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The Sentinel Crop Pressure Index (SCPI): A Conceptual Framework for Ecosystem-Level Pest Surveillance in Sri Lankan Fruit Systems

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Abstract
Monitoring pest populations in fruit production systems remains challenging because pest activity is influenced by multiple host crops, environmental conditions, and landscape characteristics. Conventional surveillance methods, such as trap catches and crop-specific infestation assessments, provide valuable information but often capture only part of the broader ecological picture. This paper proposes the Sentinel Crop Pressure Index (SCPI), a conceptual framework for assessing pest pressure at the ecosystem level in Sri Lankan fruit-growing regions. The framework is based on the idea that selected fruit crops can serve as sentinel crops whose responses reflect wider pest activity across agricultural landscapes. To support this concept, SCPI combines information from sentinel crop responses, pest surveillance, environmental suitability, host availability, and remote sensing observations into a single integrated indicator. By bringing together these complementary sources of information, the framework offers a broader perspective on pest risk than approaches based solely on traps or damage observations. An illustrative example is presented to demonstrate the structure and interpretation of the index. While the framework requires future validation using field data, it provides a foundation for ecosystem-oriented pest surveillance, risk assessment, and the development of data-driven early warning systems for sustainable fruit production in Sri Lanka.

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1. Introduction

Fruits play a key role within the overall Sri Lankan agriculture industry. A large variety of tropical and subtropical fruits are grown within Sri Lanka including bananas, mangos, papayas, pineapples, rambutans, avocados, citrus fruits and guavas. Fresh and processed fruit products allow for trade across international markets and therefore provide economic benefits to farmers, harvesters, processors and exporters. The fruit and vegetable industry is seen as an area in which export growth could be increased, particularly with value added products [22]. Therefore, any factors which may cause reduced yields or quality in fruits (such as pest damage) can have a severe effect on economic gains within both the fruit producing sector and agriculture as a whole.

Due to their broad host ranges and generalist feeding habits, fruit flies and other polyphagous pests pose significant threats to tropical fruit production in Sri Lanka [1, 2]. Mixed cropping of various fruits, including mango, guava, papaya, citrus, banana and others, occurs commonly in farming systems throughout Sri Lanka. Therefore, fruit pest populations are seldom specific to one crop-type. Fluctuations in the availability of host species, environmental factors, and landscape characteristics, result in complex pest pressure dynamics across multiple crops [1, 2, 4].

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tropical fruit production in Sri Lanka [1, 2]. Mixed cropping of various fruits, including mango, guava, papaya, citrus, banana and others, occurs commonly in farming systems throughout Sri Lanka. Therefore, fruit pest populations are seldom specific to one crop-type. Fluctuations in the availability of host species, environmental factors, and landscape characteristics, result in complex pest pressure dynamics across multiple crops [1, 2, 4].

Recent advances in precision agriculture, environmental and remote sensing technologies allow for larger scale monitoring in agricultural systems. Data can be collected over large production areas using satellite imaging; Unmanned Aerial Vehicles; environmental sensors and sophisticated analytical techniques [3, 5, 13-16]. However, monitoring efforts often focus on a single parameter (pest population, cropping status or environmental factors) and do not allow for an overall understanding of pest pressure within an ecosystem [3, 5].

Sentinel species are widely used in ecological and environmental studies as indicators of environmental conditions [7-10]. Biological responses within sentinel species often indicate changes within an ecosystem earlier than direct measurements. Therefore, it is suggested that, within agricultural systems, certain fruit species may act as sentinel species. This would allow information to be obtained regarding pest pressure over a larger agricultural landscape, in comparison to that obtained in individual crops [6-10].

In this paper, a new conceptual framework to monitor pest pressure in tropical fruit ecosystems in Sri Lanka has been developed using a Sentinel Crop Pressure Index (SCPI). Selected fruit crops are considered as biological sensors. Responses within the selected sentinel crops can be correlated to pest monitoring data, environmental suitability, host availability and remote sensing data. By integrating information from multiple sources, this framework aims to provide a more comprehensive measure of pest pressure within an ecosystem, compared to measures taken from trapping data or infestation levels in individual crops [8-12].

While a functional validated index is not presented in this study, this work provides the concept of an integrated framework to include biological, environmental and technical data to provide an overall pest pressure estimate within an ecosystem. This supports further research into pest monitoring, risk assessment and early warning systems to allow for sustainable fruit production in Sri Lanka.

2. Theoretical Foundation

Pest monitoring in agricultural systems can be achieved through observing pest catches, host plant damage and levels of infestation. However, this monitoring information is often specific to particular crops. In multi-host fruit production systems, pests move among different host plants and respond to changes in environmental conditions, seasonal patterns, and resource availability. Therefore, monitoring data collected from individual crops may not give a representative picture of overall pest pressure within the wider agricultural environment [1, 2, 4]. In ecology, sentinel species are widely used as early indicators of environmental disturbance. Bioindicators and sentinel species are frequently utilized to provide an indication of the status of ecological environments and associated risks, as their response to environmental changes incorporate multiple complex environmental factors [7-10]. Within agricultural systems, ‘sentinel crops’ can be used as early indicators of pest pressure. Sentinel crops provide information on pest pressure within the wider agricultural environment, using biological/pest infestation responses in the crop. Therefore, sentinel crops act as indicators of pest pressure in the wider landscape, rather than within individual crops [6-10].

Infestation and pest pressure in agricultural systems must be differentiated. Infestation indicates the extent of damage caused by pests to a particular insect host within the crop. Pest pressure in agricultural ecosystems indicates the potential for pest establishment, reproduction, movement and spread within a defined area. Host availability, suitable environmental conditions, pest population levels and landscape connectivity all influence pest pressure within an agricultural area. Therefore, high levels of infestation within one crop do not necessarily equate to high pest pressure in the wider agricultural system. Likewise, low infestation levels in an agricultural area can occur even in conditions that make it likely for pest outbreaks to occur within that area in the future. Current monitoring techniques focus on single indicators of pest pressure, such as number of pests caught, infestation levels or environmental measurements. Therefore, these monitoring techniques may only give a limited representation of pest pressure. Ecological indicator theory suggests that complex systems are often better represented using multiple complementary observations rather than a single measurement, i.e. complex systems are best represented using multiple complementary observations [8, 9]. This theory is the basis of development of the Sentinel Crop Pressure Index (SCPI), which integrates multiple sources of information to create an indication of pest pressure at an agricultural ecosystem scale in fruit production systems in Sri Lanka.

3. Literature Review

Pest monitoring within agricultural systems is becoming more sophisticated with developments in remote sensing and Artificial Intelligence (AI). Traditional pest monitoring methods include visual assessments and trap monitoring. However, these methods typically provide only local data and so may not give enough information across wider agricultural systems. [1, 2, 4] Recently, with improvements in remote sensing and precision agriculture, data can be collected using satellite data, Unmanned Aerial Vehicles (UAVs), environmental sensors and vegetation indices. This allows for data to be obtained across large areas of agriculture, to inform data driven decision making. [13-16] In addition, AI has improved pest monitoring, identification and predictive analysis by combining a variety of data. However, many of these systems focus on monitoring pest pressure at crop level and predicting pest pressures for specific species and do not provide ecosystem level pest pressure. [3, 5, 13-15]

Within environmental science, it is common practice to use sentinel species within an environment, to give representative data of the conditions within an ecosystem. [7-10] Composite indices, such as the Air Quality Index and Water Quality Index have shown benefits in bringing together different variables into one understandable index to aid decision making. [11, 12] Therefore, there appears to be potential to develop pest monitoring systems focused on ecosystems.

Current pest monitoring systems consider pest pressure, pest damage, environmental suitability and sensor data as separate data sources. Few current pest monitoring systems combine sentinel crop data, pest data, environmental suitability, host availability and sensor data into one ecosystem level index. While significant progress has been made in precision

agriculture, ecological monitoring and integrated pest management, [13-20] there is little work bringing together pest pressure at an ecosystem level.

Despite recent developments in pest monitoring, precision farming, ecological monitoring and pest management strategies, current techniques consider these variables separately [3, 5, 13-20]. Although there has been progress in pest monitoring, precision farming, ecosystem monitoring and integrated pest management, current methodologies treat pest numbers, plant responses, climatic suitability and sensor information as separate data sets. To the authors' knowledge there is currently no conceptual framework in literature combining sentinel plant responses, pest monitoring, host availability, climatic suitability and remote sensing data to produce an ecosystem level summary measure of pest pressure in fruit growing systems. In this work we overcome this by developing the Sentinel Crop Pressure Index (SCPI).

4. Research Framework

The Sentinel Crop Pressure Index (SCPI) is proposed as an index to aid pest monitoring at an ecosystem scale in fruit production systems in Sri Lanka. It combines biological, environmental and technological data within one index, in order to overcome limitations associated with using just singular data sources such as trap data, crop infestation data or environmental data to represent pest pressures in the ecosystem. The overall objective of this framework is to produce a standardized measure of pest pressure at an ecosystem scale to aid monitoring, risk analysis and develop early warning systems in the future.

5. Framework Architecture of the Sentinel Crop Pressure Index (SCPI)

The Sentinel Crop Pressure Index (SCPI) combines biological, physical and technological data to provide an overall measure of pest pressure. As it is not possible to accurately characterize pest pressure in a complex agro-ecosystem using only one monitoring variable, multiple data sources must be combined. Trap catch data may be very high, but if conditions within the environment are unfavorable then this may not indicate a high risk. Equally, if conditions are favorable, this does not necessarily mean that pests are present and active. Therefore, multiple complimentary data sources must be used in order to assess pest pressure within an ecosystem.

The SCPI framework combines five key components

- **Sentinel Crop Response (S):** biological responses observed in selected sentinel fruit crops.
- **Pest Surveillance (T):** direct observations of pest abundance obtained through trapping and field monitoring.
- **Environmental Suitability (E):** environmental conditions that influence pest survival, reproduction, and dispersal.
- **Host Availability (H):** availability and distribution of suitable host plants within the landscape.
- **Remote Sensing (R):** landscape-scale observations derived from satellite, drone, or sensor-based monitoring.

The information flow within the framework is illustrated as follows:

Sentinel Crop Response + Pest Surveillance + Environmental Suitability + Host Availability + Remote Sensing → Data Standardization → Indicator Integration → SCPI → Ecosystem Pest Pressure Assessment

Combining information from different sources to form a single index is common in many fields such as ecological assessment and composite indicators [8, 11, 12]. In this work, the SCPI is not intended to replace individual monitoring techniques. It rather acts as a synthesis to combine different observations and produce one standardized measure of pest pressure at the ecosystem scale. Combining ecological, monitoring and sensor-based data allows the development of tools for risk assessment and early warning, which can support evidence-based pest management within Sri Lankan fruit production systems.

6. Mathematical Formulation of the Sentinel Crop Pressure Index (SCPI)

The Sentinel Crop Pressure Index (SCPI) provides an integrated measure of pest pressure within ecosystems. It combines data from biological, environmental and monitoring sources. Pest pressure is assumed to be the result of combined effects from pest population density, crop response, environmental parameters, host availability and landscape characteristics.

The SCPI is calculated as:

$$SCPI = \sum_{i=1}^{n} w_i x_i$$

where $x_i$represents a normalized indicator value and $w_i$represents its corresponding weighting factor, subject to:

$$\sum_{i=1}^{n} w_i = 1$$

Based on the proposed framework, the SCPI can be expressed as:

$$SCPI = w_1 S + w_2 T + w_3 E + w_4 H + w_5 R$$

where:

- S = Sentinel Crop Response
- T = Pest Surveillance
- E = Environmental Suitability
- H = Host Availability
- R = Remote Sensing Indicator

The weighting factors represent the relative contribution of each information source and may be determined using expert knowledge, statistical approaches, or machine-learning methods.

Equal weights have been applied within this study as this framework is conceptual and as such has not been validated with empirical data. Choosing equal weights prevents any subjective assumptions about the relative importance of each component. In practice different weighting schemes may be used in future applications of SCPI. If expert knowledge is available, expert-based methods such as the Delphi method or Analytical Hierarchy Process (AHP) can be implemented. When data is available, data driven methods such as statistical optimization or machine learning can be used to derive weights based on field data and previous pest data sources. Methods used to determine weights should therefore

depend on data availability, monitoring objectives and the nature of the production system being monitored.

$$x_i = \frac{x - x_{min}}{x_{max} - x_{min}}$$

where 0 indicates minimal contribution and 1 indicates maximal contribution to ecosystem pest pressure.
The resulting SCPI value represents relative ecosystem pest pressure and may be interpreted as,

Table 1

SCPI Range	Interpretation
0.00-0.30	Low
0.30-0.65	Moderate
0.65-1.00	High

These values are indicative. Further calibration will be performed using field data. The method used to create an overall index value from the separate indices, as performed by SCPI, is common in ecological and environmental assessments [11, 12].
A simple method to calculate an index at an ecosystem level from multiple observations was devised, allowing the index to be validated further, mapped and used to make decisions within fruit production systems in Sri Lanka.

7. Illustrative Application of SCPI

Assuming equal weighting for illustrative purposes only (w = 0.20) and the following normalized observations:

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Assuming equal weighting for illustrative purposes only (w = 0.20) and the following normalized observations:

Table 2

Component	Value
S	0.70
T	0.65
E	0.80
H	0.60
R	0.55

The SCPI is calculated as:

$$SCPI = (0.20 \times 0.70) + (0.20 \times 0.65) + (0.20 \times 0.80) + (0.20 \times 0.60) + (0.20 \times 0.55) = 0.66$$

Based on the proposed interpretation thresholds, this value indicates relatively high ecosystem pest pressure.
The SCPI is calculated as:

$$Scpi=(0.20\times0.70)+(0.20\times0.65)+(0.20\times0.80)+(0.20\times0.60)+(0.20\times0.55)=0.66$$

Based on the proposed interpretation thresholds, this value indicates relatively high ecosystem pest pressure.

8. Application of SCPI in Sri Lankan Fruit Systems

In fruit growing ecosystems within Sri Lanka, multiple host species provide resources for fruit flies, including mango, guava, papaya, citrus and banana. As fruit flies are generalist feeders and often utilize different host species in these agroecosystems, analysis at an ecosystem scale is important [1, 2, 21]. However, given that pest activity depends on seasonal changes in host availability, pest pressure may not be accurately assessed using data collected from just one host species or trap location.
The SCPI combines biological, environmental and monitoring data to provide an ecosystem level representation of pest pressure. Within a fruit growing ecosystem, SCPI can provide an ecosystem scale indication of pest pressure by combining data from 5 sources. such as,
monitoring data from sentinel crops, pest monitoring data from traps, environmental conditions, host availability and remote sensing data.
Indicators from each variable have been combined to produce a standardized pest pressure measure for the whole production system. In fruit fly monitoring, sentinel crop data may include incidences of infestation, damage to fruits, pre-mature shedding of fruits or indications of stress in crops. Sentinel crop data can be combined with trapping data, weather data, host availability and vegetation condition to produce a single value for SCPI. Therefore, an indication of pest pressure is obtained across a wider area within the ecosystem compared to using trapping data or crop damage data alone.
As the SCPI consolidates information from various sources, it provides a useful framework for monitoring fruit flies at an ecosystem scale within fruit growing systems in Sri Lanka. Furthermore, it lays the groundwork for development of future early warning systems and risk assessment systems.

9. Future Validation of the SCPI Framework

Empirical validation represents a critical step in the future development of SCPI. Future studies should aim to confirm that the SCPI effectively captures pest pressure at the ecosystem scale, and that it provides more useful information than monitoring individual variables.
The validation of SCPI should be based on field data from fruit cropping systems within Sri Lanka. Data collected from sentinel crops, pest monitoring traps, environmental variables, host resources and remote sensing can be combined to calculate SCPI values and compared against observed pest pressure and crop damage. If there is a strong relationship between SCPI and field observations, then this will support the validity of this framework.
Future studies should also aim to identify if SCPI can be used as an early warning, what optimal weightings are, and how SCPI performs over different seasons and production systems. Validation of indicator systems has been widely used within ecology, environmental assessment and precision agriculture systems [8, 9, 13]. These studies will indicate how reliable, flexible and useful this system is for pest monitoring at the ecosystem scale.
Finally, validating the SCPI will be an important step in converting this concept into a decision-making tool for sustainable pest management in fruit agro-ecosystems within Sri Lanka.

10. Implications and Future Directions

The Sentinel Crop Pressure Index (SCPI) allows for pest pressure assessment at an ecosystem level. Through combining sentinel crop data, pest occurrence, environmental factors, host availability and remotely sensed data, it provides a holistic overview of pest pressure within an ecosystem. This approach provides a more comprehensive overview of pest

pressure in comparison to simple trap counts and observed crop damage.

The framework itself is flexible and although designed for pests in fruit cropping systems in Sri Lanka, it can be applied to various crops, pest types and monitoring tools. However, due to the conceptual nature of this framework, further investigation is required to utilize within practice. Careful consideration is needed to determine which indicators should be included, weights assigned and thresholds applied within this index, which can be refined with field data.

Future work should focus on validating this model in field conditions, creating spatial risk maps and incorporating new technologies within digital agriculture (remote sensing, automated monitoring and AI) [13-16]. This could allow this framework to become a useful early warning and decision support system for managing pests at an ecosystem level. This is in line with advancements in precision agriculture and integrated pest management [15, 19, 20].

A major limitation of this research is that this framework has not been validated with field data.

11. Conclusion

This study proposes the Sentinel Crop Pressure Index (SCPI), a conceptual framework for assessing ecosystem-level pest pressure in Sri Lankan fruit production systems. While trap data and/or crop specific data are traditionally used for pest monitoring, this method combines data from sentinel crops, pest monitoring, climatic suitability, availability of hosts and remote sensing data to provide an overall index of pest pressure. The principal contribution of this study is the concept of using sentinel fruit crops as ecosystem indicators and integrating their responses with pest surveillance, environmental suitability, host availability and remote sensing information to estimate ecosystem-level pest pressure. By combining biological data with environmental and pest monitoring data, an understanding of pest risk in multi-host agro-ecosystems can be gained.

While this is a conceptual framework, it does provide a starting point for future work to develop SCPI as a monitoring tool with early warning capabilities and data driven pest management strategies. This approach provides a novel method for pest monitoring in this system and could help develop more holistic pest monitoring systems in order to encourage sustainable fruit production in Sri Lanka.

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