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Long-term effects of management intensity and bioclimatic variables on leatherjacket (*Tipula paludosa* Meigen) populations at farm scale

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Abstract

Leatherjackets (*Tipula* spp.) are soil-dwelling pests associated with agriculture. Land management decisions made at farm scale can have subsequent effects on their populations. Between 1980 and 2020, surveys were conducted across Scotland to collect field histories and larval population data from grassland farms. To assess the impact of management and bioclimatic factors on leatherjacket occurrence over time, this study investigated data from fields continuously sampled between 2009 and 2018. We utilized a Generalized Linear Mixed-Effect Model on a dataset of 61 fields on 19 farms. Results indicated three significant factors affecting larval populations; field size, grazing type and application of insecticides or herbicides (referred to collectively as pesticides). Larval populations were significantly lower in fields that were larger in size and under sheep grazing, compared to no grazing. Pesticide application also caused a significant reduction in larval populations. Management variables were amalgamated to create a Management Intensity Index, revealing significantly increased larval populations under low-management systems. These results, coupled with significant effects of bioclimatic variables, pinpoint predictive signals for high infestations and potential routes for control strategies.

KEYWORDS
agriculture, annual survey, farm management intensity, leatherjacket, long-term data, pest, tipula

1 | INTRODUCTION

Tipula spp. larvae (leatherjackets) are common agricultural pests in Britain and Ireland (Blackshaw, 1983; Moffat et al., 2022). When occurring in high densities, their feeding on the roots and stems of crop plants can cause significant damage. In 1985 a monetary value for this damage in grasslands was estimated to be in the regions of £15 million per annum for Northern Ireland (Blackshaw, 1985), based on the cost of insecticide application and use of fertilizer. Chlorpyrifos, an effective insecticide used for leatherjacket control, was completely withdrawn for agricultural use in 2019, due to its genotoxic potential and associated environmental risk (Moffat et al., 2022). No updated value for leatherjacket damage has been calculated since. Moffat et al. (2022) highlighted that grassland fields were more vulnerable to *Tipula* larval feeding compared to cereal fields, potentially due to a lack of cultivation, and reported recent Irish larval populations that surpassed any of those recorded from Scotland and the UK between 1965 and 1982 (Blackshaw, 1983). These higher numbers could reflect three possible explanatory components: (i) the revocation of chlorpyrifos for agricultural use across the European Union, limiting control options for farmers, (ii) the ongoing effect of extreme weather variation, due to climate change on the larval lifecycle and habitat, and (iii) significant changes in farm management practices, including some that could benefit the larval lifecycle. As larvae are soil dwelling for up to 10 months and prefer wet, damp soils, unpredictable bioclimatic variables have the potential to consequently affect population levels.

Annual leatherjacket surveys have been conducted across Scotland for the last half century. The Scottish Agricultural College (SAC) established the survey in the 1970s (McCracken et al., 1995) to predict the risk of leatherjacket damage in grassland and spring cereal crops in the west of Scotland. Data collected from the survey in 1992/93 were used to relate larval populations to general soil characteristics and environmental variables, confirming the positive correlation between waterlogging and larval populations (McCracken et al., 1995). Bearup et al. (2013) analysed the data collected from 38 fields between 1980 and 1994, to address *Tipula paludosa* population dynamics; patterns, processes and scale, and demonstrated synchronization amongst populations across Scotland, primarily due to long-distance wind-assisted dispersal. Blackshaw and Petrovskii (2007) examined individual field counts from the data between 1975 and 1994 to show that population regulation occurs at both local and regional scales. Apart from these studies, the dataset as a whole remains unpublished, with no analysis from more recent years.

Long-term ecological surveys (LTES) are fundamental in the understanding of ecosystem dynamics (Cauvy-Fraunié et al., 2020) and for assessing trends in insect communities (Masetti et al., 2018). For example, Rothamsted-type suction traps have been collecting aerial insect samples across the UK for approximately 50 years. One in particular, based at the edge of the University of Stirling campus, has been in operation since 1972 (Benton et al., 2002), and has helped link insect population declines to agricultural practices (Benton et al., 2002). While Blackshaw and Perry (1994) looked at climate-based models to accurately predict leatherjacket population likelihoods and potential risk to farmers, models in this study will aid in developing essential management and mitigation techniques. Through examining effects of common long-standing farm practices and management intensity on leatherjacket populations, our results will further establish pest management strategies, where there are currently few viable options. Climate models investigating temperature and precipitation rate in relation to population densities will give an updated view on how climatic conditions influence population fluctuations over several years.

In this study, annual leatherjacket count data from 2009 to 2017 were augmented with recent sampling from 2018/2019. Meteorological data were analysed alongside the historic leatherjacket data to determine the effects of temperature and rainfall on each of the active life stages of *T. paludosa*. The full suite of environmental data collected from the long-term survey were examined for factors influencing larval populations. Finally, farm management intensity was calculated based on the data provided and investigated as an influential factor on larval populations. The aims of this study were (i) to determine the *T. paludosa* life stages potentially vulnerable to abiotic effects, (ii) to extrapolate the farm practices that influence larval populations across multiple years and (iii) to determine the effect of farm management intensity on this pest species.

2 | MATERIALS AND METHODS

2.1 | Field sampling

Field sites included within this study were sampled uniformly between 2009 and 2018. Landowner permission was sought prior to soil sampling, and all locations were anonymized for data analysis. All sites were under grassland management regimes, and 25 cylindrical soil cores (of 6.5 cm diameter x 10 cm length) were collected in each field, as in the methods of McCracken et al. (1995). Leatherjacket larvae were extracted through the Blasdale (1974) method, using a heat source from above to expel the soil organisms. Field counts were extrapolated to population/ha, by transforming the total surface area of all cores to 1 ha. Field areas ranged from 2.3 to 22.3 ha. Throughout the time of Scotland's Rural College (SRUC) annual leatherjacket surveys, where possible, SRUC aimed to re-visit and sample the same fields each year in the autumn/winter period.

In 2018 and 2019, 20 farms and a total of 61 grassland fields were sampled across Scotland between November and February. As an annual leatherjacket survey had been previously established in Scotland by SRUC, a subsample of sites was selected in collaboration with SRUC researchers and field histories were exchanged. Three fields were selected on each farm, based on their most recent leatherjacket populations, and a range of high (greater than the economic threshold of 1 million/ha), medium (500,000–1 million/ha) and low pressure (less than 500,000) fields were selectively sampled to reflect the breadth of population densities.

In Ireland, sets of three water traps were deployed at three locations in 2019, one on the west coast (Clare) and two on the east (Dublin and Wexford). Traps were yellow in colour and placed at ground level. Trap basins were filled with water and detergent, and contents were collected and sorted weekly between August and October. These were used to track emergence and peak adult flight time of *T. paludosa* as per Mowat and Jess (1986). Data collected from these helped to inform the analysis of the meteorological data within this study.

2.2 | Data management and statistics

Raw data received from SRUC were partially incomplete. The number of fields sampled per farm were not uniform throughout, and the managerial variables were inconsistently recorded each year. As is common practice within this research area (Fu et al., 2021), data with complete sets of values were used for statistical analysis, carried out using R 4.0.2 (R Core Team, 2021). The dataset finally used for management intensity analysis therefore included 16 farms, 43 fields and a total of 188 observations across the 10-year timespan (Table S1). Access to a limited range of historic data in relation to these fields was subsequently obtained. This included the size of field, field aspect, altitude, time since cultivation, use of field and details of field applications including, but not limited to, fertilizer and pesticide. This field information was not collected in 2019/2020, so these years were only included in the leatherjacket population and meteorological analysis. Packages used to clean, graph and test the data included *ggplot2*, *tidyverse*, *FactoMineR*, *factoextra*, *missMDA*, *MASS*, *lmerTest*, *car* and *ggpubr* (Fox & Weisberg, 2019; Josse & Husson, 2016; Kassambara, 2020a, 2020b; Kuznetsova et al., 2017; Lê et al., 2008; Venables & Ripley, 2002; Wickham, 2016; Wickham et al., 2019). Box–Cox Power transformation was applied to the larval counts to normalize the data distribution (Fox & Weisberg, 2019) and the 'lmerTest' package (Kuznetsova et al., 2017) was used to create linear mixed effect models. All variables were modelled against the response variable: larval counts, using 'Farm' as a random effect. Model assumptions of variance, independence and normality were checked and satisfied, through appropriate plots and using D'Agostino Pearson and Shapiro–Wilk tests. Farm was assigned as a random variable due to the frequency of population fluctuations being similar in all fields on the same farm, and variables suggesting that farm management decisions were made at farm level, across all fields. The proximity of fields to each other ensured that abiotic variables were uniformly applied. Continuous variables included in the dataset were: field size (6.7 ha mean ± 0.21 *SE*), sward height (8.3 cm mean ± 0.24 *SE*) and altitude (101.1 m mean ± 3.74 *SE*). Categorical variables are outlined further in Table 1.

2.3 | Management intensity index

A Management Intensity Index (MII) was calculated following the model outlined in Anhar et al. (2021). Using data on infield management available within the SRUC longitudinal dataset (excluding 2018/2019), nine management variables were chosen reflecting specific management practices (e.g. time since cultivation) and were assigned Management Intensity Scores (MIS) based on their individual category and author domain knowledge of common agronomic practices (e.g. a score of four for a sward cultivated in the last 5 years, and one for a sward that has not been cultivated for over 15 years). The assigned MIS are detailed in Table 3, column 2. These scores were transformed to fall within a 0–1 range, using the MII calculation (Anhar et al., 2021).

TABLE 1 Explanation of categorical variables used throughout the longitudinal dataset.

Variable	Categories
Years since last cultivation (Age)	<5 years 5–10 years 10–15 years >15 years
Livestock grazed last year (Livestock)	None Sheep Cattle Both
Cuts of silage last year (Cut)	None One Two Three Four Five
Application of inorganic fertilizer last year (Inorganic)	Yes No
Application of organic fertilizer last year (Organic)	Yes No
Application of pesticide last year (Pesticide)	Yes No
Intended use of field next year (Intention)	Grazing Grazing and Silage Plough and resown Grazing, silage and plough/resown
Tendency to waterlog (Waterlogging)	Yes No
Presence of weed species in field (Weed)	Yes No
Aspect of field (Aspect)	Flat North East South West
Distance from sea (km) (Sea)	≤10 >10

$$MII = \frac{(\text{value observed} - \text{minimum value})}{(\text{maximum value} - \text{minimum value})}$$

A sum of these MII scores was generated for each field, creating a Total Management Intensity index (TMI). The TMI scores ranged from 2.5 to 8.3, and based on this range, were grouped into three management intensity categories, similar to Anhar et al. (2021), specifically: low (less than 4.5), medium (4.5–6.4) and high (greater than 6.4). There were 64 (34.0%) fields within the low-intensity group, 104 (55.3%) in the medium and 20 (10.6%) in the high.

2.4 | Meteorological data

To investigate the effect of precipitation and temperature on leatherjacket populations, monthly mean values (recorded at the Auchincruive SRUC campus meteorological station, Ayrshire, Scotland) were utilized. For the meteorological analyses, the dataset from 2009 to 2020 was further refined to eight farms within Ayrshire, where the weather station was located. Representative averages were calculated to reflect each lifecycle stage of *T. paludosa*. In this way, average temperatures and rainfall levels for the life stages prior to sampling were calculated. For the fourth instar larvae (L4), this was an average of both variables across February, March and April. For the *T. paludosa* adults it was averaged for August and September. Eggs and first larval instars (L1) were grouped together, incorporating September and October, followed by larval instar two (L2) (October and November). Finally, larval instar three (L3) incorporated December and January. Adult timings and the start of the larval lifecycle were informed by data collected from water traps across Ireland, and larval rearing data (Figures S2–S3). The period chosen for L4 is reported as the most active stage for feeding damage (Oestergaard et al., 2006), however the fourth instar does persist past April. As the duration of pupal stages is largely speculative (Blackshaw & Moore, 2012), this stage was not considered within the analysis. Therefore, meteorological analysis will focus on the most active and agriculturally damaging stages of the *T. paludosa* lifecycle.

3 | RESULTS

3.1 | Leatherjacket populations from the recent and longitudinal scottish survey

From the entire dataset, including historic and recent counts, larvae were collected from 84.6% of the 246 fields surveyed. From the fields where larvae were collected, 41.3% were above the economic threshold for grasslands, of 1 million larvae/ha.

Annual population means show fluctuations across the years (Table S2). The highest average population of 3,117,826 larvae/ha was recorded in the winter of 2013/14, highlighted in red on Figure 1. This was followed by a steep decline, to the lowest average population calculated across all 10 years; 230,543 larvae/ha, highlighted in blue (Figure 1).

3.2 | Lag effect of changes in temperature and precipitation on annual larval populations

Separating the lifecycle stages of *T. paludosa* enabled an assessment of the effect of temperature and precipitation on each specific lifecycle stage. Temperature had a significant negative effect on larval populations during the adult ($p = 0.012$) and L2 stage ($p < 0.001$), but a strong positive effect on the L3 stage ($p < 0.001$) (Table 2). This indicates that warmer temperatures during summer might reduce adult populations, however, warmer conditions may increase overwintering larval population densities. Precipitation levels at L2 ($p = 0.037$) and L3 ($p = 0.044$) had a significantly positive effect on larval counts.

When temperatures at L3 stage were investigated for each year, significant interactions with larval populations occurred in 7 of 9 years (Table S3). This was most pronounced in 2013/14 ($p < 0.001$), where average temperature at L3 stage was 8.6°C and temperature had a positive relationship with larval populations. In the winter of 2014/15, an overall population decline was observed across all farms. In this year, temperatures at L3 stage had a significantly negative effect on larval populations, with an average temperature of 7.7°C (Table S4). In the same year, precipitation levels at L1 also had a negative effect on larval populations ($p = 0.005$). Average rainfall at this stage was 69.5 mm (Table S5). Overall, rainfall at L1 stage had a significant variable effect on larval populations in 7 of 9 years.

3.3 | Determining the impact of field and management attributes on leatherjacket larval populations

A linear mixed effect model of all variables within the historic dataset (excluding 2018/19) was used to determine farm scale factors that influenced larval populations. From this, four factors were significant in relation to larval counts. Three had negative effects on larval populations: field size ($p < 0.05$), grazing sheep compared to no grazing ($p < 0.05$), and the use of pesticide the year prior to sampling, compared to no pesticide application ($p < 0.01$). While one had a significant positive effect: taking four or more cuts of silage the previous year compared to none ($p < 0.01$). However, replicates of these categories are limited. These are highlighted in Table 3.

Field size within this survey ranged from 2.8 to 12.1 hectares, with an average of 6.4 (±0.2 SE). The highest leatherjacket count was collected from a field of 5.7 hectares, and high populations were most commonly recorded in field sizes ranging from 3 to 9 ha.

3.4 | Management intensity index

In relation to the effect of overall farm Management Intensity on larval populations, farms classified as high intensity had lower ($p = 0.048$, Table S6) larval populations when compared to low-intensity management. Average larval counts related to average intensity factors across the dataset of the 188 fields can be observed in Figure 2. When observing larval counts across the three intensity ratings per year, our observed result of higher populations occurring at lower intensities is seen in 7 of 10 years.

4 | DISCUSSION

Both temperature and precipitation have significant effects on key life stages of *T. paludosa*. Bearup et al. (2013) found that rainfall influences

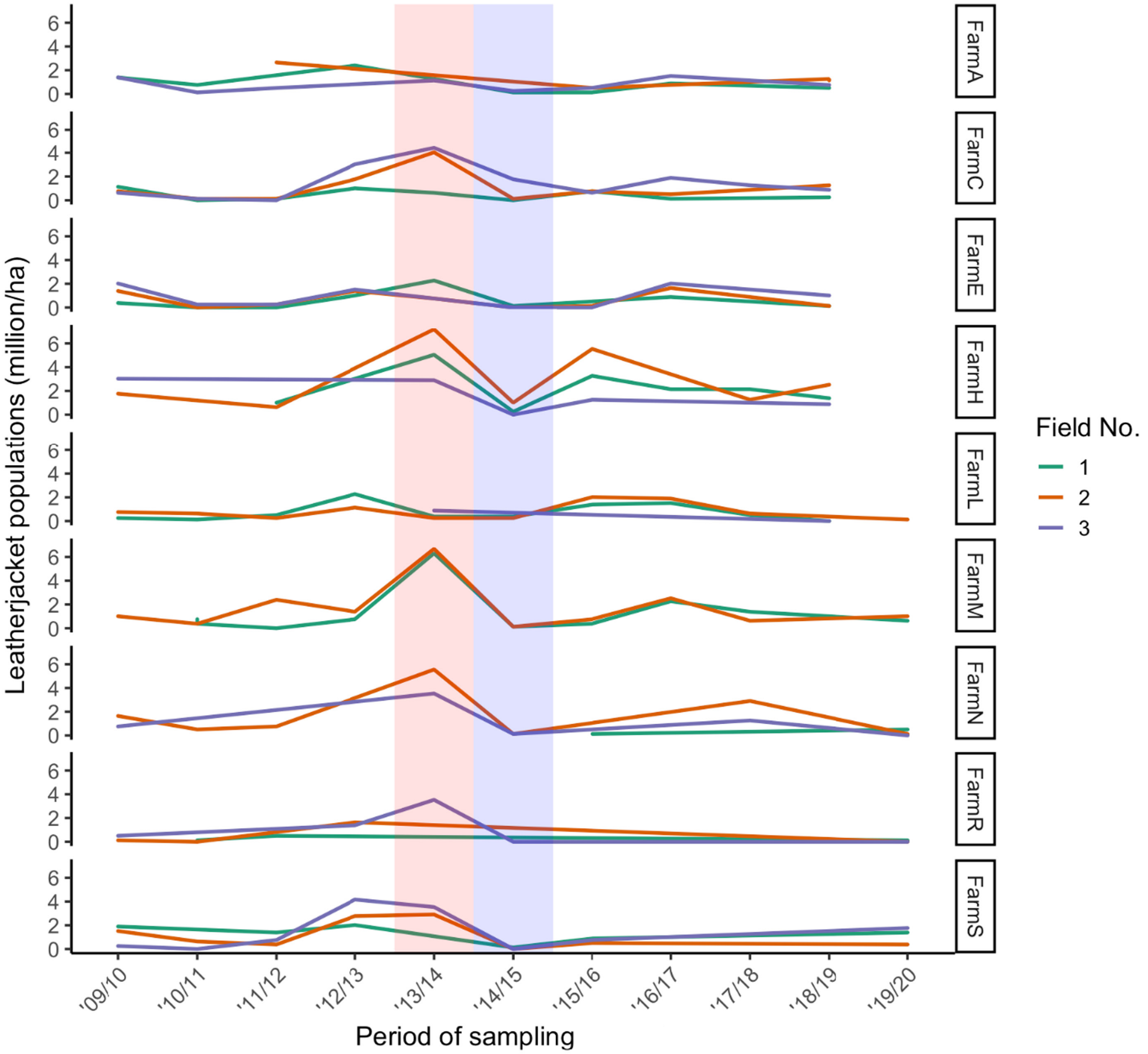

FIGURE 1 Fluctuations in larval populations (millions/ha) per field and farm from a subset of nine farms, which had complete data records between 2009 and 2020 It is useful to visualize such fluctuations to pinpoint periods of interest, for example, the rapid population increase in 2013/14 (red shading) and the population decline in 2014/15 (blue shading).

larval populations, specifically at egg hatching, and noted increased susceptibility to desiccation when extremely dry conditions are observed in September and October. Milne et al. (1965) also reported that a drop of 50% in average rainfall during August and September resulted in a sharp decrease of *T. paludosa* populations, indicating that eggs are specifically vulnerable to desiccation. Rainfall had a significantly positive effect on L1 stages in 2013/14, indicating that the overall decline in rainfall may have led to a decline in larval populations, which is mirrored by the population decline in 2014/15. This also explains the negative effect of rainfall on L1 in 2014/15 as rainfall increased compared to the previous year, but populations were low. This highlights the lag effect of these population dynamics, as highlighted by Bearup et al. (2013), but in relation to dispersal.

Different relationships between temperature and larval counts have been found throughout literature. Milne et al. (1965) reported little effect of temperature on *T. paludosa* dynamics, again focusing on the effect of egg desiccation due to increased temperature or reduced rainfall. Blackshaw and Moore (2012) reported temperature during the autumn period as being influential on larval development. Decreased temperatures in October were reported to prolong the first larval instar stage, while colder temperatures in December shortened the duration of the third larval instar stage (Blackshaw & Moore, 2012). While the dataset in this survey did not allow for in-depth lifecycle duration analysis, a significant effect of temperature on larval instar three was observed, indicating the potential susceptibility to temperature changes. The use of Irish-collected

TABLE 2 Results from the linear mixed effect model on meteorological data against larval counts.

Life stage	Variable	Regression coefficient	SE	*t*	Confidence interval		*p* value
					Lower	Upper	
Adult	T	−1.11	0.437	−2.5	−1.32	0.22	**0.012**
	P	0.00	0.021	0.1	0.01	0.07	0.977
L1	T	0.80	0.392	2.0	−0.39	0.63	**0.043**
	P	0.00	0.015	0.3	−0.05	−0.01	0.779
L2	T	−2.14	0.445	−4.8	−1.63	−0.72	**<0.001**
	P	0.02	0.008	2.1	−0.01	0.01	0.037
L3	T	0.98	0.176	5.6	0.44	0.82	**<0.001**
	P	0.01	0.003	2.0	−0.01	0.01	**0.044**
L4	T	−0.20	0.141	−1.4	−0.30	0.07	0.152
	P	−0.01	0.013	−0.9	−0.03	0.01	0.321

Note: The variables 'T' and 'P' here represent 'temperature' and 'precipitation' respectively. Estimates here represent the regression estimate, SE is the standard error of the mean. Significant *p* values are highlighted in bold. Also included are the lower and upper confidence intervals.

data to establish life cycle stage durations for Scottish populations was initially justified due to similar climatic conditions across both countries. However, to ensure the accuracy of this, full comparisons between *T. paludosa* lifecycles in each country are needed.

McCracken et al. (1995) found seven variables to have significant effects related to larval populations. These were the aspect of the field, silage use, field waterlogging tendency, distance to the Atlantic, use of organic fertilizer and leatherjacket counts from the previous year. In the 1995 analysis, a generalized linear interactive model was conducted using Poisson errors and log link functions, and interaction effects were observed. In the current study, interaction effects were not used due to the high number of variables, internal categories and the limited sample size. McCracken et al. (1995) found that east facing pastures had positive correlations with larval counts, compared to flat, north, south or west facing pastures. Larval counts were higher where waterlogging occurred, and in fields that were closer to the Atlantic (McCracken et al., 1995). This reflects results of Moffat et al. (2022), where populations were highest on the west coast of Ireland. Finally, larval counts were higher in fields that had fertilizer applied or silage harvested the year previous (McCracken et al., 1995). No significant factors were overlapping between this study and that of McCracken et al. (1995). This could be due to a number of factors including increased sample size or number of variables, incorporation of farm as a random factor, or overall difference in statistical testing. McCracken et al. (1995) looked at population records from 1 year (1992/93), across 68 fields. While the overall geographical spread of fields from both surveys was similar, McCracken et al. (1995) included 25 pastures located on the island of Islay, off the west coast of Scotland. This is important to consider in relation to the distance from the Atlantic variable as these sites could be causing a confounding effect. Similar analysis including a wider range of geographic sites would further allow for the coastal effect.

From this survey, increased field size had a significant negative effect ($p < 0.05$) on larval counts. There has been considerable debate surrounding field size as a factor influencing pest populations. Throughout the years, increased field sizes have been a reflection of agricultural intensification, in order to produce an increased yield to meet food demands (Segoli & Rosenheim, 2012). With the expansion of monocultures, there is an associated reduction in the non-crop habitats that act as a refuge for natural enemies and more diverse insect species. As Rosenheim et al. (2022) stated, within agroecological literature, field size has thus become a proxy for diverse and sustainable production. However, this is over-simplifying an inherently complex factor that is specific to each pest species, their associated natural enemies and the habitats both pest and natural enemies require throughout their lifecycle. For *T. paludosa*, it is well established that gravid females are poor fliers (Blackshaw & Coll, 1999; Blackshaw & Petrovskii, 2007; Petersen, 2013) limiting their dispersal ability. From in-field observations, when disturbed, *T. paludosa* adults fly to adjacent hedgerows for refuge, so it could be hypothesized that smaller field sizes would lead to a more enclosed environment, offering increased shelter for *T. paludosa* adults depending on the specific boundary feature.

Rosenheim et al. (2022) found that field size was significantly negatively correlated with *Premnotrypes* spp. (Andean potato weevil) and *Epitrix* spp. (Potato Flea Beetle). Both species have soil dwelling larval stages that feed heavily on potato tubers. Adult dispersal for both species is limited to a short distance, and infection of new fields is primarily due to the planting of larval-infested potato tubers. The larval phases of these pests share similarities with *T. paludosa*, in terms of being soil dwelling, root feeding and having a limited dispersal range. Hence the mutual significance of large field sizes relating to decreases in these pest populations is not surprising. In contrast to this, Gagic et al. (2021) found that larger fields were associated with early mirid pest immigration and the highest probability of pest presence in untreated fields. Mirid pests are foliar-feeding, migrating insects (Hill, 2017), with lifecycles differing vastly to that of *T. paludosa*. Predicting the effect of field size alteration should consider the established pest and natural enemy abundance in a field, as well as their associated overwintering biology and movement capacities

TABLE 3 Results from the linear mixed effect model and all variables from the longitudinal survey.

Variable	MIS	Replicates	Regression coefficient	Confidence interval		*p* value
				Lower	Upper	
Age (<5 years)	4	29				
5–10 years	3	34	0.13	−0.50	0.76	0.684
10–15 years	2	32	−0.38	−1.10	0.35	0.304
Permanent pasture	1	93	0.19	−0.54	0.91	0.614
Size			−0.10	−0.20	−0.01	**0.036**
Altitude			0.00	−0.01	0.02	0.419
Sea (<10 km)						
>10 km			−0.00	−1.28	1.27	0.994
Livestock (none)	1	1				
Sheep	2	16	−2.64	−5.26	−0.02	**0.048**
Cattle	2	6	−1.89	−4.59	0.82	0.170
Both	3	165	−2.28	−4.82	0.26	0.078
Cut (none)	1	141				
One	2	15	0.43	−0.75	1.60	0.476
Two	3	22	−0.03	−1.10	1.05	0.963
Three	4	8	−0.03	−1.50	1.43	0.964
Four or more	5/6	2	3.34	0.81	5.87	**0.010**
Inorganic (no)	1	185				
Yes	0	3	−0.77	−2.25	0.71	0.304
Organic (no)	1	114				
Yes	0	74	0.37	−0.13	0.88	0.146
Weed (no)	1	8				
Yes	0	180	−0.28	−1.29	0.72	0.580
Height			0.00	−0.06	0.06	0.920
Aspect (flat)	n/a	41				
North	n/a	40	−0.26	−1.17	0.64	0.567
East	n/a	24	0.42	−0.39	1.24	0.305
South	n/a	40	0.28	−0.45	1.02	0.449
West	n/a	43	0.01	−0.76	0.78	0.972
Waterlogging (no)	1	64				
Yes	0	124	0.36	−0.09	0.80	0.115
Pesticide (no)	1	35				
Yes	0	153	−0.74	−1.24	−0.24	**0.004**
Intention (grazing)	1	136				
Graze and silage	2	13	−0.37	−1.38	0.65	0.478
Plough + resow	3	38	−0.69	−1.55	0.17	0.114
Graze silage plough and resow	4	1	−2.04	−4.51	0.42	0.104

Note: Significant *p* values are highlighted in bold. MIS in column 2 represents the Management Intensity Scores assigned to each categorical variable.

(Rosenheim et al., 2022). In addition, complex relationships between field size and farm management intensity cannot be overlooked. More targeted research on these topics is needed for informing pest-specific management decisions at farm level. Additionally, while decisions can focus on specific pests, altering field size has adverse impacts on the overall biodiversity of the field (Clough et al., 2020) and this therefore must be considered.

During the Scottish leatherjacket survey of 2018/19, there were anecdotal reports from farmers that damage from leatherjacket feeding was less evident under sheep grazing management. The significant results from this model reinforce that claim, however, the significance is based on the reference category of 'no grazing', where only one replicate is recorded. This highlights limitations of the significance. Sward grazing by sheep results in a more even pasture

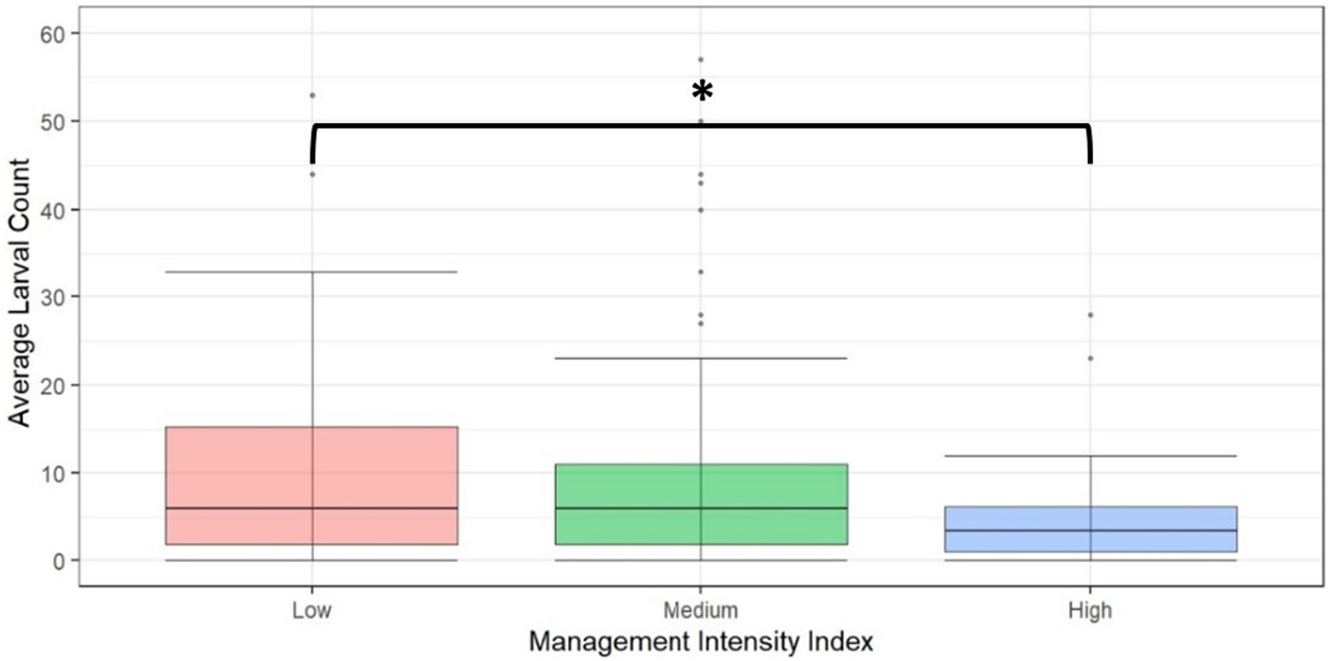

FIGURE 2 Average leatherjacket counts per field in relation to farm Management Intensity Index across all years; pink indicating 'low', green 'medium' and blue 'high' intensity. Larval populations are significantly lower in high-intensity farms compared to low intensity, indicated here using an asterisk (*).

height, and short sparse swards (Ewing et al., 2020). Cattle grazing results in a more tussocky sward, with swards of uneven heights (Stiles, 2022). Sward height is especially important during the adult life stage of *T. paludosa*, as reports have shown that long grass facilitates cranefly adult presence within fields, preventing them from being blown away (McCracken et al., 1995). *Tipula paludosa* females cling to long grass for mating, for oviposition and for stability in general. Once adults are mated and eggs are laid, remnants of cranefly adults are found dried-out, with legs wrapped around the grass. In a study looking at alpine soil macro-invertebrates, Steinwandter et al. (2018) reported sheep grazing intensity having a strong effect on the soil macro-invertebrate community structure ($p < 0.001$). In particular, Nematocera larval abundance was increased under high sheep grazing intensity. The reported families of *Nematocera* within this study were midge larvae (Chironomidae and Cecidomyiidae) and gnats (Mycetophilidae); however, Tipulidae also falls under this *Nematocera* sub-order. This might indicate a similar association between the suborder, therefore it is important to incorporate stocking rate or grazing intensity into any further research.

The negative effect of pesticide use on larval populations was expected to be significant, and results acted as an insurance of model efficiency. Pesticide use here encompasses the use of both insecticides and herbicides. Dawson et al. (2003) showed that the use of chlorpyrifos resulted not only in reduced *T. paludosa* larval numbers, but also an overall reduction (sometimes complete elimination) of insect larvae of all species, including cutworms, wireworms and clover weevils. Linzell and Madge (1986) reported a negative effect of phorate and aldicarb, two well-known pesticides, on leatherjackets, significantly so in Italian ryegrass swards. Herbicide application has also been shown to negatively affect soil and ground dwelling insect populations (Brust, 1990; Kalia & Gosal, 2011), however findings in relation to leatherjackets are limited.

The significant impact of high-intensity farm management on reducing overall larval populations echoes findings from Garratt et al. (2011), where pest populations increased under low-intensity agricultural techniques. While the variables used within this dataset do not comprehensively summarize farm management intensity, they do suggest management decisions that can be used to limit larval populations. The calculated high-intensity values included incorporation of soil cultivation and adequate field drainage. It is unsurprising that these factors resulted in lower overall larval populations. Also within the high-intensity category was the use of organic and inorganic fertilizer. While the precise effects of each fertilizer type are unknown, the significance of high management intensity highlights that increased inputs at field scale are likely to reduce pest populations. This mirrors the finding of a significant negative effect of pesticide use on larval populations. Garratt et al. (2011) reported that fertilizer type played an important role, showing the use of plant composts benefitted arthropod pests, while manures did not. It was also observed that most natural enemy groups had a positive response within organic farming systems (Garratt et al., 2011), highlighting the benefits of low-intensity techniques for biodiversity promotion. In the same vein, Blackshaw and Newbold (1987) reported the benefits of fertilizer applications to increase herbage yield and mitigate the feeding damage caused by leatherjackets. Lundgren et al. (2006) classified grasslands as the lowest intensity treatment when compared to cereals and horticulture. Intensity was based on the number of costly inputs used, soil disturbance, associated labour and overall economic return (Lundgren et al., 2006). They found that management intensity influenced the activity and abundance of biological control agents, with higher densities being observed in the low-intensity grasslands, however predation by insectivores was reduced (Lundgren et al., 2006). The variables included within management intensity calculations will vary according to both the farming system and the pest in question. Other variables that are beneficial to include in relation to *T. paludosa* would be stocking rate, plant species/sward varieties, signs of soil compaction and details of exact fertilizers or soil amendments used. The calculation within this study does not encompass the environmental practices that farmers can use, such as planting diverse field margins, adopting multi-species swards, rotational or adaptive multi-paddock grazing, density of hedgerows etc. The impact of these sustainable practices on larval populations would also be beneficial to research.

In summary, factors that influence leatherjacket populations have been previously reported, such as the vulnerability of eggs and first larval instars to desiccation (Milne et al., 1965), and the use of soil inversion to reduce populations (Evans, 2003), but questions remain about the impact of management and bioclimatic factors. The benefit of this longitudinal survey is that it allows long-term analysis of population fluctuations and observation of repeated trends. Our results highlight that both management practices and local weather conditions have a role to play in determining leatherjacket population densities. Younger L2 larvae are very susceptible to desiccation, and this is reflected by the highly significant negative effect of temperature. While L3 seem to benefit from warmer winters. At the farm scale, greater field size and sheep grazing result in lower larval populations. Farm management intensity was also shown to impact population size, with highly intensive farms having reduced pest occurrences. From an Integrated Pest Management perspective this highlights that local weather patterns may provide a means of forecasting leatherjacket risk. Our study highlights that management practices may provide a means of helping to control leatherjacket populations in the absence of chemical control measures. What will be essential for leatherjacket control research going forward is insight into more specific and sustainable farm management techniques, to create successful IPM approaches.

AUTHOR CONTRIBUTIONS

A. Moffat: Conceptualization; methodology; data curation; software; investigation; validation; formal analysis; visualization; project administration; resources; writing – original draft; writing – review and editing. **L. Cole:** Conceptualization; data curation; formal analysis; investigation; software; supervision; writing – review and editing. **S. Lacey:** Validation; writing – review and editing. **B. Harrison:** Data curation; resources. **A. Konkolewska:** Software; visualization; writing – review and editing. **D. McCracken:** Data curation; project administration; resources; writing – review and editing. **K. A. Evans:** Supervision. **M. T. Gaffney:** Supervision; writing – review and editing. **F. Brennan:** Supervision; writing – review and editing. **G. E. Jackson:** Supervision; writing – review and editing. **L. McNamara:** Conceptualization; funding acquisition; project administration; resources; supervision; writing – review and editing.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are opening available in Figshare at https://doi.org/10.58073/SRUC.25000007.v1

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