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Towards Enhancing Integrated Pest Management Based on Volunteered Geographic Information

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Abstract: Integrated pest management (IPM) involves integrating multiple pest control methods based on site information obtained through inspection, monitoring, and reports. IPM has been deployed to achieve the judicious use of pesticides and has become one of the most important methods of securing agricultural productivity. Despite the efforts made to strengthen IPM during the past decades, overuse as well as indiscriminate use of pesticides is still common. This problem is particularly serious in underserved farming communities which suffer from ineffectiveness with respect to pest management information collection and dissemination. The recent development of volunteered geographic information (VGI) offers an opportunity to the general public to create and receive ubiquitous, cost-effective, and timely geospatial information. Therefore, this study proposes to enhance IPM through establishing a VGI-based IPM. As a starting point of this line of research, this study explored how such geospatial information can contribute to IPM enhancement. Based on this, a conceptual framework of VGI interaction was built to guide the establishment of VGI-based IPM. To implement VGI-based IPM, a mobile phone platform was developed. In addition, a case study was conducted in the town of Shuibian in Jiangxi province of China to demonstrate the effectiveness of the proposed approach. In the case study, by analyzing infestation incidents of an overwintering outbreak of striped rice stem borers voluntarily reported by farmers through mobile phones, spatiotemporal infestation patterns of the borers throughout the study area were revealed and disseminated to the farmers. These patterns include the dates and degree-days the pest infestations intensified, and the orientation or spatial structural variations of the clustering of the infestations. This case study showcased the unique merit of VGI in enhancing IPM, namely the acquisition of previously unrecorded spatial data in a cost-effective and real-time manner for discovering and disseminating previously unknown pest management knowledge.

Keywords: integrated pest management; volunteered geographic information; conceptual framework; mobile phones; pest infestations

1. Introduction

Since 1959, due to the rising pest resistance to pesticides, integrated pest management (IPM) has been proposed to improve the control of agricultural pests [1]. IPM involves integrating multiple pest control methods based on site information obtained through inspection, monitoring, and reports. It has been deployed to achieve the judicious use of pesticides and has become one of the most important methods for securing agricultural productivity [2–5]. Traditional IPM approaches used since the 1960s are linear, expert-led, and research-driven, such as training and visit extension, the integration of biological control and chemical control, habitat management, genetic engineering, semio-chemicals, selective pesticides and botanicals, and cultural control [1,3]. However, due to the lack of sense of farmer participation and thus farmers' ownership of the programs [6,7], the ineffectiveness of traditional IPM programs has surfaced. Despite working closely with professionally trained IPM extension workers, practitioners of traditional IPM approaches have made limited progress without involving farmers participating directly in official decision-making processes [8].

Participatory IPM, a non-expert-led, non-closed-system, which is a non-research-driven strategy, therefore emerged [1,3,8,9]. It advocates farmer involvement as a means to enhance IPM by leveraging on the farmers' own experiences in their own crop pest management [10]. It takes advantage of the complementarity of farmer and expert knowledge to improve the effectiveness of pest management. Existing participatory IPM approaches mainly include Farmer Field School, Farmer First, Rapid Rural Appraisal, Participatory Rural Appraisal, focus groups, structured workshops, and farmer congress [1,3]. Among these approaches, perhaps the most widely adopted is Farmer Field School, through which IPM has moved from training towards education, exploration, and empowerment [1,3]. Despite these benefits, the existing participatory IPM approaches are costly in terms of each farmer reached, thus severely limiting their outreach capacity to only a relatively small proportion of farming communities [11]. Therefore, the questions remain as to how to enable participatory actions of millions of farmers to reveal IPM knowledge; and how personalized pest management information can be diffused to them cost-effectively. As such, despite efforts in strengthening IPM during the past decades and the deployment of various IPM approaches (non-participatory or participatory), overuse and indiscriminate use of pesticides are still common [1,3]. This problem is particularly serious in underserved farming communities of developing countries which suffer from the ineffectiveness of information collection and dissemination for solving or alleviating pest problems [1,3].

The recent development of geographical information science (GIS) towards a new paradigm, namely volunteered geographic information (VGI) [12], offers an opportunity to the general public to create and receive ubiquitous, cost-effective, and timely geospatial information. This seems to be a promising solution to the ineffectiveness of traditional IPM information collection and dissemination. Indeed, VGI has featured prominently in various application domains which include but are not limited to disaster, emergency, and crisis management [13,14]; surveillance or monitoring programs [15,16]; urban or environmental management and planning [17,18]; new generation of gazetteer [19,20]; and land use/cover mapping [21,22]. It has largely facilitated spatial information collection and dissemination in these application domains. Therefore, we propose to establish a VGI-based IPM which is expected to enable interactions among all pest management stakeholders (e.g., farmers, scientists, extension workers, and policy makers) beyond geographic boundaries, taking care of their daily observations, perceptions, resource constraints, and objectives in pest management. VGI-based IPM has the potential to drive IPM towards a new paradigm of greater participation, communication, collaboration, and transparency that necessitates a timely, ubiquitous, and constant flow of diverse pest management information.

Despite such potential, no previous study has explored VGI as a contributing component of IPM. We lack the understanding of how exactly VGI, as an emerging GIS paradigm, can enhance IPM information collection and dissemination. Therefore, this study explored this issue from both practical and theoretical angles, based on which a conceptual framework of VGI interaction was built to guide the establishment of VGI-based IPM. To implement VGI-based IPM, a mobile phone platform was developed. In addition, a case study was conducted in the town of Shuibian in Jiangxi province of China to demonstrate the effectiveness of the proposed approach. In the case study, by analyzing infestation incidents of an overwintering outbreak of striped rice stem borers voluntarily reported by farmers through mobile phones, spatiotemporal infestation patterns of the borers throughout the study area were revealed and disseminated to the farmers. These patterns include the dates and degree-days the pest infestations intensified, and the orientation or spatial structural variations of the clustering of the infestations. This case study showcased the unique merit of VGI in the enhancement of IPM, namely the acquisition of previously unrecorded spatial data in the most cost-effective and timely manner for discovering and disseminating previously unknown pest management knowledge.

The remainder of this article is organized as follows. Section 2 discusses how VGI can enhance IPM and proposes the conceptual framework. Section 3 presents the mobile phone platform, followed by the case study presented in Section 4. Lastly, Section 5 concludes this article.

2. Towards VGI-Based IPM

2.1. VGI for Enhancing IPM Information Collection and Dissemination

Traditional IPM typically sends experts to fields [23] or deploys pest monitoring traps [24] to collect data for managing pests. These data collection methods are well-known for their issues with respect to high human resources costs, the experts' lack of indigenous knowledge, inaccessibility to remote rural areas, coarse temporal resolutions to reflect changes on the ground, and inaccurate geo-registrations of the data (e.g., pest traps can attract pests from outside the targeted area). Despite the development of some participatory IPM approaches such as Farmer Field School, they are costly in terms of each farmer reached due to the limited number of farmer educators, thus severely limiting the outreach capacity to only a relatively small proportion of all farming communities [11]. Fortunately, a VGI approach has the potential to remediate these issues as it enables real-time, cost-effective, and ubiquitous pest data collection through the general public [12].

Regarding information dissemination, in contrast to traditional participatory IPM approaches (e.g., Farmer Field School) that accommodate only a limited number of participants, a VGI-based IPM platform permits the exchange of information between all pest management stakeholders. VGI-based IPM therefore allows for the sense making (knowledge discovery) of ubiquitous data from individual participants and for the dissemination of personalized IPM information that is of close interest to the participants. It also allows for feedback from information receivers in a cost-effective manner. These are the great advantages of VGI-based IPM information dissemination as compared to traditional ones (e.g., radio programs), which are often aimed at a large heterogeneous audience without adjusting its information to individual needs and allowing for any further interaction [3]. In addition, data collection in a VGI platform can be real-time across a large area. This can enable instantaneous and ubiquitous information dissemination for time-critical scenarios (e.g., pest outbreaks). Pest management stakeholders enabled with Internet or mobile phone connections can receive and view the information almost anytime and anywhere.

2.2. VGI for Satisfying the Information Diversity Requirement of IPM

Successful IPM depends not only on the effectiveness of pest management information collection and dissemination, but also on its diversity. IPM information can be quantitative, qualitative, or the combination of both [1,3]. VGI as an emerging GIS paradigm has the potential to meet such an information diversity requirement. To better guide the establishment of VGI-based IPM, this section discusses the theoretical basis of VGI, and hence answers how this new GIS paradigm satisfies the information diversity requirement of IPM.

It is often argued that traditional GIS rests on and amplifies an essentially positivist philosophical perspective [25]. According to Kwan [26], traditional GIS has been largely understood as a positivist or empiricist science, which is rooted in the quantitative revolution of geography and as such inherits the corresponding positivism or empiricism. Ontologically, positivism recognizes one reality that can be known with certain probability; there is a universal law independent from spatiotemporal contexts [27]. Epistemologically, positivism is associated with subject–object dualism, in which the knower is thought to be value-free and separated from the reality [28]. Methodologically, quantitative approaches drive positivism. The research process is largely deductive in that it focuses on testing theories rather than developing theories [29,30]. It privileges the quantitative and the observable which are context-free rather than issue-driven. The qualitative and the non-observable are underprivileged.

Space in traditional GIS is represented as a Cartesian coordinate system defined by Euclidean geometry. It follows Newton who views spatiality as absolute conceptualizations, representing space as independent spatial features (e.g., discrete vector features or raster cells), rather than Einstein and Leibnitz who view space as relational [31]. Therefore, traditional GIS has often been criticized for its inadequacy in representing relational spaces of social power and subjective differences among its analyzed objects [26,32]. It lacks the power to enable researchers to understand neighborhood-level knowledge about the lived experiences of local people, or social ties and attachments of local people to their communities [33]. Therefore, researchers and decision-makers alike lack well-grounded, rich descriptive, communicative, and explanative local contexts for approaching realities to make the best decisions.

To address the critiques on traditional GIS, a range of qualitative GIS approaches have emerged in the postmodern era [25]. A diverse range of qualitative materials and situated perspectives (e.g., photographs, sketch maps, grounded visualizations, videos, personal experiences, preferences and perceptions, and narratives) can be incorporated into GIS. Among the existing qualitative GIS approaches, perhaps public participation GIS (PPGIS) is one of the most well-known [33–35]. PPGIS is typically targeted at enhancing public participation in planning and policy issues [36]. Differing from traditional GIS, PPGIS is rooted in constructivist philosophy [37,38]. In this paradigm, people are motivated to produce their own GIS outputs based on public available GIS tools or settings. Although the development of PPGIS addressed the critiques on traditional GIS, its qualitative nature falls short of the approach that can better satisfy the information diversity requirement of IPM. Surpassing PPGIS, VGI is not limited to planning and policy issues. VGI interaction is neither limited to qualitatively-dominant approach nor to quantitatively-dominant approach. For example, OpenStreetMap (https://www.openstreetmap.org/) mainly includes traditional quantitative map information (features); Flickr (https://www.flickr.com/) mainly involves qualitative information, i.e., spatial context-associated photographs; GeoCommons (http://geocommons.com/) includes both quantitative data such as the U.S. Unemployment Rate map (http://geocommons.com/maps/206016), and qualitative data such as Binders Full of Women which maps the geotagged Tweets responding to the U.S. presidential debate (http://geocommons.com/overlays/284513); and Wikimapia (http://wikimapia.org) includes quantitative-qualitative-combined information, i.e., traditional quantitative map features added with people's qualitative descriptions and comments about the mapped features. Comparatively, the information collected in PPGIS projects are generally qualitatively dominant.

Therefore, this paper argues that one considerable relevance to VGI is the transformative paradigm [27,39,40]. The transformative paradigm can be seen as an "emerging paradigm" that combines both the positivist and constructivist perspectives [41]. The transformative paradigm values marginalized individuals, groups, and communities [42]. Ontologically speaking, the transformative paradigm acknowledges that knowledge are influenced by human interests; there are multiple socially constructed realities, but it recognizes the influence of personal values in determining what is real [40]. This is in contrast to the absolute relativism of the constructivist point of view in which all perspectives have an equal legitimacy [27]. Indeed, determining the best or most trusted information through quality enhancement processes is among the core issues of any VGI program [43,44]. From an epistemological angle, the transformative paradigm seeks a balanced and complete view of a phenomenon to achieve accurate knowledge, which requires in-depth interactions with the communities on which the program has impacts [27]. Lastly, in methodological terms, the transformative paradigm may involve quantitative, qualitative, or combined methods (no single type of approach is always dominant). Knowers need not prescribe a specific methodological orientation [27]. It might include the use of deduction, induction, abduction, or a combination of them.

2.3. A Conceptual Framework

The above features of VGI discussed from theoretical angles are suited for the information diversity requirement of an effective IPM [1,3]. This section presents a conceptual framework of

VGI interaction based on these features (Figure 1), which can not only be adapted to various VGI applications in general but also IPM in particular.

The framework incorporates single or combined methods, suited in the transformative paradigm. It serves as a framework of reference for utilizing VGI to revolutionize traditional IPM which is rooted in positivism as mentioned by Douthwaite, et al. [45]. Data collection and sense making may be conducted simultaneously (in a real-time manner) in the context of VGI. VGI collection and sense making are therefore put together in the framework, represented using a bigger box. Information dissemination is represented using a separate smaller box, connecting to the bigger box. Given the diversity feature of VGI, a variety of choices of ways for creating and analyzing VGI should be supported. The forms of VGI creation can be active (e.g., OpenStreetMap) or passive (e.g., Twitter) [46], or facilitated (e.g., see Seeger [18] and Cinnamon and Schuurman [47]). VGI collection and sense-making methods can be quantitative or qualitative solely, or can be quantitative–qualitative combined either sequentially at different stages or interactively throughout the process. In cases with quantitative–qualitative combined methods, qualitative information can provide contexts for the patterns generated by quantitative information, and vice versa [48]. Qualitative and quantitative methods can be utilized with equal weights or with different priorities. In addition, data quality assurance is stressed in the VGI collection and sense-making box. The extent to which a user can trust VGI has always been called into question, due to VGI's heterogeneity, diversity, lack of adherence to standards required in the creation of conventional authoritative data (e.g., government generated data), and lack of data quality descriptions (e.g., standard metadata) for determining its fitness-for-use [49]. Therefore, developing a VGI quality assurance infrastructure that can deal with quantitative, qualitative, and quantitative–qualitative combined VGI is required.

Indeed, for VGI project management, building or framing VGI systems should consider the abovementioned elements (i.e., the types of data contributions and sense making, and data quality assurance methods) at the onset of a project [50–52]. Defining clearly these elements guides the establishment of a VGI system (VGI-based IPM, in our case) and enables better management of VGI contributions and contributors, which should be constantly comprehended, evaluated, and expanded to ensure efficiency and effectiveness of the system [50–52].

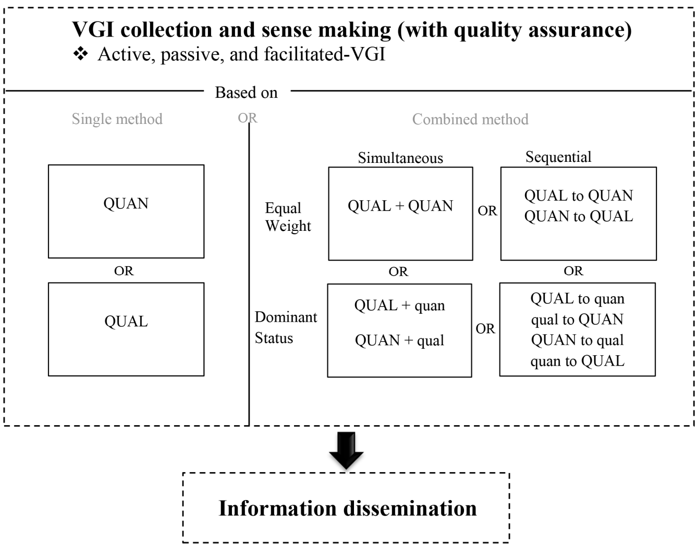

Figure 1. A conceptual framework of volunteered geographic information (VGI) interaction. To develop this framework, we were mostly influenced by Mertens [27], Johnson and Onwuegbuzie [48], and Deng and Chang [53]. Note. "qual" stands for qualitative, "quan" stands for quantitative, "+" stands for simultaneous, "to" stands for sequential, capital letters denote high priority or weight, and lower-case letters denote lower priority or weight.

3. The Mobile Phone as a Platform

Based on the conceptual framework proposed above, this section introduces our current software implementation of VGI-based IPM with mobile phones. Mobile phones have become more affordable and increasingly prevalent. Most importantly, mobile phones are portable and are capable of real-time positioning, which are essential for capturing and uploading location-based data anytime and anywhere. Therefore, we set out to establish VGI-based IPM by leveraging on the mobile phone as a platform to enable farmers to share their pest observations and receive pertinent pest management information.

Specifically, our Village Tree project has developed a mobile phone platform to help farmers from two different groups. That is, for farmers without Internet access, short message service (SMS) is supported; for farmers with Internet access, we have developed several smartphone applications for information interaction. Details can be found in the webpage of our Village Tree project (https://cosmic.nus.edu.sg/index.php/projects/mpest-mobile-pest-management-for-underserved-communities). Note that the current stage of the mobile phone platform development is limited to quantitative VGI collection (i.e., pest incidents and their quantity). The platform enables farmers to collectively share pest incidents observed in crop fields. The scattered pieces of information from individual farmers will be subsequently analyzed to assist pest management. Village Tree also helps farmers find relevant advices for alleviating their pest problems and alerts them about pest problems around their region.

4. Case Study: A VGI Approach for Managing Infestations of a Pest Outbreak

4.1. Background

To put the concept of VGI-based IPM into practice, we conducted a case study in the town of Shuibian in Jiangxi province of China (Figure 2) which was an area covering 60.38 square kilometers. As a starting point of our field testing of VGI-based IPM following the conceptual framework proposed above, the case study was based on quantitative VGI solely. This is the first time that crop pests have been managed with the help of VGI collection and dissemination. The case study utilized pest infestation reports provided by farmers to manage the infestations caused by an overwintering outbreak of striped rice stem borers. The borers intensively emerge after every winter, which can cause severe economic losses to various crops such as corn, sugarcane, oilseed rape, and especially rice (the major crop planted in the town of Shuibian).

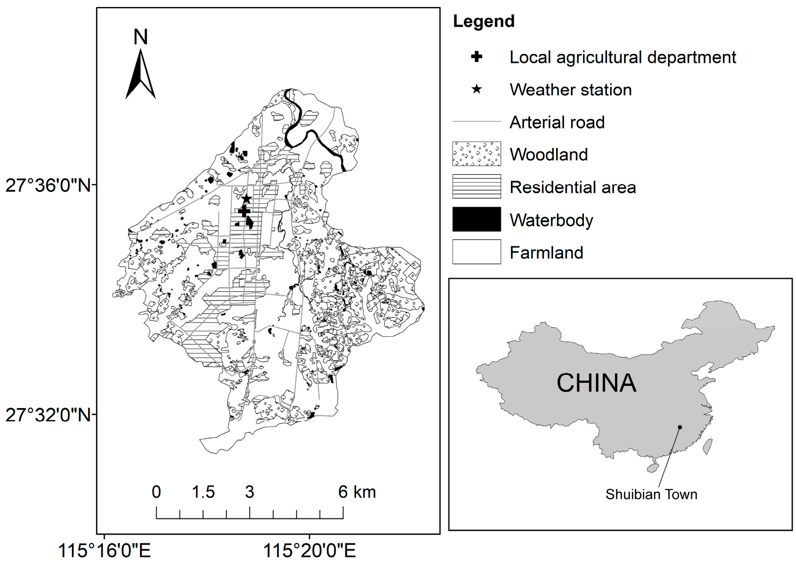

Figure 2. Study area: Shuibian town of Xiajiang prefecture, Jiangxi province, China.

Pest management staff from the local agricultural department have made much effort to reduce infestations of this pest. They monitor the pest occurrences typically by deploying pest traps and conducting field pest surveys. However, the monitoring based on pest traps has never revealed any spatial pattern of the pest outbreak across the town overall, as planting pest traps across a large area is financially and materially demanding. Counting number of trapped pests is also laborious and time-consuming. On the other hand, although the monitoring using pest traps can identify the temporal pattern of adult occurrences of the pest in the local experimental farms, it is not able to identify any temporal pattern of the actual infestations of the pest across the entire town. This is because the pest traps can only capture the adults which are not harmful (in fact, larvae of the pest damage crops). A systematic survey regarding infestations of the larvae across the entire town is also time-consuming, laborious, and costly, leading to the inability to monitor the regionwide infestations in a real-time manner.

4.2. Study Setup

To possibly reveal spatiotemporal infestation patterns of the pest throughout the region, this case study encouraged local farmers to collaboratively monitor the pest infestations (began from 15 April and ended on 27 May 2015). A local agricultural extension practitioner was hired to recruit participants several months prior to the specified pest monitoring period. Farmers were randomly approached initially, and only the farmers who were experienced in stem borer observation and expressed willingness of participation were recruited, which resulted in 233 farmer participants. Most participants were aged between 26 and 40 (45.5%). Elder farmers showed less interest in the project than the younger farmers, and many people aged below 25 in the study area have moved to big cities to make their livings.

The recruited farmers were requested to report incidents of the pest infestations observed during their routine farming work in real-time using mobile phones. They were motivated by their own interest in alleviating pest risks to their crops through receiving personalized feedbacks. In other words, no monetary or material remuneration was provided. The rationale, goals, and process of the project were explained to the farmer participants. The reports collected in the case study fall into facilitated-VGI [18,47]. Facilitated-VGI is created through an assisted data contribution model in which a targeted group of participants (with necessary abilities) is requested to contribute geospatial data according to predefined questions or criteria, in order to achieve a pre-established objective within an established geographic extent. This case study was considered as an initial step of this line of research, facilitated-VGI approach appeared to be pragmatic because it was relatively more controllable in terms of data quality. Note that although we have previously developed a fuzzy expert system to assess the quality of volunteered pest data [54], it is good at informing us the trustworthiness rather than the binary true or false of the data. Therefore, a facilitated-VGI approach was adopted in this case study to assure the correctness of famer-generated pest infestation reports.

The participants could report pest infestation incidents either through SMS (SMS fees were reimbursed) or through a smart phone application (Figure 3) developed based on ArcGIS online (ESRI Products, Redlands, CA, USA). However, as a field test confirmed unstable mobile Internet connection in the rural area, we decided to request all the participants to contribute pest infestation reports through SMS. In fact, SMS was also easier for the farmers to take in. Since SMS reports did not include any location information about observed infestations, the participants' crop fields were coded, and thus each crop field had an identification number (ID) ranging from one to 281. The geographic locations of the participants' crop fields were pre-collected using a Trimble®GeoXT handheld global positioning system (GPS) device. A SMS report should include the ID of the crop field in which an incident of the pest infestation was observed and the observer name (SMS format: "Crop field ID, Observer name"). Training was provided to ensure that the participants would generate the reports correctly.

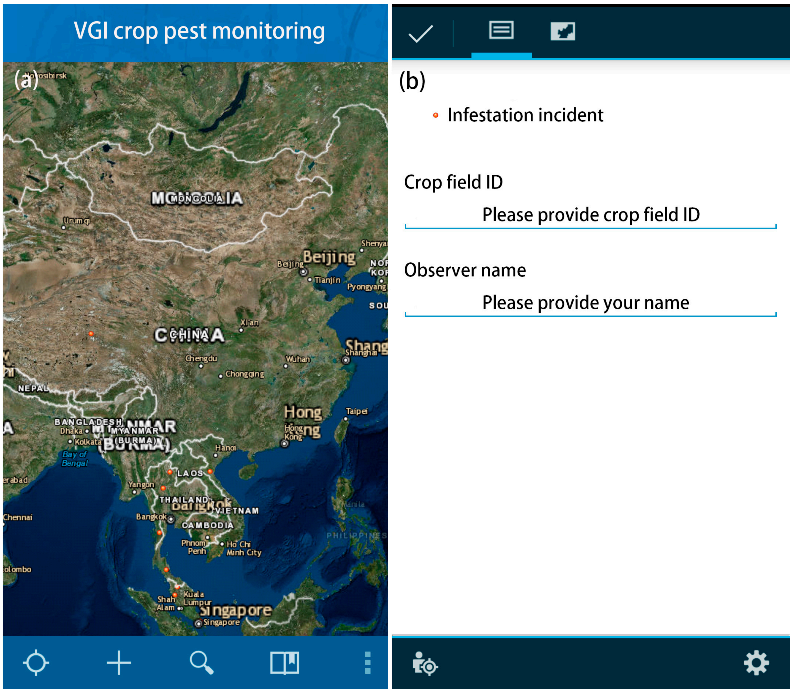

Figure 3. The interface of the smart phone application for reporting pest infestation incidents. (**a**) The home page; (**b**) the page after clicking the symbol "+" which allows users to report infestation incidents, "√" is for submitting a report. Note that a Chinese version was available for Chinese users.

4.3. Analysis

A total of 293 reports were collected (Figure 4a). The reports fell in the same crop field were integrated, creating a "stack" of reports. Spatial distribution of the reports was examined using Getis-Ord Gi* statistic [55]. This enabled the detection of hot and cold spots of the reports. A Hot Spot Analysis tool is available in ArcMap (ESRI Products, Redlands, CA) for calculating Getis-Ord Gi* statistic, and this study used ArcMap 10.1. Getis-Ord Gi* was adopted because of its ability to test the statistical significance of the results [56]. Following Bruce et al. [57], a symmetric one/zero spatial weight matrix (i.e., the spatial weight between a given feature and each of its surrounding features is one if the distance between them is within an assigned distance band, and is zero if otherwise) was applied to generating the Gi* statistics using fixed distance band weighting. This ensured the same scale of analysis across the entire study area. A distance band of 2120 m was specified using incremental spatial autocorrelation (Global Moran's I) tool of ArcMap 10.1, which reflected the most pronounced spatial autocorrelation of the dataset. In addition, a change point analysis was conducted to explore the time series of the reports, using the Change-Point Analyzer (http://www.variation.com/cpa/tech/changepoint.html) with one thousand bootstrap samples. This analysis method is capable of determining whether a change has taken place. In our case, it can determine whether there is any significant change in daily quantity of the reports.

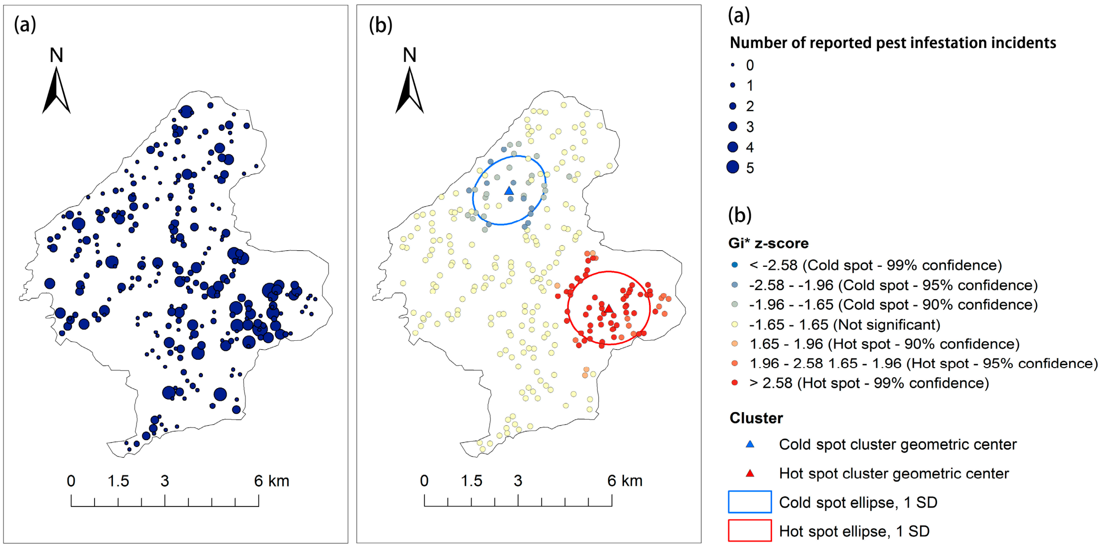

Figure 4. (**a**) Incidents of pest infestations reported by the farmer participants; (**b**) The corresponding Getis-Ord Gi* statistics (z-scores) and the hot and cold spot clusters highlighted using standard deviational ellipses, with size capped at one standard deviation (1 SD).

Once a change point is detected, the degree-days accumulated from 1 January (i.e., biofix, see Herms [58]) until the detected change point can be calculated. The concept of degree-day is rooted in the theory that insect development is directly related to temperature and time [59]. Degree-day modelling simulates the mechanistic relationship between pest development and daily temperatures, the computation of which is associated with a pest's phenological event (e.g., the date that the infestations of a pest strongly intensify) which provides a strong physiological basis for extrapolating the relationship to future years to predict future pest infestations [58]. Single sine wave method with a horizontal cut-off was used to calculate the degree-days [60]. This method makes use of the fact that daily temperature pattern over a 24-h period closely resembles a sine wave function, and determines the number of degree-days by calculating the area under the temperature curve that is found between the upper developmental temperature threshold and the lower developmental temperature threshold of a pest. In this study, the upper developmental temperature threshold and the lower developmental temperature threshold for the stem borer were 30 °C and 12.9 °C, respectively [61]. The daily temperature data used for the degree-day calculation was obtained from the local weather station which collected weather information from the middle-upper part of the study area (Figure 2). We have programmed a Python script to calculate the degree-days using ArcMap 10.1.

Furthermore, except for the Getis-Ord Gi* statistics computed for all the 293 reports, Getis-Ord Gi* statistics were computed for the reports (subsets of the 293 reports) collected until the change points (if any). A change point can indicate a phenological event of the pest. A cluster of hot or cold spots can be further highlighted using a one standard deviational ellipse polygon which encloses approximately 68% of the spots in the cluster [62]. The ellipse can be used to measure the distribution of a cluster, exhibiting its orientation or spatial structure. The cluster geometric center can be calculated to exhibit the central location of a cluster.

4.4. Results and Interpretations

The analysis revealed spatial patterns of the infestations of the pest outbreak that have never been discovered through the traditional pest monitoring approaches deployed in the study area. The results showed that the reports exhibited clustered hot and cold spots (Figure 4b). A large hot spot cluster was detected in the east part of the study area, which exhibited a structure that showed slight elongation in a roughly east–west direction. A large proportion of the hot spots were found as having high statistical significance (z-score ≥ 2.58). The hot spots were far from the local agricultural department and closer to the main woodlands. A cold spot cluster was detected in the northwest part of the study area, which had a structure that extended roughly in a southwest–northeast direction. A large proportion of the cold spots were within a 95% confidence level. No cold spot was observed at the 99% confidence level. The cold spots were closer to the local agricultural department and the main residential areas.

The change point analysis detected three statistically significant ($p < 0.01$) change points (Figure 5, Table 1). Prior to the first change point (1 May, 350.85 degree-days) the average of the daily report quantities was 1.4, while after that it was 7.6. The second change point occurred on 6 May (397.35 degree-days). The average of the daily report quantities increased from 7.6 to 13.9 around the second change point. The third change point was observed on 20 May (551.61 degree-days) with the average of the daily report quantities decreased from 13.9 to 4.6. According to the pest management experts from the local agricultural department and the past local experiences about the pest outbreak, the three change points probably indicated three phenological events, i.e., onset of the pest infestation outbreak, beginning of peak period of the outbreak, and end of the outbreak period, respectively.

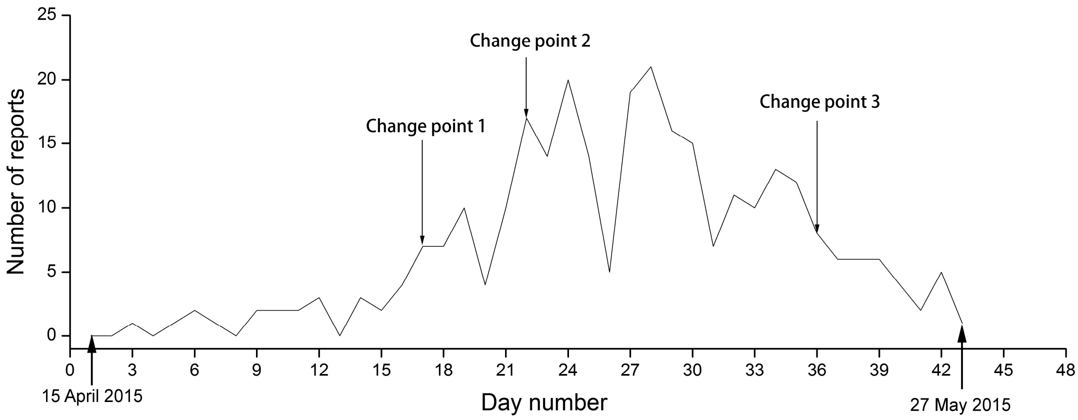

Figure 5. Time series of the farmer reported pest infestation incidents, and the three detected change points.

Table 1. A summary of the detected change points.

Change Point	Date	Trend	Possible Phenological Event	Accumulated Degree-Days
1	1 May 2015	increasing	onset of the pest infestations outbreak	350.85
2	6 May 2015	increasing	beginning of peak period of the outbreak	397.35
3	20 May 2015	decreasing	end of the outbreak period	551.61

Therefore, the Getis-Ord Gi* statistics were further computed for two of the detected change points (i.e., 1 May 2015 and 6 May 2015) which indicated two significant increases ($p < 0.01$) in the daily quantity of the reports (suggesting intensification of the infestations). Hot spot clusters and cold spot clusters were also discovered for the two change points, of which the orientations or spatial structures are also represented using standard deviational ellipses with its size capped at one standard deviation (Figure 6). It was observed that the hot spot clusters were expanding eastward towards high woodland density areas and the cold spot clusters were expanding south-westward towards the local agricultural department and the main residential areas.

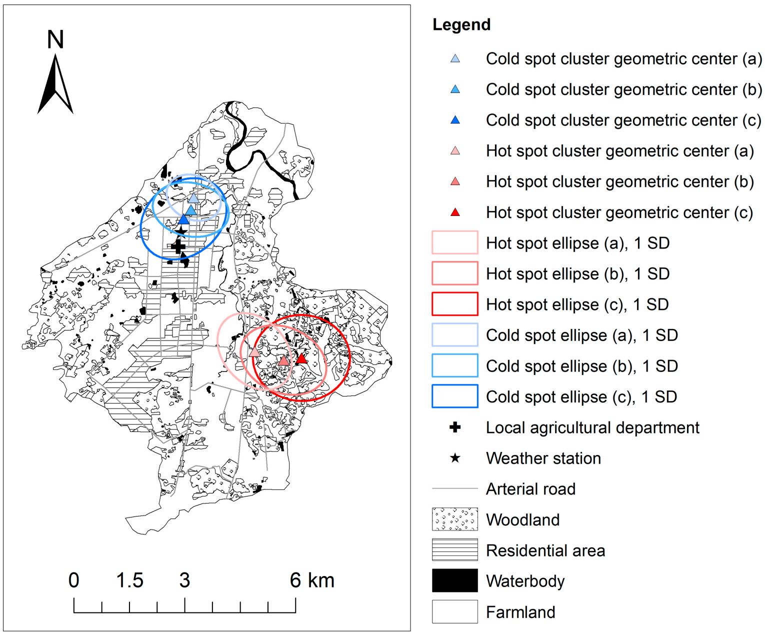

Figure 6. Structural and locational changes of the hot spot clusters and cold spot clusters of the pest infestations over time, represented using standard deviational ellipses, with size capped at one standard deviation (1 SD). "a" represents 1 May 2015; "b" represents 6 May 2015; "c" represents 27 May 2015 (the last day of the pest infestation monitoring).

These observations suggest that the woodland coverage, residential coverage, and distance to the local agricultural department may be related to the occurrences of the hot and cold spots. Three possible explanations are: (1) An area with a high woodland coverage may provide a cozy microclimate and diverse overwintering sites for the stem borers, where the pest's overwintering larvae were difficult to manage; (2) Conducting straw burning after autumn harvest that kills overwintering larvae for preventing spring outbreak is easier in an area with low woodland coverage; and (3) Closeness to residential areas and the agricultural department implies higher accessibility to important pest management resources and information from the local markets or government, and thus the pest can be better monitored and controlled.

Lastly, spatiotemporal patterns of the infestations of the pest outbreak throughout the region were disseminated to the individual farmer participants. The discovered spatiotemporal patterns of the infestations could be beneficial to both the local farmers and pest management authorities. They would be able to know which areas should be prioritized for infestation alleviation. They can target the allocation of limited pest management resources (e.g., pesticide) to narrowly defined geographic areas and directions (e.g., those areas with a high woodland coverage, the direction where a hot spot cluster extends). Additionally, the spatial patterns of the infestations discovered from the overwintering pest generation was important to the management of the subsequent generations of the pest. For example, an area found with serious infestations caused by the overwintering generation was also likely to undergo serious infestations from the subsequent generations. Moreover, with the detected temporal change points indicating significant increases in daily quantity of the reports, the farmers could combine such information with their own farming experiences to determine the best timings for pesticide spraying. The accumulated degree-days associated with the change points are also helpful for future prediction of the pest infestations.

Overall, this case study showcased the unique merit of VGI in the enhancement of IPM. That is, the acquisition of previously unrecorded spatial data (i.e., the larvae infestations records) in the most cost-effective (i.e., the case study did not depend on deploying pest traps or conducting field pest surveys which were expensive and laborious) and timely manner (i.e., real-time data were collected through mobile phones, rather than counting manually number of the stem borers captured by pest traps or conducting pest infestation surveys in the field which were time-consuming), for discovering and disseminating previously unknown pest management knowledge (i.e., the regionwide spatiotemporal infestation patterns).

5. Discussion and Conclusions

This study proposed to enhance IPM through establishing a VGI-based IPM. It explored from both practical and theoretical angles how exactly VGI can enhance IPM. Based on this, a conceptual framework of VGI interaction was built to guide the establishment of VGI-based IPM. The VGI-based IPM has been implemented on a mobile phone platform, and a case study was conducted in China to demonstrate the approach. In the case study, by analyzing the volunteered pest infestation reports, spatiotemporal infestation patterns of an overwintering outbreak of striped rice stem borers were revealed and disseminated, which were lacking from the traditional pest management in the study area. Note that the size of the samples collected in the case study was small. Therefore, the results and our interpretations tend to be indicative as compared to being statistically robust. It is necessary to scale up the study to larger areas, collecting more samples and performing more robust statistical calculations. This could be achieved with the help from agricultural departments, crop protection units, agricultural extension practitioners, or non-governmental organizations. In addition, our case study found that the Internet connection for mobile phones was problematic in the rural area, and the farmers were more used to using SMS. Nevertheless, we expect that better mobile phone Internet infrastructures will be built up and smartphones will be more popularized in rural areas in the future.

Furthermore, some important work pertinent to the future development of VGI-based IPM is necessary. As mentioned above, IPM information is diverse, including quantitative and qualitative information, and the combination of both. The current implementation of the VGI-based IPM is limited to the provision of quantitative pest monitoring data. Haklay [63] introduced four ascending levels of participation and engagement in citizen science projects. The status of our VGI-based IPM lies at the lowest level, i.e., crowdsourcing, in which cognitive engagement in IPM is minimal. A comprehensive VGI-based IPM should ascend to higher levels to encourage participants' cognitive engagement, e.g., farmers' knowledge, attitudes, and practices [64]. Participants can be enabled to also play the roles of problem definers, data analyzers, and knowledge interpreters. At the highest level, participants could actively involve themselves in the whole process of the project, and are encouraged to be inquisitive and innovative. Therefore, being suited to the transformative paradigm, exploring high level VGI-based IPM approaches is suggested for future research. Indeed, this has been echoed by Gómez-Barrón et al. [51] who draw a line between crowd-based participation and community-driven participation, describing that volunteers' level of involvement or engagement ranges from simple participation to collaboration, and up to co-creation. A successful VGI-based IPM should offer greater flexibility, collaboration, and co-creation possibilities. This will enable a big virtual community with a shared interest in mitigating pest risks and greater control in pesticide uses.

Lastly, the quality issue of VGI must be stressed. The quality of VGI in our case study was assured through facilitated-VGI approach. However, VGI-based IPM should not be limited to facilitated-VGI. In fact, diverse forms of VGI-based IPM community can be established based on different forms of VGI creation (e.g., active VGI creation as mentioned above) and with more heterogeneous participants. More robust VGI quality assurance approaches are therefore needed to satisfy the diverse scenarios of VGI-based IPM. Fortunately, we have preliminarily developed an expert system based on fuzzy set theory to assess the quality of volunteered pest monitoring data (quantitative) [54]; and we have developed image recognition techniques to assist users to correctly identify pest species through taking photos of observed species (https://cosmic.nus.edu.sg/). Future research will extend the work to the quality assurance of qualitative and quantitative–qualitative combined VGI.

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