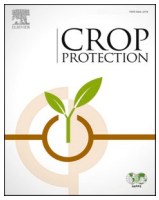
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Review

Pest management in potato: crop physiology, thresholds, and decision support for sustainable crop protection

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ABSTRACT

Potato production in the United Kingdom has not progressed beyond roughly 45 t ha^{-1} for many years, a stagnation attributable in part to pest-management practices and action thresholds that were established under agronomic, chemical, and climatic conditions that no longer prevail. This review revisits the principal invertebrate and nematode threats to UK potatoes and evaluates existing thresholds through a contemporary, physiology-centred lens. Potato yield is determined by two distinct developmental phases: tuber initiation, which fixes sink capacity, and tuber bulking, which is limited by canopy-driven assimilate supply. The yield impact of pest injury differs substantially between these phases and is further modulated by cultivar determinacy. Current thresholds rarely incorporate these physiological distinctions or the variable tolerance of modern varieties, rendering many of them empirically weak. We also assess current decision support systems that are available for potato pest management. Recent innovations in pest forecasting—spanning machine-learning models for virus-vectoring aphids and mechanistic simulations of below-ground pests—offer a foundation for dynamic, field-specific risk assessment, yet they remain largely uncoupled from crop growth stage and varietal traits. The evidence indicates that robust, integrated pest-management strategies will require recalibration of economic-injury levels using contemporary cultivars, explicit quantification of crop tolerance parameters, and full integration of real-time phenology and risk-forecast models. Such an approach is essential for delivering sustainable, climate-resilient pest control while safeguarding yield and environmental integrity in UK potato systems.

1. Introduction

Globally, potato (*Solanum tuberosum* L.) is one of the top five staple food crops. In the UK, potato production contributes around £1 billion to the agri-food economy (Thomsan, 2024) and potatoes provide 7% of the total energy intake and 14% of vitamin C to consumers (Devaux et al., 2021; Gibson and Kurilich, 2013). Like other agricultural crops, potatoes are exposed to a range of herbivorous invertebrates (hereafter referred to as pests) that damage plants and vector disease (Haverkort and Struik, 2015), ultimately reducing crop yield. Severe pest infestations can cut marketable yield by 80% (Orlando and Boa, 2023) and global analysis puts average potato losses due to pests at ~17%, with the magnitude of loss dependent on the pest's feeding mechanism, the tissue targeted, and the crop growth stage (Savary et al., 2019). The main pests affecting potato in the UK, and their period of activity, are detailed in Fig. 1. This review will focus on the major and minor pests that are of economic importance in the UK and northern Europe.

In order to manage pest infestations and reduce yield loss, potato production has been heavily reliant on synthetic pesticides. However, regulatory measures at both the European (Directive, 2009/128/EC) and UK-level have severely restricted, or banned, many active ingredients. There are currently eight actives approved for use in the UK, comprising three nematicides (fosthiazate, fluopyram, and nemguard) and five insecticides (acetamiprid, flonicamid, spirotetramat, lambda-

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cyhalothrin, esfenvalerate). Overreliance on some chemistries, such as pyrethroids (lambda-cyhalothrin and esfenvalerate) for aphid control, has accelerated the development of pesticide-resistant populations and reduced pesticide effectiveness (Bass et al., 2014; Motter et al., 2024). Growing concern over non-target effects of these chemicals, in addition to emerging pesticide resistance, has increased the need for more sustainable pest management strategies, and integrated pest management (IPM) is one approach that is increasingly used to manage crop pests more sustainably (Barzman et al., 2015). The overarching goal of IPM is to maximize pest management through: i) increased uptake of preventative strategies; ii) the utilisation of pest monitoring and thresholds to inform decision-making processes; and iii) the optimisation of non-chemical control methods with minimal use of pesticides where needed (Barzman et al., 2015). To avoid over-reliance on synthetic pesticides, limit pesticide resistance development, and promote more sustainable production, pest management decisions increasingly need to be guided by knowledge of the risk of economic damage presented by each pest.

Economic thresholds, hereafter "thresholds", are often used to estimate crop risk. Thresholds act as a baseline to guide pest management decisions, with a threshold representing the pest density per plant or unit area at which the expected cost of damage exceeds the cost of control, making pest management interventions economically rational (Higley and Pedigo, 1993; Pedigo et al., 1986). Although thresholds are widely used in advisory literature and grower practice, their empirical underpinnings are surprisingly thin (Ramsden et al., 2017). Many were calibrated decades ago (Carden, 1965) and are therefore not fully representative of the current agronomic and climatic situation. Moreover, these thresholds commonly fail to capture crop traits that modulate resistance and tolerance to pests, such as age-related resistance/tolerance, a phenomenon where a plant shows innate resistance or tolerance to a given pest once the plant reaches a certain developmental stage (DeMell et al., 2023; Chikh-Ali et al., 2019). Thresholds have been developed for most of the key potato pests (Table 1), although not all of these have been experimentally validated and few account for variations in crop physiology or plant stage of development.

Physiology-centred, tolerance-based approaches have been recommended, or adopted, in other crops. For example, pollen-beetle thresholds in oilseed rape now adjust for 'excess flower' compensation (Skellern and Cook, 2018) and incorporating important aspects of crop physiology, such as critical growth stages, into thresholds has recently been proposed for wheat (Leybourne et al., 2024). While elements of potato physiology are recognised as important in pest tolerance, a comprehensive, validated framework that systematically incorporates the physiological traits into economic thresholds remains under-developed. These conceptual and empirical advances offer a valuable precedent for potato systems, where crop traits and the location of damage (canopy or tuber) also influence risk.

Here, we review current thresholds and predictive models available for major and minor invertebrate pests of concern to potato growers in the UK (Fig. 1; Table 1). First, we provide an overview of the physiological processes that determine yield in potato, highlighting limiting factors at the source and the sink. Following this, we review thresholds and predictive models for each and discuss how we could better account for crop tolerance in pest management strategies. We conclude by highlighting how threshold-based tolerance schemes can be used to develop future sustainable pest management schemes.

2. The physiological basis of yield in potato

Potato tuber yield is a function of the interaction between the canopy's efficiency in fixing carbon (source capacity) and the tuber's ability to import and store photoassimilates (sink strength). From a pest management perspective, yield loss occurs when pest injury disrupts this source–sink balance beyond the crop's capacity to compensate. Understanding how this balance changes across growth stages is therefore central to developing growth-stage-explicit economic thresholds. This can be assessed through Equation (1).

$$Y = (R \times f \times RUE) \times HI$$

Equation (1): The framework established by Monteith (1977), yield (Y) can be fundamentally expressed as the product of the total incident solar radiation (R), the fraction of radiation intercepted by the canopy (f), the radiation use efficiency (RUE), and the harvest index (HI).

2.1. Source capacity: Radiation interception and efficiency

The primary driver of dry matter production is the interception of photosynthetically active radiation (PAR). As described by Haverkort and Harris (1987), physiological "source" potential is determined by the rapidity of canopy establishment and the persistence of green leaf area, known as Leaf Area Duration (LAD). Early crop vigour serves to maximize the fraction of radiation intercepted (f) during days of high insolation. However, while interception determines the quantity of energy captured, RUE defines the efficiency of converting that energy into biomass (g.MJˆ-1). Biotic stressors affect these variables as foliar herbivores reduce yield by destroying leaf area (lowering f) and soil borne pests impair RUE by directly affecting the biochemical processes of photosynthesis such water/nutrient uptake.

2.2. Sink strength: initiation and establishment

Tuber initiation establishes the potato sink capacity by determining yield potential as tuber number. This process is triggered by the photoperiod-sensitive protein StSP6A, synthesized in leaves and transported to stolon tips where it activates tuber identity genes (Bao et al., 2025). This signal requires reduced gibberellin levels to halt stolon elongation and initiate radial swelling. Once initiated, plants enter the tuber bulking phase and compete for assimilates based on their sink strength. The potential maximum size of a tuber is largely determined during the weeks following tuber initiation. During this phase, the

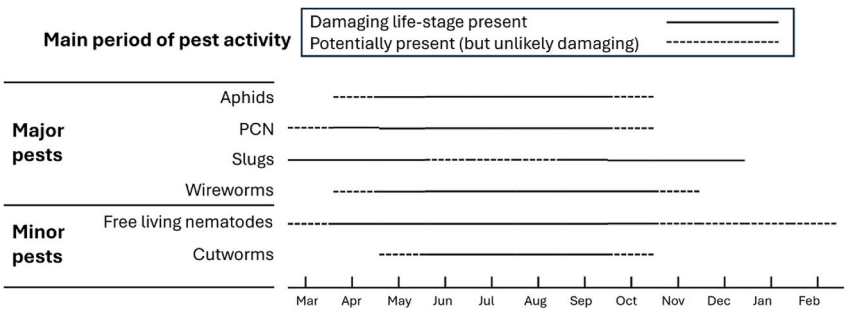


Fig. 1. Periods of activity for the damaging stage(s) of the major and minor pests affecting potato crops in the UK, and an indication of the likely period of pest activity for key high-risk invasive species.

Table 1
Overview of the main invertebrate pests affecting potato crops in the UK, the period where potatoes are at greatest risk of each pest, the potential damage caused by each pest, and an overview of current thresholds.

Pest	Period of greatest crop risk	Level of economic damage and yield loss	Current thresholds	Additional comments
Major pests				
Aphids	May–Sep (feeding damage at tuber bulking; virus risk from emergence to tuber initiation)	Feeding: up to 44% yield loss	Five aphids per compound leaf	Threshold was developed for Buckthorn-potato aphid during tuber bulking phase.
Aphid-vectored viruses (e.g., potato virus Y; potato leaf roll virus)	May–Sep	Seed rejection or downgrades	Threshold levels for combined PVY/PVA/PLRV incidence per seed potato grade: - PBTC: 0.00% - PB: 0.00% - Basic S: 0.02% - Basic SE: 0.10% - Basic E: 0.40%	Thresholds used for seed potato grading under the UK Seed Potato Classification Scheme. Thresholds above E grade are downgraded to ware.
Potato cyst nematode	Mar–Jul (hatch & root invasion)	Up to 80% loss at >60 eggs g^{-1} soil	Seed: zero tolerance; Ware: $\leq$10 low, 11–60 moderate, $>$ 60 high	-
Wireworms	Apr–Sep (tuber initiation → harvest)	Quality loss $>$ 50% tubers scarred	No fixed threshold; risk if >1 larva per bait trap	-
Slugs	Jun–Oct (post-canopy closure to harvest)	5–10% tuber damage downgrades ware	≥ 1 slug/trap overnight	-
Minor pests				
Free-living nematode	Apr–Jul (root initiation → early bulking)	Quality loss from tobacco rattle virus (corky ringspot)	Stubby-root nematode: 100/250 g soil; Root-lesion nematode: 100–200/100 cm^3 soil	-
Cutworm	May–Aug (larval surface feeding window)	20% to 80% depending on severity	None available	-

PVY: Potato Virus Y; PVA: Potato Virus A; PLRV: Potato leafroll virus. PBTC: Pre-Basic Tissue Culture; PB: Pre-Basic (field grown).

tubers undergo rapid cell division (hyperplasia); tubers with a higher cell number will contain a larger "sink capacity" compared to one with fewer cells. Once cell division ceases, growth proceeds exclusively via cell expansion (hypertrophy) driven by starch accumulation (Struik et al., 1990).

Thresholds that ignore whether injury occurs during sink formation or source limitation risk under- or over-estimating pest impact.

3. The current thresholds and predictive models for major potato pests

In order to follow thresholds, growers must monitor, or be able to accurately estimate, insect populations and use this to determine the level of crop risk, and this is often difficult to do under field conditions (Ramsden et al., 2017). Predictive models can assist in this regard. Models have been developed to estimate the abundance of pest populations, predict the occurrence of phenological events (e.g. migration), and to determine the overall level of crop risk to a specific pest. These models are useful standalone tools that can help with the monitoring and management of pest populations, and they can also be combined with thresholds to better support sustainable management practices (Leybourne et al., 2024).

3.1. Aphids: virus transmission and direct-feeding damage

Aphids are the primary sap-feeding insect pests of potato crops, with the peach-potato aphid (*Myzus persicae*) and the potato aphid (*Macrosiphum euphorbiae*) two of the most significant species affecting yield and quality (Fox et al., 2017; Xu and Gray, 2020). Aphids feed by establishing a feeding site within the phloem tissue where the aphid directly depletes plant resources, causing physiological stress in the plant (Xu and Gray, 2020). Aphids that cause direct feeding damage are categorised as crop-colonising species (i.e., aphids that can successfully establish populations and feed from the phloem of potato plants). *M. persicae* and *M. euphorbiae* are two of the most economically impactful crop-colonising aphid species in the UK (Fox et al., 2017; Steinger et al., 2015). There are also a range of non-colonising species, such as the grain aphid (*Sitobion avenae*) and the willow-carrot aphid (*Cavariella aegopodii*); these species don't cause direct damage to the plant, but they probe plant tissue which can result in virus transmission.

Aphid vectored plant viruses can be broadly categorised into non-persistent and persistent viruses. Potato virus Y (PVY; non-persistent), potato virus A (PVA; non-persistent), and potato leafroll virus (PLRV; persistent), are among the most agriculturally impactful viruses of potatoes in the UK (Basky, 2002; Bhoi et al., 2022). PVY and PVA can be vectored by both crop-colonising and non-colonising species, whereas PLRV can only be vectored by crop-colonising aphid species. PVY can also be divided into several strains (Davie et al., 2017), namely: $PVY^{O,}$ PVY^{N}, and PVY^{NTN}. These strains have variable phytopathological effects, with PVY^{O} often perceived as the more moderate strain and PVY^{NTN} the most impactful. Each vector species can transmit PVY, PVA, and PLRV with varying efficiency (Fox et al., 2017; Fenton et al., 2013), and this influences the level of risk experienced by the crop.

Taken together, aphids present a multi-variable physiological threat to the affected plants. Aphids simultaneously affect plant radiation use efficiency (RUE; Equation (1)), through virus infection, and canopy function, via direct feeding. Table 2 details the key aphid species that vector PVY, PVA, and PLRV in the UK and provides an overview of the relative transmission efficiency (transmission index) for each vector-virus combination. *Myzus persicae* is the most efficient vector of PVY, PVA, and PLRV (Table 2). Virus infection is especially important in seed potato production systems where virus presence can result in significant crop downgrading and economic loss (Fox et al., 2017). In 2025, over 17% of Scottish potatoes were downgraded due to PLRV infection. With increased incidence of PLRV possibly driven by the emergence of new isolates (Cowan et al., 2025).

3.1.1. Period of pest activity and crop risk

Feeding damage: Aphids are active, and potentially damaging, across the main potato growing period (May – Sep; Fig. 1). Direct feeding damage is source-limited and of greatest concern during the tuber bulking phase (BBCH 40–70, June to August), around six-to-eight weeks before potato harvest. Under severe infestations aphid feeding up-regulates plant senescence pathways, accelerating haulm senescence

Table 2
Transmission index values for PVY, PVA, and PLRV. Values for individual PVY strains and PVA are based on Fox et al. (2017); where strain-level information for PVY is unavailable the PVY index values described in Fenton et al. (2013) are followed. PLRV index values follow those reported by Science and Advice for Scottish Agriculture and The Agri-Food and Biosciences Institute. Note that this list is non-exhaustive.

Species	Common name	Crop colonising	PVY index	PVA index	PLRV index
Myzus persicae	Peach-potato aphid	Y	PVY^{O}: 1.00 PVY^{N}: 1.00 PVY^{NTN}: 1.00	PVA: 1.00	PLRV: 1.00
Aphis fabae	Black bean aphid	Y	PVY^{O}: 0.06 PVY^{N}: 0.00 – 0.03 PVY^{NTN}: 0.00 - 0.13	PVA: 0.45	PLRV: 0.30 – 0.56
Aphis nasturtii	Buckthorn-potato aphid	Y	PVY: 0.40	Vector, no established index	PLRV: 0.25
Aulacorthum solani	Glasshouse potato aphid	Y	PVY: 0.20	Vector, no established index	PLRV: 0.10 – 0.30
Macrosiphum euphorbiae	Potato aphid	Y	PVY^{O}: 0.30 PVY^{N}: 0.00 – 0.66 PVY^{NTN}: 0.00 – 0.38	PVA: 0.91	PLRV: 0.15 – 0.89
Rhopalosiphoninus latysiphon	Bulb and potato aphid	Y	PVY: 0.20	Vector, no established index	PLRV: 0.30
Rhopalosiphoninus staphyleae	Mangold aphid	N	PVY: 0.00	Not known or not a reported vector	PLRV: 0.10
Aphis gossypii	Melon and cotton aphid	N	Vector, no established index	Not known or not a reported vector	PLRV: 0.50
Aulacorthum circumflexum	Mottled arum aphid	N	Not known or not a reported vector	Not known or not a reported vector	PLRV: 0.90
Myzus nicotianae		N	Not known or not a reported vector	Not known or not a reported vector	PLRV: 0.35
Phorodon humuli	Damson-hop aphid	N	Not known or not a reported vector	Not known or not a reported vector	PLRV: 0.12
Myzus ascalonicus	Shallot aphid	N	PVY: 0.20	Not known or not a reported vector	PLRV: 0.30
Myzus ornatus	Violet aphid	N	PVY: 0.20	Not known or not a reported vector	PLRV: 0.30
Acyrthosiphon pisum	Pea aphid	N	PVY^{O}: 0.77 - 1.24 PVY^{N}: 0.00 - 0.33 PVY^{NTN}: 0.07 - 0.88	PVA: 0.00 – 0.50	N/A
Brachycaudus helichrysi	Leaf-curling plum aphid	N	PVY: 0.21	Vector, no established index	N/A
Brevicoryne brassicae	Cabbage aphid	N	PVY^{O}: 0.00 PVY^{N}: 0.00 PVY^{NTN}: 0.00 - 0.04	PVA: 0.00	N/A
Cavariella aegopodii	Willow-carrot aphid	N	PVY^{O}: 0.77 PVY^{N}: 0.00 – 0.49 PVY^{NTN}: 0.00 – 0.96	PVA: 0.53	N/A
Hyperomyzus lactucae	Blackcurrant-sowthistle aphid	N	PVY: 0.16	PVA: 0.00	N/A
Rhopalosiphum padi	Bird cherry-oat aphid	N	PVY^{O}: 0.77 PVY^{N}: 0.00 – 0.57 PVY^{NTN}: 0.00 – 0.95	PVA: 0.02	N/A
Sitobion avenae	Grain aphid	N	PVY^{O}: 0.33 PVY^{N}: 0.00 - 1.10 PVY^{NTN}: 0.00 – 0.49	PVA: 0.60	N/A
Metopolophium dirhodum	Rose-grain aphid	N	PVY^{O}: 0.00 PVY^{N}: 0.02 – 0.87 PVY^{NTN}: 0.00 – 0.07	PVA: 0.03	N/A

(Machado-Assefh et al., 2014). This process shortens the functional lifespan of the canopy, effectively reducing leaf area duration (LAD) during the period when sustained photosynthesis is required to support tuber bulking.

Feeding during tuber bulking reduces photosynthetic assimilation, with heavy infestations cutting biomass by up to 54% (Petitt and Smilowitz, 1982) and causing significant yield reductions (Dedryver et al., 2010). Furthermore, the excretion of honeydew by feeding aphids can lead to the growth of "sooty mold," which reduces the effective incident solar radiation of the plant (R; Equation (1)). Aphid feeding redistributes soluble carbohydrates away from tubers to feeding sites (Xu and Gray, 2020), affecting tuber quality. Aphid feeding can also result in leaf curling, leading to "false top roll" symptoms. The risk period for feeding damage is the same for both ware and seed crops.

Virus: Ware crops. Most of the virus burden in a potato crop enters the field as infected seed stock. Long-term surveys show that 60–90% of the PVY and PLRV detected at harvest was already present in the planting tubers (Robert et al., 2000; Thomas-Sharma et al., 2016). Nonetheless, virus-free certified potato seed can still be infected in-season by virus-carrying aphids. The primary period of virus risk spans from crop emergence to tuber initiation (BBCH 10–40, roughly May–June; Fig. 1). Early virus infections interrupt sink determination by stunting canopy growth, this limits total leaf green area with negative consequences on tuber set and size (Chikh-Ali et al., 2019). Following tuber initiation, plants can naturally resist new PVY infection (Chikh-Ali et al., 2019), although certain PVY^{NTN} strains can still blemish skin finish via tuber-necrotic ringspot disease (Karasev and Gray, 2013). PLRV behaves differently: PLRV infection limits the movement of sugars to the developing tubers, affecting sink development and reducing crop yield and processing quality (Kumar et al., 2025). Crop losses are often heightened in mixed PVY + PLRV infections (Li et al., 2013; Byarugaba et al., 2020). These viruses (PVY/PLRV) cause systemic physiological stress that impairs the potato plant's ability to fix carbon, directly reducing radiation use efficiency (RUE; Equation (1)).

Virus: Seed crops. For seed potatoes, however, any infection renders the crop unmarketable due to strict virus tolerance standards. Certification tolerances are far tighter (≤0–0.4% PVY/PVA/PLRV at final inspection); hence any infection acquired between emergence and haulm destruction can downgrade or condemn a crop (Lindner et al., 2015). Early-season cases remain biologically most severe—virus spreads systemically and contaminates almost every daughter tuber—but even a single late-season plant can be detectable in some cases. Across north-western Europe, downgrades and rejections account for ~26% of the total PVY-related economic loss in seed-potato systems (Dupuis et al., 2024).

3.1.2. *Overview of current thresholds*

In the UK, there is a common threshold for direct aphid feeding damage on potatoes, specifically for ware potato crops. Aphid risk to potatoes also considers the associated risk of aphid-borne virus

transmission, particularly PVY and PLRV. Thresholds differ between seed and ware potato crops due to their distinct economic impacts and certification requirements.

For ware crops, the threshold is five aphids per compound leaf at three canopy strata: top, middle and bottom. This threshold was established by Carden (1965) based on historical data linking this density to significant feeding damage at tuber bulking stage. Originally developed for the buckthorn-potato aphid (*Aphis nasturtii*), this threshold targeted a species no longer considered a significant pest in modern potato production. The threshold was later reevaluated, with aphid populations observed to peak at an average of 500 aphids per 100 leaves (equating to five aphids/leaf), with *Macrosiphum euphorbiae* (potato aphid) as the dominant species. However, this threshold may not fully reflect current pest dynamics or varietal responses, as it was established based on older potato cultivars that could differ significantly in growth habit from those commonly grown today. Further, life-history and physiological traits can differ significantly between aphid species, and this current threshold might over or underestimate damage for some species, particularly where aphid development and population growth differs significantly from the potato aphid. Despite these limitations, advisers continue to use this threshold. In the absence of up-to-date aphid economic-injury findings, the threshold provides a simple and precautionary trigger for aphid management decisions. This threshold, however, overlooks aphid-species diversity, the severity of infestation, and cultivar-specific responses. The threshold focuses on aphid population numbers rather than the viruses they carry; hence it assumes potato plants tolerate virus transmission risk as long as feeding damage stays below threshold levels.

For seed potatoes, there is a zero-tolerance policy for aphid presence, driven by the unacceptable risk of virus transmission compromising certification standards (Basky, 2002). Monitoring typically prompts immediate action upon detection of a single alate aphid, as any level of aphid can render crops unmarketable if they are contaminated with viruses (Dupuis et al., 2024). The seed potato threshold assumes high virus prevalence and transmission efficiency, suggesting that any aphid presents a definitive risk of PVY/PLRV infection and spread, necessitating immediate action to protect certification standards (EPPO, 2023).

3.1.3. Estimating crop risk

Virus risk, particularly PVY and PLRV risk, is calculated using a combination of aphid monitoring and virus transmission indices. To achieve this, aphid migration and activity is monitored through surveillance traps with the composition of aphid species at each trap location determined. Each species has a defined index for virus transmission, estimated through empirical transmission studies (Fox et al., 2017), and the cumulative index is calculated based on the combined index value for all species present in the trap (see Table 2 for an overview of the indices used for key aphid species in the UK). This approach helps to estimate virus risk and can inform aphid and virus management strategies. Across the UK several organisations run a semi-coordinated aphid monitoring network; Rothamsted Research, SASA, and AFBI operate a series of suction towers that monitor aphid flight and migration across the UK. This monitoring network provides an estimation of aphid risk for a range of arable crops; however, the specific aphid species that are monitored and reported varies between the institutions. AFBI and SASA also run water trap networks in Northern Ireland (AFBI) and Scotland (SASA) to monitor PVY risk in key seed potato growing areas. These traps are used to provide a near real-time estimation of PVY risk across the key seed potato growing regions. There are also *ad-hoc* monitoring networks delivered by some commercial companies and other sector stakeholders. Together these networks provide a timely and effective means of estimating aphid and virus risk. The species identification methods could potentially vary between the institutions, and the development of shared and standardised approaches could streamline the delivery of these services in the future.

Effective forecasting through modelling can also help estimate risk, particularly for PVY. Forecasting systems have attempted to predict PVY impact via local aphid monitoring. To date, many of these have focussed on predicting the time of first flight for important non-colonising PVY vector species, including *Brachycaudus helichrysi* in Switzerland (Steinger et al., 2015), *Aphis fabae* in Finland (Kirchner et al., 2011) and cereal aphids in North America (Galimberti et al., 2020). Models that predict peak summer abundance of *M. persicae,* the primary aphid vector of PVY and PLRV, have been developed by SASA and Rothamsted Research and a flight risk model has been developed by the UK Met Office. Recent modelling also suggests that, due to climate change, the likelihood of early aphid flights is increasing in the UK (Hemming et al., 2022).

In Scotland, a new interpretable machine-learning model has been developed to forecast PVY incidence and potential risk using historical crop infection data, seed quality records, and landscape-scale predictors (Skelsey, 2024). The landscape features incorporated include the proportion and spatial configuration of potato fields, grassland, woodland, and semi-natural habitats within defined buffer zones around monitoring sites. These land-use features help represent potential aphid habitats and virus spread corridors. This spatially contextualised approach for predicting virus risk based on both agronomic and ecological landscape structure opens a new way of predicting virus risk based on landscape and agronomic features.

However, while PVY has received considerable attention in forecasting development, PLRV—despite its importance in seed systems—remains under studied. No dedicated, validated models currently exist to predict PLRV risk in the field, and the emergence of new PLRV isolates (Ryabov et al., 2026) has increased the need for new management strategies (Cowan et al., 2025).

3.1.4. Proposed areas for future development

Current virus management strategies in seed potatoes operate under a functional zero-tolerance policy for aphid presence, assuming that any aphid—particularly *M. persicae*—will carry and transmit PVY or PLRV. Due to the risk of downgrading in virus-infected seed crops (EPPO, 2023), and the economic impact this can have on potato growers, a zero-tolerance approach continues to remain essential. However, technological advances could lead to the development of more sophisticated and real-time forecasting and surveillance tools, ultimately leading to better optimisation of surveillance and management strategies that could reduce the need for a zero-tolerance approach.

In ware potatoes, the threshold of five aphids per compound leaf, developed for *A. nasturtii* during tuber bulking, no longer reflects modern pest pressures. Feeding damage can also affect canopy growth earlier, during emergence to tuber initiation, with aphids affecting radiation use efficiency and leaf area duration. Refined thresholds should account for each crop growth stage, the resilience of the crop variety, and environmental stress, recognizing that some varieties can compensate for early damage, while others cannot. Forecasting tools, particularly for PVY incidence, should combine aphid trap data, weather, variety susceptibility, and historical virus presence to improve prediction accuracy. This would help prioritise interventions where risk is highest to support more sustainable, IPM-aligned aphid and virus management. For PLRV, new approaches are needed to respond to the emergence of new PLRV isolates; the development of models to predict PLRV incidence and risk could form the basis for new management strategies.

Future aphid and virus management strategies could focus on breeding for resistance to aphids or/and aphid-vectored viruses. Further, recent shifts in UK policy around gene editing also provide ample opportunity to develop crop varieties that are better able to tolerate pests, disease, and environmental extremes.

3.2. Potato cyst nematodes (*Globodera spp.*)

Potato cyst nematodes (PCN), comprising *Globodera rostochiensis* and *G. pallida*, are globally significant pests that inflict substantial economic

damage on potato production. These sedentary endoparasites invade host roots, disrupting water and nutrient uptake and stunting plant growth. In the UK annual losses have been estimated at £31 million (Price et al., 2021). Once established, PCN are difficult to eradicate, primarily due to the long-lived cysts that remain viable for decades (Ochola et al., 2020). Both species are subject to international quarantine regulations due to their persistence and potential to spread through infested soil, tubers, or equipment. As climate change and global trade continue to reshape pest dynamics, investment in assessing PCN risk and predictive modelling will be critical to mitigate the ongoing threat posed by PCN.

3.2.1. Period of pest activity and crop risk

Potato cyst nematode activity is tightly synchronised with crop phenology. The life cycle begins when second-stage juveniles (J2) which hatch from cysts in response to chemical signals exuded by the roots of potato or other solanaceous hosts. These exudates contain a complex mixture of host-derived hatching factors, such as steroidal glycoalkaloids, which induce J2 hatch from eggs and provide chemotropic cues that direct J2 toward the roots (Ochola et al., 2020; Kud et al., 2022). In the absence of a host, spontaneous hatching occurs at a negligible rate, insufficient to sustain populations or cause economic damage (Ryan and Devine, 2005). Upon reaching the host, J2 invade the roots and induce the formation of specialized feeding structures known as syncytia (Price et al., 2021). These structures act as metabolic "sinks," redirecting the plant's resources to the nematode. This diversion directly impairs the biochemical efficiency of photosynthesis and reduces the plant's overall radiation use efficiency (RUE; Equation (1)).

The timing of PCN life cycle is primarily dictated by accumulated temperature. While hatching is generally most active when soil temperatures range between 10 °C and 20 °C (Kaczmarek et al., 2014), the completion of the life cycle depends on specific thermal requirements. *G. pallida* and *G. rostochiensis* require approximately 450°-days (base 4 °C) and 398°-days (base 6 °C), respectively, to reach the cyst stage (Ebrahimi et al., 2014).

Potato cyst nematode risk is therefore temporally constrained to periods when soil temperatures permit J2 activity and successful establishment within host roots. In temperate potato systems, this risk is greatest early in the growing season, when rising soil temperatures coincide with active root development and canopy formation. Damage initiated at this stage persists throughout the season, because syncytia remain metabolically active until plant senescence, continuously diverting host resources (Trudgill et al., 2014).

3.2.2. Overview of current thresholds

Economic thresholds for PCN are based primarily on pre-plant population densities and the intended market use of the crop—whether ware or seed potatoes. PCN thresholds also vary by region due to differences in climate, soil type, cultivar susceptibility, and regulatory standards.

The statutory threshold for seed potato production in the UK is effectively zero; the presence of *G. pallida* or *G. rostochiensis* in any pre-plant soil sample disqualifies a field from certified seed use (Price et al., 2023). This reflects the high risk of nematode spread via infested tubers and the long-term persistence of cysts in soil.

For ware potatoes, action thresholds are generally defined in terms of eggs per gram of soil, and infested soils can be generally grouped into three categories: i) Low infestations of $\leq$10 eggs g^{-1} soil; ii) moderate of 11–60 eggs g^{-1}; and iii) high of >60 eggs g^{-1} (Lane and Trudgill, 1999). Nematicide recommendations become stronger with increasing PCN densities. However, cultivar susceptibility significantly influences these values. Susceptible varieties suffer greater yield reductions compared to resistant/tolerant varieties at same nematode levels in similar soil conditions. Quantifying PCN risk depends on reliable soil sampling and extraction techniques. The standard method involves collecting up to 50 soil cores (0–25 cm depth) per hectare, pooled into composite samples, and analysed via extraction and microscopy or PCR diagnostics. However, the patchy field distribution of potato cyst nematode complicates interpretation, and current thresholds are often based on broad approximations. Furthermore, thresholds do not always account for population dynamics, such as the relative proportion of viable eggs or the influence of resistance-breaking potato cyst nematode pathotypes.

3.2.3. Predictive models to estimate crop risk

Predictive models developed to estimate crop risk from PCN can be broadly categorised into four groups: empirical yield-loss models, process-based life cycle simulations, spatial infestation risk models, and integrated decision-support tools.

Empirical models establish quantitative relationships between initial population densities and yield loss and form the foundation of many practical threshold-based recommendations (Contina et al., 2019a; Jones and Perry, 1978; Phillips et al., 1991). However, these models do not account for the "patchy" distribution of PCN cysts in the field, which can lead to significant underestimation of risk.

Process-based models simulate how PCN population dynamics interact with the potato crop over time (Kaczmarek et al., 2019; Beniers et al., 2019; Ewing et al., 2021). Due to strong influence temperature has on *G. pallida* development, reproduction, and life cycle (Kaczmarek et al., 2019; Jones et al., 2017; Kettle and Nutter, 2015) many of these models use temperature as a predictor. Additionally, cultivar resistance is increasingly simulated, with resistant varieties reducing *G. pallida* multiplication compared to susceptible types, and repeated use of partially resistant cultivars shown to drive virulence shifts, requiring dynamic model updates (Kaczmarek et al., 2019; Beniers et al., 2019; Ewing et al., 2021).

Spatial risk models enable precise risk assessment and targeted control strategies. Schomaker and Been (1999) developed an exponential gradient model to describe PCN infestation foci across Dutch fields, showing that bivariate normal distributions could effectively predict spread regardless of nematode species or agronomic variables. Building on this concept, Contina et al. (2018) applied spatial point pattern analysis, revealing *G. pallida* spread via a contagion effect around initial foci, likely through soil and machinery transfer. A subsequent study introduced spatiotemporal models and power-law functions, identifying edge-based spread driven by cultivation patterns (Contina et al., 2019b).

Integrated decision support systems combine multiple model types and agronomic variables—such as crop rotation interval, nematicide use, and cultivar resistance—to guide long-term planning. In recent years two tools have formed a cornerstone of potato cyst nematode management: the PCN Calculator, developed by The Agriculture and Horticulture Development Board in the UK, and NemaDecide, developed by researchers in The Netherland (Been et al., 2005; Teklu et al., 2019). A new system, the PCN Scenario Planner, has recently been developed by PCN Action Scotland. These decision support systems provide growers with tools to simulate population changes and assess the effectiveness of different control strategies under various scenarios of infestation, resistance, and management intensity. These models are steps in the right direction to enhance PCN management by offering tailored strategies for risk assessment and control.

3.2.4. Proposed areas for future development

Potato cyst nematode risk modelling currently faces several limitations that reduce its effectiveness in informing threshold-based management decisions. A major challenge lies in the inadequate calibration of existing models to real-world variability in potato cultivar tolerance, soil properties, and environmental conditions, leading to systematic misrepresentation of PCN population dynamics. Commonly used models have been shown to underestimate PCN multiplication at low initial population densities and overestimate it at high densities, reducing the reliability of long-term predictions and potentially misguiding management strategies (Trudgill et al., 2014). More fundamentally, most current risk assessments remain centred on nematode population

density alone (number of eggs/g of soil), with limited representation of the physiological processes through which PCN causes yield loss in potato.

Existing modelling frameworks rarely account explicitly for the crop's capacity to compensate for assimilate diversion caused by PCN-induced root sinks, despite evidence that yield loss depends on the plant's ability to maintain growth under nematode infection (Trudgill, 1991), and that potato yield formation is governed by the supply of assimilates from the canopy (source) relative to the demand from developing tubers (sink) (Kooman, 1996). As a result, thresholds derived from population density alone may fail to capture why similar PCN infestations result in contrasting yield outcomes across seasons and sites. In addition, genetic diversity within PCN populations, especially pathotype composition, is often insufficiently represented, despite its strong influence on virulence and the durability of host resistance (Ewing et al., 2021; Contina et al., 2019a). Efforts to integrate PCN dynamics with crop growth models, such as the SUBSTOR–DSSAT framework, represent an important step towards mechanistically linking nematode pressure with yield formation. However, wider application remains constrained by high data requirements and challenges in parameterising nematode–crop interactions within complex cropping systems (Contina et al., 2019a, 2019b). Climate-driven changes in soil temperature and moisture regimes further complicate risk prediction by modifying both nematode development rates and the crop's physiological capacity for compensation, yet these interactions remain insufficiently resolved in most modelling approaches (Ewing et al., 2021). Enhanced field diagnostics, particularly molecular tools for species and pathotype identification, will be essential to provide robust baseline data for model calibration, validation, and targeted control strategies (Orlando and Boa, 2023).

To improve PCN risk modelling, future research should prioritise localised calibration, explicit linkage between nematode pressure and crop physiological response, incorporation of population genetic diversity, and improved representation of environment-driven variation in crop tolerance. Collectively, these advances would support the development of more robust, physiology-informed decision frameworks capable of underpinning sustainable PCN management.

3.3. Wireworms

Wireworms, the larval stage of click beetles (Coleoptera: Elateridae), are significant and persistent soil-dwelling pests that affect many arable crops, including potato, with notable economic impact across temperate regions. Larvae feed on potato tubers, creating deep, irregular holes that reduce marketability—especially in high-value fresh and processing markets where cosmetic standards are stringent (Johnson et al., 2008). Additionally, these feeding sites act as entry points for opportunistic bacterial pathogens, exacerbating postharvest decay and rendering affected tubers unsuitable for sale. The most prevalent wireworm species include *Agriotes lineatus*, *A. obscurus*, and *A. sputator*, which have broad host ranges that encompass potatoes, cereals, and other grasses (Benjamin et al., 2018; Parker and Howard, 2001). This broad host-range, extended life cycles (typically 3–5 years), and subterranean habitat allow wireworm populations to persist undetected across crop rotations, complicating detection and management strategies (Barsics et al., 2013; Parker and Howard, 2001).

3.3.1. Period of pest activity and crop risk

Adult click beetle emergence and activity depend on species-specific life cycles. Non-overwintering adults such as *A. ustulatus* emerge in late spring and survive for a few days to weeks, while overwintering species like *A. sordidus*, *A. obscurus*, and *A. lineatus* emerge earlier, often from March to April, and can remain active for several months (Barsics et al., 2013; Parker and Howard, 2001). Peak adult flight and mating activity generally occur from April to July. Females lay eggs in grassy or uncultivated areas shortly after emergence, with oviposition influenced by habitat conditions and soil characteristics (Traugott et al., 2015).

Wireworm larval activity occurs predominantly in spring (March–May) and autumn (September–October), when conditions near the soil surface are favourable. They migrate upward to feed when soil temperatures reach 11 °C - 13 °C and soil moisture levels are around 31% by volume in loam or 8–16% by weight in sandy loam. During summer and winter extremes, larvae retreat to depths of 60 cm or more, becoming less active to avoid desiccation or freezing (Barsics et al., 2013; Parker and Howard, 2001). However, actively feeding wireworm larvae will remain in the upper layers of the soil and continue to damage plant tissue.

Wireworm damage to potato tubers tends to increase throughout the growing season, with the highest levels of injury occurring later in crop development as tubers enlarge (tuber bulking stage). Kuhar and Alvarez (2008) demonstrated that tuber damage was minimal early in the season but escalated significantly after mid-June, coinciding with tuber bulking and increased tuber diameter. Similarly, a literature synthesis by Parker and Howard (2001) indicated that injury typically intensified from mid-August onward, approximately 12–16 weeks post-planting, regardless of initial wireworm population densities. Recently, Brunner and Traugott (2026) showed that wireworm damage during tuber ripening is strongly influenced by harvest timing and tuber mass, with larger tubers and delayed harvest associated with increased feeding damage. Collectively, these findings indicate that potato tubers are most vulnerable to wireworm attack during the latter part of the growing season, particularly during the tuber bulking phase, hence limiting potato sink strength as tubers are fully developed and remain exposed to feeding larvae in the soil. This damage directly reduces the proportion of total biomass allocated to marketable tubers and therefore lowers the harvest index (HI; Equation (1)).

3.3.2. Overview of current thresholds

Economic thresholds for wireworm damage in potato crops have not been formally established, primarily due to variability in pest behaviour and the challenges of accurate population assessment. However, in the UK growers are encouraged to monitor wireworm pressure through soil sampling (Ramsden et al., 2017). Nonetheless, establishing validated and actionable thresholds is important, as even low larval densities can cause significant economic losses.

In other crops, pheromone traps have been used to develop thresholds based on adult migration (Furlan et al., 2024, 2025). For example, in maize a threshold of >210 *Agriotes brevis* adults per trap per year has been suggested (Furlan et al., 2020) however, these values are not crop transferable. Potatoes differ markedly in vulnerability and market tolerance, necessitating species and crop-specific thresholds. Moreover, adult beetle catches often correlate poorly with soil larval densities and damage outcomes due to variable oviposition behaviour, larval survival, and the longevity of wireworm larvae within the soil over multiple years (Rashed and van Herk, 2024). Larval behaviour is also strongly influenced by microclimatic soil factors, particularly temperature, moisture, and the presence of root networks that influence their vertical distribution and feeding activity (Brunner and Traugott, 2026; Horton, 2006; Booth et al., 2022). These factors introduce temporal and spatial variability that challenges threshold precision. As such, risk assessments must consider multiple interacting variables rather than relying on single indicators. The lack of robust, empirically validated economic injury levels for wireworms in potatoes highlights the need for integrated decision support tools that incorporate wireworm species identification, field history, and environmental parameters. Until such tools are calibrated for potato systems, pest management will rely on cautious, often prophylactic, strategies guided by local knowledge and field scouting.

3.3.3. Predictive models to estimate crop risk

Several predictive models have been developed to estimate wireworm larvae damage risk in potato crops, although their precision

remains constrained by ecological complexity and data limitations. Notably, risk is often modelled through proxies such as adult *Agriotes* spp. trap catches, habitat characteristics, and climatic variables rather than direct measures of larval pressure. For example, the SIMAGRIO-W model, developed in Germany, simulates larval activity based on soil temperature, moisture, and soil type, predicting periods of highest damage risk by estimating vertical larval movement into crop-rooting zones (Jung et al., 2014). While this model offers insight, its accuracy depends on high-resolution meteorological data, including soil moisture and soil temperature, and does not directly predict yield loss or economic damage. Notably, although the model performed well in field tests in western Germany, it performed poorly when evaluated in eastern Austria, highlighting the limitations of its broader applicability (Poggi et al., 2018). Alternatively, long-term monitoring studies in maize linked adult pheromone trap catches to larval risk thresholds (Furlan et al., 2020), but these findings are crop-specific and cannot be reliably extrapolated to potatoes due to differing susceptibilities and market quality standards. Moreover, adult-larval correlations are often weak or inconsistent, undermining the utility of adult trap data alone as predictive indicators (Benefer et al., 2012). Landscape-based models integrating grassland history, organic matter, and soil pH can explain patterns of wireworm abundance and damage risk (Hermann et al., 2013; Poggi et al., 2018), yet their resolution may be too coarse for field-scale decision support. Consequently, while these predictive models can inform relative risk and support site selection or planting decisions, their limitations in forecasting precise economic thresholds or real-time larval pressure necessitate cautious interpretation.

3.3.4. Proposed areas for future development

A critical limitation in current wireworm risk models and threshold frameworks is their failure to account for the alignment between pest activity and the physiological development of the potato crop. This is especially problematic considering that economic losses from wireworms stems more from quality degradation than yield reduction. Wireworms remain present from planting through harvest, but existing models rarely incorporate physiological sensitivity windows. While tuber initiation (14–30 days after emergence) influences tuber count, the most consequential damage occurs during tuber bulking and skin set, when larval feeding creates entry wounds that compromise tuber appearance, increase susceptibility to secondary infection, and disqualify crops from fresh, seed, or processing markets. Integrating wireworm phenology with crop growth stage and harvest index could inform optimised harvest timing and threshold refinement, especially in late-season scenarios when senescence delays periderm maturity and tubers remain exposed to feeding.

Equally important is recognizing that not all wireworms pose equal risk—larger, later-instar larvae inflict greater damage than early-instar individuals. Current monitoring approaches often emphasize total abundance, overlooking the damage potential associated with larval size distributions. This can lead to inaccurate risk classifications, where a field with a few large larvae may present greater economic risk than one with numerous small ones. Accurate and scalable assessments of both population density and developmental stage are thus essential. Incorporating larval biomass or instar ratios into monitoring protocols would enable size-sensitive risk forecasting and more targeted interventions. For instance, a population composed mostly of small larvae during bulking may allow for deferred action, whereas the detection of larger individuals—even at low densities—could necessitate immediate control. Such refinements would bring a new level of precision to decision-support tools, supporting cultivar-specific and market-specific management strategies in systems where even minor blemishes lead to substantial financial losses. Together, these innovations represent a vital shift toward truly integrated, physiology-informed pest management frameworks for wireworms in potato production.

3.4. Slugs (Deroceras reticulatum and others)

Slugs are among the most economically important invertebrate pests in temperate cropping systems particularly in damp environments that favour their survival and activity on a broad range of crops (Douglas and Tooker, 2012). In the UK, they are associated with substantial economic losses across a range of crops, including potatoes.

In potato crops, slugs cause characteristic damage by feeding on developing tubers, producing irregular, deep cavities that reduce quality and marketability (Kozłowski et al., 2019). The feeding wounds also facilitate secondary infections by fungi and bacteria, further compounding the economic losses. The damage is most prevalent in fields with high moisture levels and dense foliage, which provide ideal microclimates for slug activity. Critically, because the damage is subterranean, it often goes unnoticed until harvest, by which time intervention is no longer possible.

Several slug species are common agricultural pests in the UK. The most notorious is *Deroceras reticulatum*, which is responsible for the majority of crop damage due to its wide distribution and high reproductive rate. Other species include *Arion hortensis*, *Arion vulgaris* and *Limax maximus*. These species have broad host ranges, feeding not only on potatoes but also on brassicas, legumes, and cereals. Their generalist feeding behaviour and adaptability make them difficult to manage.

3.4.1. Period of pest activity and crop risk

Slug damage to potato crops is highly seasonal, with the greatest risk occurring in late summer and autumn when tuber bulking coincides with favourable moisture conditions for sustained feeding therefore depleting the sink strength. A shorter, but still important, risk period can precede this during crop emergence and early haulm growth in April–May, when seedlings and developing shoots may experience significant damage under damp conditions or where crop establishment is slow, potentially reducing plant stand and early canopy development (Kozłowski et al., 2019). Potatoes suffering from slug damage primarily have reduced harvest index (HI; Equation (1)), thereby lowering the proportion of total biomass allocated to marketable tubers, with only minor early-season effects on canopy development (f; Equation (1)).

Slug activity is driven by their lifecycle and environmental conditions, with both juveniles and adults contributing to crop damage. In addition, preceding crop history can influence slug pressure, particularly where favourable host crops have been grown (Keiser et al., 2012).

Risk increases markedly during tuber bulking, as larger tubers become accessible near the surface and soil cracking exposes vulnerable tissue (Kozłowski et al., 2019). Slugs preferentially attack mature or wounded tubers, often exploiting entry points created by wireworms or harvest damage (Kozłowski et al., 2019; Ester and Trul, 2000). Risk also varies between crop cultivar. For example, late-maturing cultivars are exposed to slug pressure for a longer period, and often suffer increased damage, whereas early varieties escape severe injury through earlier harvest (Gould, 1965; Kozłowski et al., 2019). In some cases, the risk continues post-harvest, as slugs carried in soil clods into storage facilities can continue feeding on wounded tubers during the first few weeks in store (Ester and Trul, 2000).

Overall, the period of greatest potato risk aligns with late summer and early autumn, particularly in moist years, with damage severity shaped by slug species behaviour, environmental conditions, cultivar maturity, crop rotations, and the timing of harvest (Keiser et al., 2012; Howlett, 2012).

3.4.2. Overview of current thresholds

Treatment thresholds for slugs in potato crops are based on both population-density assessments and predicted risk factors (Ramsden et al., 2017). Thresholds for treatment are typically determined with surface refuge traps. For potatoes, the accepted damage-risk threshold is an average of one or more slugs per trap (using the standard nine-trap "W" pattern, or 13 traps in fields $>$ 20 ha) when soil is moist and

temperatures are 5–25 °C. This low numeric trigger reflects the crop's very limited tolerance for feeding damage. Field studies have confirmed that when catches reach or exceed this level, particularly under moist and mild conditions, early molluscicide application is beneficial in reducing tuber damage (Keiser et al., 2012). However, the distribution of slugs is often patchy but spatio-temporally stable (Forbes et al., 2021); mapping these hot-spots with the refuge-trap network allows pellets to be targeted where they are most needed, cutting chemical use without sacrificing control. Sampling should still be carried out before planting and repeated just ahead of tuber bulking, especially if environmental conditions remain favourable for slug activity.

3.4.3. Predictive models to estimate crop risk

Predictive models for estimating the risk of slug damage to potato crops often incorporate environmental, management, and biological factors influencing slug populations, particularly those influencing *D. reticulatum*. These models still primarily utilise meteorological data, especially soil moisture and air/soil temperature, as these parameters strongly affect slug survival, reproduction, and activity. Initial forecasting models developed by Young et al. (1991, 1993) identified foundational relationships between slug activity and accessible meteorological data, highlighting soil moisture as a key predictor. Subsequent models built on these insights by incorporating aspects of slug life-history, population growth, and spatial dynamics, while also accounting for temporal trends and forecasting impacts under future climate scenarios (Choi et al., 2006; Shirley et al., 2001; Willis et al., 2006). More recently, Puliga et al. (2024) introduced a comprehensive Slug Risk Index that layers site characteristics (soil texture, topography), management practices (cultivation system, crop), and weather to map slug presence and damage potential at 10 m resolution.

3.4.4. Proposed areas for future development

One aspect that could be better considered in risk models is spatial variation in slug density and the impact of meteorological factors on spatial-temporal risk. This is important as while variation can be significant within a field, patches are temporally stable (Forbes et al., 2021) but can be disrupted by extreme meteorological events (Price et al., 2024). Better accounting for these factors when estimating risk would support the development of more practical decision support systems, potentially contributing towards IPM approaches that blend agronomic tactics, weather-based action thresholds, and targeted molluscicide application.

4. Minor pests

4.1. Free-living plant parasitic nematodes

There are three main groups of free-living plant parasitic nematodes that affect potato production and yield.

Stubby-root nematodes feed on root surfaces and tips and vector tobacco rattle virus (causing spraing). Several species are of concern to UK potato production, including *Trichodorus primitivus, T. similis, Paratrichodorus pachydermus*. Feeding damage causes truncated, "stubby" root systems that restrict water and nutrient uptake, leading to uneven crop emergence and reduced vigour. The threshold for economic injury is approximately 100 individuals per 250 g of dry soil (Dale and Neilson, 2006), although crop risk increases if the nematode population is viruliferous for tobacco rattle virus, in which case immediate action is recommended. Very few tools are available to support stubby-root nematode management, although advances in molecular technology have led to the development of rapid diagnostic tests (Lawaju et al., 2023; Huang et al., 2018). In North America, a degree-day model has been developed to guide nematicide applications by estimating nematode population growth (Schneider and Ferris, 1987). However, this model has not been validated under UK climatic conditions, limiting its direct applicability due to differences in temperature profiles and growing seasons.

Needle nematodes, *Longidorus sp.* feed externally on potato roots, primarily at the root tips. In potatoes they primarily cause feeding damage, and while they also vector tomato black ring virus this is not thought to be of economic concern in the UK. In most plants, needle nematode feeding damage constricts root development (Palomares-Rius et al., 2017) and results in the formation of galls at root tips, further arresting root growth. The current threshold is 25 individuals per 250 g soil (Dale and Neilson, 2006). No predictive or decision-support models are currently available for this group of nematodes.

Root-lesion nematodes are migratory endoparasites of plant roots. The main species of concern in the UK are *Pratylenchus penetrans*, *P. neglectus*, and *P. scribneri* (Orlando et al., 2020). Feeding and migration of the nematode within roots damages root cells, creating lesions and necrotic spots (Zunke, 1990). This ultimately reduces root growth and limits the uptake of water and minerals, resulting in slow canopy development and early haulm senescence. The feeding damage caused by these nematodes also facilitates secondary infections by pathogens such as *Verticillium dahliae*, with co-infected plants suffering from potato early dying complex (LaMondia, 2006). Additive effects have also been observed for the fungal pathogen *Rhizoctonia solani,* with tuber mass lower for plants co-infected with root-lesion nematodes and *R. solani* (Viketoft et al., 2020). The main threshold used for *Pratylenchus* is 100 to 200 nematodes present in 100 cm^3 of soil (Dale and Neilson, 2006; Holgado et al., 2009). In fields with a history of *V. dahliae* infection, *Pratylenchus* thresholds are more stringent due to the risk of potato early dying complex. No predictive or decision-support models are currently available for this group of nematodes.

While established thresholds provide valuable guidance for managing free-living nematodes, the current reliance on static population densities, particularly in the absence of comprehensive predictive models, presents significant limitations. As highlighted, the interactive effects with viruses and other pathogens (e.g., *Verticillium dahliae*) further complicate direct feeding damage assessments and underscores the dynamic nature of these pest-crop interactions. Furthermore, free-living nematodes are highly susceptible to unfavourable environmental conditions that threaten their survival, making yield losses through direct feeding on potato roots and the associated costs to the UK potato industry difficult to accurately estimate. Moving forward, a deeper understanding and quantification of these environmental factors, alongside the development and validation of robust predictive models that incorporate both nematode density and pathogenicity, are critical. Such advancements would not only refine damage estimations and associated costs to the UK potato industry but also enable more precise and economically sound nematode management.

4.2. Cutworms

Cutworms are the soil-dwelling larvae of several *Agrotis* species (noctuid moths) that damage a range of root crops, including potatoes (Esbjerg and Sigsgaard, 2014). Females oviposit singly or in small clusters near host plants or on the soil (Alyokhin et al., 2022; Joshi and Solanki, 2020). The main risk to the crop occurs when the activity of early-stage larvae overlaps with the tuber initiation period. These first- and second-instar larvae feed on the stems near the soil surface at night, and burrow into the soil to feed on the plant roots during the day. Damage to potato crops is primarily caused by larvae feeding on young tubers during tuber initiation, this affects yield quality and can result in downgrading.

Cutworms usually go through one or two generations each year (Bowden et al., 1983; Esbjerg and Sigsgaard, 2014). Moth flights, which indicate adult emergence and reproductive activity, occur from May through October, varying by species. Time of flight, period insect activity, and probability of a second generation are also influenced by environmental conditions, including winter temperature and summer precipitation (Esbjerg and Sigsgaard, 2014; Bowden et al., 1983), and

several species are shifting to earlier timings of first flight in response to a changing climate (Esbjerg and Sigsgaard, 2014). Occurrence of a second generation is increasing under climate change, however the larvae of this second generation often fail to overwinter leading to lower overall cutworm risk in the following year (Esbjerg and Sigsgaard, 2014).

There are no validated thresholds for cutworm management in potatoes, although some agronomists assess the soil surface for larvae activity and use larvae presence to inform management strategies. Despite the lack of economic injury thresholds, models that estimate crop risk have been developed (Bowden et al., 1983). The Cutworm Risk Model predicts adult flight following the accumulation of 340 day-degrees above a 7 °C baseline, starting on January 1st (Bowden et al., 1983). From this first flight, the model accumulates day-degrees above 10 °C to forecast egg hatch, then tracks a 20-day "vulnerability window" during which early-instar larvae remain on the ridge surface. A single rainfall or irrigation event delivering $\geq$ 10 mm in 24 h within that window is assumed to cause $>$ 90% larval mortality, effectively resetting the risk (Bowden et al., 1983). Conversely, a prolonged hot, dry spell is predicted to increase cutworm survival, triggering warnings for potato growers.

Effective cutworm management in UK potatoes relies on understanding their life cycle and using the Cutworm Risk Model to estimate adult migration, larvae activity, and crop risk (Bowden et al., 1983). While formal thresholds are lacking, the weather-based Cutworm Risk Model offers a vital tool. This model helps growers anticipate pest activity and vulnerability, moving beyond simple observations to enable precise, timely interventions. This targeted approach not only reduces crop damage but also promotes sustainable pest control by minimizing unnecessary treatments. Ongoing model refinement and collaboration between researchers and growers will be crucial for optimizing cutworm control and protecting potato yields. Particularly as curtworm phenology is highly sensitive to meteorological variation, making accurate risk estimation challenging (Esbjerg and Sigsgaard, 2014).

5. Conclusion

Current UK pest management thresholds are largely anecdotal and were established before the introduction of modern cultivars, contemporary pesticide regulations and recent climate pressures. They tend to treat the crop as a homogeneous system, implicitly assuming uniform tolerance to injury across sites and varieties. A physiology-explicit perspective demonstrates that this assumption is no longer valid: injury sustained during tuber initiation (sink formation) and during tuber bulking (source limitation) imposes markedly different yield penalties, and determinate and indeterminate cultivars exhibit contrasting capacities for compensatory growth. Plant phenological models that can estimate plant developmental phases (Divya et al., 2020; Streck et al., 2007), particularly those that can estimate tuber initiation and tuber bulking, could be better integrated into more holistic crop protection and production strategies and used to guide pest and disease monitoring surveys.

To improve decision making, future crop models should incorporate reducing factors—notably insect and nematode pests and the pathogens they vector—alongside potential yield (Haverkort and Struik, 2015). The reliability of any threshold derived from such models will depend on three quantified components for each pest–crop pairing.

1. Magnitude of injury: the proportion of a clearly defined crop attribute that the pest, virus, or pathogen removes or disables (e.g. stolons destroyed, canopy area consumed).
2. Physiological tolerance limit: the minimum value of that attribute below which measurable reductions in yield or quality occur.
3. Yield-loss function: the quantitative relationship between further reductions in the attribute and the consequent loss of marketable yield or quality.

Once these parameters are established, existing phenology and risk-forecast models for aphids, potato-cyst nematodes, wireworms, slugs, and cutworms can be integrated with cultivar traits and growth-stage information. Such integration will enable decision-support systems that recommend intervention only when pest pressure is predicted to exceed the crop's physiological tolerance, thereby supporting profitable and environmentally sustainable potato production.

It is important to place any new thresholds within the wider complexities of the agricultural production sector. Thresholds should, ideally, be developed under field conditions over several seasons in regions that represent the key potato production areas. These developments should also be considered within a more holistic framework that incorporates other aspects of crop production and crop protection. For example, in addition to invertebrate pests and the viruses they vector, crops are also exposed to a range of additional biotic (weeds; fungal, oomycete, and bacterial pathogens; vertebrate pests) and abiotic (environmental stress, nutrient availability) factors that influence crop production and yield. Developing thresholds and management practices that also account for multiple/co-stressors would result in more robust, dynamic, and deployable thresholds.

CRediT authorship contribution statement

Nasamu Musa: Writing – original draft, Visualization, Investigation, Funding acquisition, Conceptualization. **Josh Humphrey:** Investigation. **Tamara Fitters:** Investigation. **Steve Ellis:** Investigation. **Thomas Fleming:** Investigation. **Daniel J. Leybourne:** Writing – review & editing, Visualization, Investigation, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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