites leaf^{-1} as an arbitrary action threshold, but in the same study they concluded that the economic impact of those spider mite levels needed further study. Nevertheless, it is well-known in the hop trading industry that moderate spider mite infestation of hop plants may have a positive influence, especially on the α-acids content of harvested cones (P Hintermeier, personal communication). The explanation for this phenomenon is that within hop ingredients α-acids are part of the soft resin fraction (Neve, 1991). Spider mites feed by puncturing leaf epidermal cells and the parenchymal tissue with their stylets (Liesering, 1960), thus causing numerous small injuries to their host plant. As with other higher plants, those injuries trigger defence mechanisms in the plant, which in hop results in increased production of soft resins which are predominantly the α- and β-acids (P Hintermeier, personal communication). The β-acids are anti-feedant, repellent and oviposition deterrents for *T. urticae* (Jones *et al*., 1996).

At first sight, the results of this study do not give a simple answer to the question posed, i.e. how many spider mites are tolerable on hop plants at harvest without causing economic loss for growers? As regards yield, the range of significantly negative results, which were most probably caused by spider mite infestation, ranged from pest indices of 2.23 to 4.03, or average spider mite numbers of 88 to 414 leaf^{-1}. Conversely, increased yields were recorded in some acaricide-untreated plots with pest indices ranging from 1.60 to 3.47, or average spider mite numbers of 31 to 254 leaf^{-1}. The results for the effects on α-acids concentrations were similar: the range of significantly negative results, most likely caused by spider mite infestation, ranged from pest indices of 2.20 to 4.53, or average spider mite numbers of 63 to 664 leaf^{-1}. Increased α-acids contents of the acaricide-untreated plot were recorded in some instances where pest indices ranged from 1.67 to 3.47, or average spider mite numbers of 22 to 254 leaf^{-1}. Most surprisingly, in the majority of experimental harvests, no significant differences were found either in yield or α-acids content between acaricide-treated and -untreated hops, even in plots with leaf infestations of several hundred *T. urticae*. Clearly the relationship between leaf and cone infestation (*cf.* Fig. 1, 2) is so weak that high spider mite densities on the foliage do not necessarily result in correspondingly high numbers infesting cones. This may arise because the plant's water availability is sufficient so that leaves remain suitable for colonisation despite the injuries caused by *T. urticae* and, consequently, they are not stimulated to migrate to other parts of the hop plants in response to deteriorating food quality. Another explanation could be that the enhanced production of soft resins in the cones may help protect them from spider mite infestation (Jones *et al*., 1996, 2003).

From a critical point of view it may be argued that an economic injury level for *T. urticae* based only on a single sample date – the day of harvest in the present study – will not necessarily represent the totality of damage caused, as spider mite populations fluctuate during the whole season, and injury is likely to be cumulative. Arguably, population densities at harvest may perhaps not always correspond precisely to those experienced earlier in the season. Nevertheless, the cumulative injuries caused by the season-long spider mite infestations were quantified here. However, hops are harvested before spider mite females begin to enter diapause. During the 12 years from 1993 to 2004 in the Hallertau, spider mite numbers were still increasing at harvest time (Weihrauch, unpublished) confirming previous studies in the Hallertau (Benker, 1999) and elsewhere (Sites & Cone, 1985; Kazak *et al.*, 1995). At every study site, growers used their own judgement to minimise their perceived risks of damage occurring by applying acaricide sprays other than to the designated untreated plots. However, the dense hop foliar canopy that forms up to 7 m above ground level creates problems for assessing pest densities accurately, and presents a difficult target for sprays to penetrate, hence spider mite numbers may increase undetected by growers, as was found at some sites here.

In summary, as a threshold value for economic injury needs to be set at a level of minimum risk of damage occurring and convenient for growers to implement, the results of this study, which is the first published for *T. urticae* on hops, suggests that a pest index of 2.20 at harvest is appropriate. In all three cultivars assessed in this study, no significant damage either in yield or in α-acids content occurred below this value, which is equivalent to an average infestation of approximately 90 spider mites leaf^{-1} at harvest time (see Weihrauch, 2004). That level would be tolerable for hop growers without them running a risk of economic loss. In many instances, this study shows that the tolerable infestation level could be much higher than that suggested, provided that hops are grown on good soils and supplied with sufficient water. Interestingly, Jary (1935) commented that in some hop gardens, particularly those where the soil is retentive and does not dry out to a serious extent, *T. urticae* was almost unknown, and even in dry summers attacks were negligible.

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