

Seasonal Incidence of Fall Armyworm on Maize and Its Relationship With Weather Parameters

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ABSTRACT

Fall armyworm, *Spodoptera frugiperda*, has become one of the most closely watched pests of maize in Africa and Asia, and a large body of local work reports how its numbers rise and fall through the cropping year in relation to temperature, rainfall and humidity. This narrative review asks what that literature can and cannot tell a grower or adviser who wants to anticipate the pest. It draws on published work on the biology, migration and natural enemies of the insect, on how weather shapes its development and flight, and on the methods used to monitor it, and it reports no new data. The reviewed studies agree on a broad picture: warm conditions speed development, rainfall and humidity act in mixed and local ways, and incidence tends to follow the crop stage and the arrival of moths. The correlations between weather and pest counts, however, are site-specific and often change sign between seasons. Trap types and scouting rules differ, so counts are not directly comparable, and planting date, crop stage and natural enemies are tangled with weather in most field series. The review concludes that weather is best treated as one modifier of a seasonal pattern that is driven by crop phenology and immigration, and it sets out the design and reporting features that would let future seasonal studies be compared and combined.

Keywords: *Spodoptera frugiperda*; Fall armyworm; Maize; Seasonal incidence; Weather parameters; Pheromone traps; Narrative review

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1. Introduction

Few insects have crossed continents as quickly as the fall armyworm, *Spodoptera frugiperda*. A native of the tropical and subtropical Americas, it was reported in West and Central Africa in 2016 [1], and within a short time it had been found across much of the African maize belt [2, 3] and in South and East Asia [4, 5]. For farmers who grow maize on small plots, the pest arrived as a surprise and often as a crisis, and the first question that extension workers heard was a practical one:

when does it come, and when is it worst?

The obvious place to look for an answer is the weather. Insects are cold-blooded, their development rate follows temperature [6], and seasonal swings in numbers are among the oldest observations in entomology [7]. It is hardly surprising, then, that a long list of local studies has set weekly counts of moths, egg masses or damaged plants against temperature, rainfall and humidity and reported correlations. Some find that warmth and moderate rain go with higher

incidence; others find the reverse, or nothing at all.

This review asks why the picture is so mixed and how much of it a practitioner can use. A weather correlation is easy to compute and easy to over-read. It depends on how the insects were counted, on when the maize was sown, on how many moths flew in from somewhere else and on how many larvae were eaten before anyone looked. We set out what is known about the biology of the pest and the effect of weather on it, describe how seasonal records are produced, and then consider what the published correlations can and cannot tell us. The aim is a fair account of what the field series show and what they only appear to show.

The article is a narrative review. It draws on published work on the biology, migration and natural enemies of the fall armyworm, on methods of monitoring, and on the statistical problems of linking counts to weather, and it deliberately reports no new data. We have avoided quoting correlation coefficients from individual studies because their meaning depends on site and method, and because we could not check each of them against its primary source for this article.

2. Literature Review

2.1 The Insect and Its Spread

The fall armyworm is a noctuid moth whose larvae feed on a wide range of plants, with maize among the most heavily used [8]. Its history in the Americas is long, and the older literature, much of it from the southern United States and Latin America, still supplies the basic account of its life cycle and of its behaviour in the field [9, 10]. The African and Asian invasions then added a new set of environments, farming systems and monitoring habits, and a fresh body of local reports [1, 11].

Forecasts of the global extent of invasion, made as the pest spread, drew on climate suitability and suggested that large parts of the tropics and subtropics were open to it [4]. Such models are useful for outlining where the pest can live, but they say little about when it will be abundant at a given farm in a given month. Later syntheses bring together what is known of its invasiveness, biology, ecology and management and make the same point from the other side, namely that local seasonal dynamics are still described by a patchwork of regional studies [12, 13].

Another feature complicates the picture. The species is not a single uniform population. Genetic work has distinguished strains that differ in host

use and has used molecular markers to follow movement between regions [14], and molecular tools have also been used to confirm the identity of the pest during the early African invasion [15]. For a seasonal study the practical consequence is modest but real: the insects counted in different places may not be quite the same population, and the pest identified in a trap is only as reliable as the identification behind it.

2.2 Life Cycle and Seasonal Habit

The life cycle is easy to describe in outline. Females lay eggs in masses on leaves, the larvae pass through several stages while feeding, the full-grown larva pupates in the soil, and the moth emerges to mate and lay again [9]. Moths fly at night and can travel long distances in a single season. Because the species has no resting stage that carries it through cold weather, it survives winter only where winters are mild and must recolonise cooler regions each year by flying in [9, 16]. Figure 1 sketches how the stages of the pest typically follow the stages of a maize crop.

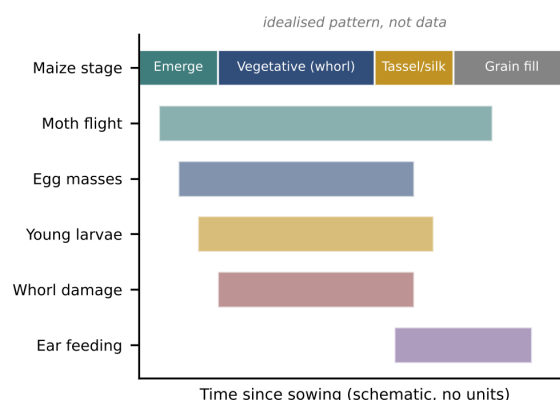


Figure 1. Idealised timeline of one maize season and the pest stages that usually follow it (schematic, not data).

The same habit is visible in the American records. Studies of early-season phenology in the southern United States describe a population that builds up first in the warmest regions and spreads outward as the season advances [17, 18]. In maize, young larvae feed in the whorl, and the damage later shifts towards the tassel and ear, so the same pest produces different kinds of injury at different crop stages [9, 19]. Counting larvae or damage on a given date therefore measures a mixture of how many insects are present and how far the maize has grown.

2.3 Weather and Development

The best-supported links between weather and the insect come from controlled studies of development. Work at constant and varying temperatures shows that the rate of development

of eggs, larvae and pupae changes with temperature, that survival falls at the extremes, and that the effect differs between the stages [20, 21]. These are the results on which degree-day and risk-zone models are built, including attempts to divide a single state into zones of differing risk for maize [22]. Temperature is, in short, the variable for which a mechanism is well documented.

Even here the step from laboratory to field is less direct than it looks. A leaf in a maize whorl is not at air temperature, development in the laboratory is measured on a standard diet, and field temperature varies from hour to hour. Broader work on climate and crop pests suggests that warming will change pest pressure in uneven ways [23], and models of future suitability for this species point in more than one direction depending on region and scenario [24]. Table 1 lists the weather variables most often related to the pest and the way each link is usually read.

Table 1. Weather variables commonly related to fall armyworm incidence and how the link is usually read.

Variable	Usual biological route	Typical reading in field series
Temperature	Speeds development and flight; extremes limit survival [20, 21]	Warm spells linked with rising counts, hot spells with declines [22, 23]
Rainfall	Washes eggs and young larvae; softens soil for pupation [9, 19]	Mixed; direction differs between sites and seasons
Relative humidity	Affects egg hatch, moth activity and disease [9, 10]	Weakly and inconsistently related
Wind	Carries moths between regions [25, 26]	Explains arrival rather than local build-up
Sunshine and cloud	Moth flight and mating behaviour [40]	Rarely analysed

Note: Qualitative summary of directions discussed in the cited literature; no coefficients are given because they are specific to site, season and method.

Rainfall and humidity are less well understood. Heavy rain is often suggested to dislodge eggs and young larvae from the plant and to affect pupation in soil, and humidity is said to influence hatching and moth activity [9, 10], but these mechanisms are tested far less often than the temperature response. Rainfall also changes the crop itself, since water supply affects the growth and succulence of maize, so a rain effect on the pest can run through the plant and through the insect at once [19]. A correlation with rainfall can thus reflect several different processes. Small differences of this kind are easy to dismiss in a single week and hard to ignore across a whole

season.

2.4 Migration and Local Build-up

Moths are strong fliers, and migration is central to the seasonal behaviour of the pest. Modelling work on North America has reproduced the northward seasonal movement of moths from source areas, driven by winds as well as temperature [25]. Studies of insect migration in general stress that such movement is organised by the atmosphere and not by conditions at the destination [26]. In eastern China, trajectory analysis has been used to forecast likely routes of the invading pest [5, 27].

This matters for the interpretation of any weather correlation. If the first wave of moths reaches a field because of a wind event several hundred kilometres away, the arrival date has nothing to do with the temperature or rain at the field itself. Local weather then acts on a population whose starting size was set elsewhere. A study that records counts at one site and correlates them with the weather at the same site is, in effect, correlating the consequences of a distant event with local conditions that happened to coincide with it [25, 27]. A population that has only just arrived behaves differently from one that has been building for several generations.

2.5 Natural Enemies and Management Influences

A third influence is biological control. Surveys have documented a range of parasitoids and predators attacking the pest in its native range [28, 29] and, within a few years of invasion, in Africa and Asia [30, 31, 32]. Parasitism and predation usually rise as host numbers rise, so natural mortality is itself seasonal, and a count of larvae at any date is the number that survived the enemies up to that date.

Farm management adds to the pattern. Farmers spray, they intercrop, they adopt companion-plant systems such as push-pull, and they sow at times that suit their rains and their labour [33, 34, 35]. Surveys of farmers show that practices and perceptions differ widely between regions and households [36, 37], and tests of insecticides and botanicals show that treatments can reduce larval numbers whatever the weather has been doing [38]. The seasonal record from a farmer's field is therefore a record of the pest after management, and the effect of that management is rarely written down.

Host-plant resistance is a further route to lower incidence, and breeding programmes aim to reduce the damage a given number of larvae can cause [39]. None of these influences is weather,

but all of them can vary through a season in step with weather, and that is what makes the separation of causes so difficult.

2.6 Monitoring Methods

Seasonal incidence is not observed directly. It is inferred from something that people count. Pheromone traps catch male moths and are widely used to detect arrival and to follow flight activity [40], though lure source and trap design have been shown to matter for how many moths are caught [41]. Plant scouting records the share of plants with fresh damage, and the practical methods differ in how plants are chosen and what counts as damage [36, 42]. Table 2 sets out these methods and the main reasons their counts differ.

Table 2. Monitoring methods that feed seasonal pest series and their main sources of difference.

Method	What it records	Why counts differ
Pheromone trap	Adult males captured per night or week [40, 41]	Lure source, trap design, height, spacing
Plant scouting	Share of plants with fresh damage [36, 42]	Plant stage, rule for counting, observer
Egg-mass counts	Egg masses per plant or per row	Laborious; hatching hidden under leaves
Larvae per plant	Larvae found in whorls or ears	Cannibalism, search effort, time of day
Light trap	Adults of both sexes and many species	Moon phase, lamp type, site

Note: The last column gives the authors' reading of what makes counts from different methods hard to compare.

Counts are ultimately used to decide whether to act, which is why the concept of an economic threshold has dominated pest management [43]. A recent review of crop impacts and action thresholds for this pest concludes that guidance varies and that the thresholds in use are not all grounded in the same kind of evidence [13]. If the thresholds themselves rest on different counting rules, the same incidence figure can trigger action in one place and not in another.

3. Materials and Methods

3.1 Scope and Question

The review asks a single question in two parts: what do published field studies suggest about the seasonal pattern of fall armyworm on maize, and how far can the reported relationships with temperature, rainfall, humidity and other weather parameters be relied on? We divided the question into the matters a reader would need to judge any one study: how incidence was measured, over what period and in how many seasons, how weather was recorded, how the two were related

statistically, and what else changed through the season. None of these steps is difficult, but each one is easy to leave out when a season is busy.

3.2 Literature Assembly

The review draws on peer-reviewed work in four areas: the biology and migration of the pest; the effect of temperature and other weather variables on its development; natural enemies and management; and methods of monitoring and of analysing seasonal counts. Sources were chosen for relevance, citation in the field and the clarity of their methods. Studies from the Americas, Africa, Asia and Europe-based syntheses are all used, since the seasonal logic of the insect is shared even where farming systems differ.

We did not run a formal systematic search and we do not claim one. This is a narrative synthesis, and the choice of sources reflects the authors' judgement. The practical consequence is that the review is a better guide to what a good seasonal study should contain than to the exact strength of any reported correlation, and it avoids quoting figures from individual studies that could not be checked against the primary papers for this article.

3.3 Appraisal Framework

To judge how far a weather-pest report can be trusted, we used a short framework with four questions. Was the pest measured by a method that is described well enough to be repeated [41, 42]? Were crop stage and planting date recorded, so that the pest could be separated from the plant on which it was counted [19, 42]? Were natural enemies, spraying and moth immigration recorded or at least discussed [25, 32]? And was the statistical treatment suited to repeated counts, with attention to correlated predictors [44, 45]? These questions guide the discussion of results that follows.

4. Results

4.1 The Broad Seasonal Picture

Across regions and decades, the reports share a loose pattern. The pest appears when the crop is young and the weather is warm, grows in numbers through the vegetative stage, and is followed by ear damage as the maize matures [9, 11]. Where maize is grown in more than one season in a year, there may be more than one peak, and where the crop is grown continuously the pest may be present throughout [17, 18]. That much is reasonably consistent and fits the biology.

What is not consistent is the detailed timing, the height of the peak and the weather conditions said

to go with it. In some regions incidence is reported to be highest in the warm dry months, in others during the rains, and a given site may change from one year to the next [11, 42]. Since the cropping calendar itself follows the rains, the crop and the weather are bound together in most seasonal records, and this alone makes the interpretation difficult. Reviews of this sort are more useful when they say where the evidence stops than when they smooth the gaps over.

4.2 Weather Parameters One by One

Our reading of how well each link is supported is summarised in Figure 2. Temperature has the best mechanistic support in the laboratory [20, 21], and field series often show a positive association with warmth up to a point, though the direction in hot spells is less clear [22, 23]. Moth movement is closely tied to wind, which is a matter of regional atmosphere more than of local conditions [25, 26].

For rainfall, humidity and other variables, the picture is looser. Reports of positive, negative and null associations sit side by side in the literature, and most studies look at a handful of seasons at one or a few sites. Rainfall is reported more often than any other weather variable besides temperature, and the lack of a stable sign is the main reason that no single rule of thumb has emerged. For humidity, sunshine and cloud, there are too few direct tests for any general statement [9, 10].

	Lab and development	Field counts	Moth movement
Temperature	better supported	mixed	thin
Rainfall	thin	mixed	thin
Humidity	thin	thin	thin
Wind	little studied	thin	better supported

authors' qualitative reading of the cited literature; not data

Figure 2. Qualitative matrix of how well-supported each weather link is (schematic of the authors' reading, not data).

Another recurring feature is the use of lagged weather. Because insects take time to develop, a rise in egg masses today can follow a warm spell a week or two earlier, and some studies relate counts to weather from preceding weeks rather than to the same week. This is biologically sensible, but it adds a choice that the analyst makes, and different choices of lag can give

different answers with the same data [44]. A grower reading a weather-pest report really wants to know whether it will hold on the next farm and in the next year.

4.3 Why Correlations Do Not Travel

Several features of the evidence explain why a correlation found at one site often fails at another. The first is that temperature, humidity and rainfall move together through a season, so their separate effects cannot be pulled apart with a handful of weekly observations [45]. A coefficient for rainfall in a model that also includes temperature and humidity is partly a statement about the model. The second is that the crop and the pest both change through the season, so any trend in time will produce a correlation between them, whatever the cause [44].

The third is confounding with factors other than weather (Table 3). Planting date decides which crop stage coincides with which weather, and a field sown late will meet a different pest pressure to an early field at the same place and time [33, 42]. Natural enemies change with host density [31, 32]. Moths may arrive early or late for reasons unrelated to local weather [16, 25], and spraying removes larvae regardless of conditions [38]. When these are not recorded, they remain inside the unexplained variation and sometimes inside the coefficient for weather.

Table 3. Factors that can be confused with weather in a field series of fall armyworm.

Factor	How it can mimic or hide a weather effect	Remedy
Planting date	Crop stage and weather move together through the season [33, 42]	Stagger sowing dates; record stage
Natural enemies	Parasitism and predation rise with host density [31, 32]	Record enemies with pests
Immigration of moths	Arrival is set by wind far from the field [16, 25]	Record trap catches from the start
Insecticide use	Sprays remove larvae regardless of weather [38]	Keep plots unsprayed or log sprays
Autocorrelation	Weekly counts and weather both trend [44, 45]	Use methods suited to time series

Note: Confounders are those discussed in the cited literature; the remedy column is the authors' suggestion.

Figure 3 gathers these influences into one picture. A recorded count is the product of several layers, of which weather is one, and only a design that records the other layers can say how much of the observed pattern belongs to the weather layer. Most published series were not designed in that way, and that is no criticism of their authors, who

usually set out to describe a local situation and not to isolate causes. Read in this way, a weak correlation in a short series is not evidence that the weather does not matter.

4.4 Can Counts Be Compared?

A fourth difficulty is that counts from different studies measure different things. A pheromone trap catches males that have flown to a lure, and the number depends on the lure, the trap and its position [40, 41]. A plant survey records damaged plants, which depends on crop stage and on the rule for scoring injury [36, 42]. A study of egg masses or larvae tells us about the immature stages but only if the search is thorough. These are not interchangeable, and a statement such as incidence was highest in a given month means something different for each of them.

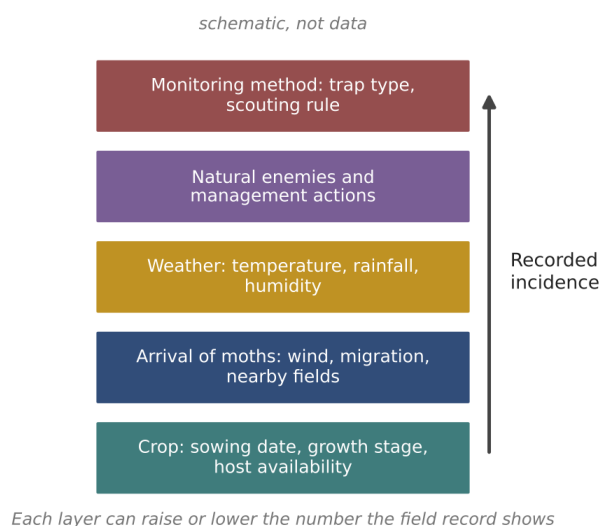


Figure 3. Layers that shape seasonal fall armyworm incidence on maize (schematic, not data).

There is also the issue of units. Some reports give catches per trap per night, others per week, others as percentages of plants, and thresholds for action are defined in whichever unit the local advice happens to use [13, 43]. Without a shared protocol, a meta-analysis of weather-pest correlations would combine estimates that do not refer to the same quantity, and a weighted average of them would have no clear meaning.

Short series are a related problem. A study that follows one or two seasons at one site records two draws from a distribution of seasons, and the correlation it finds can change with the next year's weather. Because weather in any single season is a combination of temperature, rain and humidity that may never recur exactly, a sign that holds in a short series may be a feature of that particular year [7, 44]. The point is not that a study is poor, only that its result travels less far than its abstract suggests.

4.5 Reading a Claim About Weather and the Pest

A reader meeting a statement that fall armyworm incidence is positively related to a weather variable can ask a short set of questions. How was the pest counted, and how often? How many seasons and sites does the series cover? Was crop stage recorded? Were natural enemies, sprays and moth catches from the start of the season noted [25, 32]? Was the relationship tested with a method that allowed for repeated measures and for correlated predictors [44, 45]? A report that answers all five is uncommon, and one that answers none is best read as a description of a season rather than as a rule.

Put plainly, the literature supports a cautious statement. Warm conditions favour development of the pest and the arrival of moths sets the start of the season, but the strength and sign of the link between local weather and recorded incidence differ from place to place and year to year. Weather is best treated as one modifier of a pattern set by the crop and by immigration, and a weather-based forecast built on a single local correlation should be used with care. That is a modest claim, but it is the one the literature will currently carry.

Longer-term projections raise the same caution on a larger scale. Models of climate suitability can show where the pest may become more or less able to persist [4, 24], but they rest on the same broad temperature relationships and say little about within-season timing at a given farm. The consequences of warming for pest pressure are likely to vary by region and crop calendar [6, 23].

5. Discussion

5.1 Interpretation and Practical Reading

The main finding of this review is a conditional one. Weather matters to the fall armyworm, and temperature in particular has a well-understood effect on its development, but the reported field correlations are not strong enough, consistent enough or comparable enough to be used as universal rules. A forecast that treats weather as the sole driver ignores the crop, the moths and the enemies, and may mislead in precisely the seasons when it is most needed. Nothing in this reading argues against using weather in forecasts; it argues for using it alongside the crop and the moths.

The practical consequence is that monitoring should come first and weather second. A grower who knows the crop stage, scouts regularly by a clear rule and watches the arrival of moths in

traps has more useful information than one who relies on a weather forecast alone. Weather information can still be valuable in sharpening expectations: warm spells can mean that larvae mature faster, so a scouting visit may be needed sooner, and long cold or dry periods can alter the pace at which damage builds [20, 21].

A third point concerns advice. Broad statements, such as the pest is worst in the rains or in the dry season, travel badly because they hide differences in sowing dates and in crop stage. More useful advice is tied to the stage of the crop and to what the traps show, with weather as a modifier. Management options, from push-pull to well-chosen insecticides, work at particular crop stages and are best timed by what is found in the field and not by a calendar [33, 35, 38]. These cautions apply with equal force to other migratory pests, not only to this one.

Regional contrast offers a useful test of the argument. Reports from India, from eastern and southern Africa and from China describe the same insect on the same crop, yet the timing of peaks differs with the cropping calendar, the rains and the route by which moths arrive [5, 11, 42]. That the pattern changes with place is exactly what a crop-and-migration reading would predict, and it is harder to reconcile with a single weather rule applied everywhere.

Three findings would change this reading. A multi-year, multi-site series using a common trap and scouting protocol, with sowing dates staggered and enemies recorded, that showed a stable relationship between a weather variable and incidence would justify a weather-driven forecast for those conditions. Evidence that a specific mechanism, such as rain washing away young larvae, accounts for a large share of seasonal decline would move the focus to that process. And a showing that moth arrival, not local weather, explains most of the start-of-season variation would put regional migration forecasts ahead of local weather models [25, 27].

5.2 Limitations

This is a narrative review and shares the limitations of that form. The selection of sources reflects judgement, no formal search or quality scoring was done, and the review does not quote numerical results from individual studies, because these could not be checked against the primary reports for this article. A reader who needs the strength of a particular correlation should consult the original study, applying the appraisal questions above, or wait for a formal systematic

review, which would need a common protocol for monitoring to be meaningful [12, 13].

Much of the biology in the review comes from the Americas and from laboratory work, and the field evidence from Africa and Asia is more recent and more variable in quality. The older literature describes populations and cropping systems that differ from those now affected, and the conclusions should be read in that light. It is a habit worth keeping even when the answer seems obvious.

5.3 Implications for Study Design

A study that could settle the question would record incidence by a clearly described method, with a standard trap and lure and a fixed scouting rule, at several sites and over several seasons [41, 42]. It would stagger sowing dates so that crop stage and weather can be separated, record natural enemies and sprays, and note the date and size of the first moth catches [32, 33]. It would log weather at the field and not only at a distant station, and analyse the data with methods that treat repeated counts properly and examine collinearity before drawing conclusions [44, 45].

Reporting matters as much as design. Authors can state the unit of every count, publish the raw weekly values and weather, describe the crop stage at each date and say how the pest was identified [15]. With such records, results from different places could be compared and, in time, combined, which would turn a set of local anecdotes into a body of evidence. These requirements are demanding, but they are the ones that separate a rule a farmer can rely on from one that only fits the season in which it was found.

5.4 Directions for Future Work

Three needs stand out. First, a shared minimum protocol for monitoring the pest on maize, covering the lure, trap, scouting rule and units, adopted across regions [13, 40]. Second, multi-site, multi-year series designed to separate weather from crop stage, planting date, natural enemies and immigration. Third, links between regional migration forecasts and local scouting, so that the arrival of moths and the weather on the farm are treated together instead of separately [12, 25, 27].

6. Conclusion

Fall armyworm incidence on maize follows a recognisable seasonal course, shaped by the crop, the arrival of moths and the weather, with temperature the best-understood influence on development. The published correlations between

weather parameters and recorded counts, however, are site-specific, depend on how the pest was counted and are tangled with planting date and natural enemies. They should not be turned into general rules without checking the conditions under which they were found.

For the practitioner the message is practical. Scout by a clear rule, record the crop stage and use weather to adjust the timing of attention, not to replace it. For the researcher the opportunity is a set of comparable, multi-season series with the other drivers recorded, which would let the weather layer be measured instead of guessed.

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9. Conflict of Interest

The authors declare no conflict of interest.

10. Author Contributions

J.B. conceived the review and wrote the sections on biology, migration and monitoring. A.G. wrote the sections on weather, natural enemies and field management. G.M. wrote the sections on analysis and study design. All authors revised the manuscript and approved the final version.

11. Ethics Statement

This is a review of published literature. No animals or human participants were involved and no ethical approval was required.

12. Data Availability

No new data were generated. All sources are cited in the reference list.

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