Modelling of Dubas Bug Habitat and Population Density in Oman Based on Associations with Human, Environmental and Climatological Factors

و ةيرشبلا لماوعلا و سابودلا ةرشح نيب تاقالعلا ىلع دامتعإلاب نامع ةنطلس يف سابودلا ةرشح ةفاثك و ةئيب ةجذمن ةيخانملا و ةيئيبلا

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Executive Summary

Climatological and environmental conditions are very important in determining the distribution and survival of any species, both plants and animals, and the same applies to the Dubas bug. Understanding the distribution and affinity of the bug to variables can play a key role in mapping, control and management, including resource allocation (spray teams, field personnel, etc.).

This research will use tools and techniques available in modern spatial analysis packages, such as Geographic Information Systems and Remote Sensing, to model and develop spatial links and correlations between presence/absence/density of Dubas bugs with climatological, environmental and human factors and conditions. We will develop GIS layers that give the density and distribution of the bug infestation levels and the stress observed in the date palms, and link them with rainfall patterns, humidity, wind direction, temperature, soil salinity, irrigation practices, farming practices, etc. to investigate correlates. We will also investigate whether soil types, geology, aspect, slope, elevation and available solar radiation play any part in enhancing the development, survival and spread of the Dubas bug. We will also use combinations of some of these variables, such as the humid-thermal index (HTI) to gain an understanding of preferred environments of the Dubas bug. This research will start off by using single variables to develop correlations and then move onto more complicated predictive models and regression analysis where we incorporate all factors to investigate what combinations of factors are the most conducive to the survival and spread of the bugs.

We will use modern geostatistical techniques and statistics to look at hot spots and clustering of the bugs and investigate why they are clustered in certain regions/conditions. These techniques will help us identify the most important variables or combinations of variables that help the Dubas bug develop, prosper and migrate.

The project will also use remote sensing tools and satellite images to develop early detection techniques for the Dubas bug at broad scales. We will use satellite images to map the spatial distribution of the bug, and possibly do this on a temporal scale as well to see the directions and speed of spread. The output, especially the spatial distribution and spread images, will be used as inputs to the GIS-based predictive models.

The Team

We bring a team with both local experience and knowledge and internationally recognised remote sensing and GIS experts.

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Executive Summary (Arabic)

للظروف المناخية والبيئية أهمية في الكشف عن توزيع أي نوع من أنواع النباتات والحيوانات وتحديد إمكانية بقاءها على قيد الحياة. هذا المفهوم ينطبق أيضاً على حشرة الدوباس. لذلك فهم التوزيع الخاص بحشرة الدوباس و إنجذابها للمتغيرات يلعب دوراً رئيسياً في رسم الخرائط الخاصة بها و إدارتها والتحكم بها بما في ذلك تخصيص الموارد كفرق الرش والعامليين الميدانيين.

في هذا البحث سيتم إستخدام الأدوات و التقنيات الحديثة المتاحة في حزم التحليلات المكانية مثل نظم المعلومات الجغرافية والإستشعار عن بعد لنمذجة العلاقات والروابط المكانية بين تكاثر وغياب و كثافة حشرة الدوباس وبين العوامل والظروف المناخية والبيئية والبشرية. سيتم بناء و تطوير طبقات نظم معلومات جغرافية لإبراز كثافة وتوزيع مستويات الإصابة والخطر الملاحظ على النخيل وربطها مع أنماط هطول الأمطار و الرطوبة و إتجاه الرياح و درجة الحرارة و ملوحة التربة و أشكال الري و الممارسات الزراعية. أيضاً سيتم التحقيق فيما إذا كانت أنواع التربة و الجولوجية والمنحدرات و المرتفعات و الإشعة الشمسية لها دور في تعزيز تواجد وبقاء حشرة الدوباس. سوف نقوم بإستخدام مزيج من بعض المتغيرات كمؤشر الحرارة و الرطوبة (the Humid-Thermal Index) لمعرفة البيئات المفضلة لتكاثر حشرة الدوباس.

سيتم الإعتماد في بداية هذه الدراسة على العلاقة بين كل عامل على حده و الحشرة ومن ثم الإنتقال إلى المزيد من العلاقات و النماذج التنبؤية المعقدة و لتحليل الإنحدار لدمج جميع العوامل لمعرفة ما العوامل التي تساعد على بقاء حشرة الدوباس و تساعد من تكاثرها.

كذلك سيتم إستخدام التقنيات الجيوإحصائية الحديثة والإحصاءات الرياضية الحديثة لتحديد المواقع الساخنة وتركزها والتحقيق في الأسباب التي أدت إلى تركزها في تلك المواقع. هذه التقنيات سوف تساعدنا على معرفة أهم المتغيرات التي تساعد في تطور حشرة الدوباس وتكاثرها.

سيتم إستخدام صور الأقمار الإصطناعية لرسم خرائط التوزيع المكاني و الزماني للحشرة و كذلك إتجاهات وسرعة إنتشارها. مخرجات هذه المرحلة و خاصة مخرجات التوزيع المكاني و الزماني ستستخدم كمدخلات للنماذج المستنده إلى نظم المعلومات الجغرافية التنبؤية.

Keywords :

Spatial modelling, Hot-spot analysis, image segmentation, Humid-Thermal Index, Dubas Bug,

Climate, Environmental Modelling

1. Introduction and statement of the problem/project

Climatological and environmental conditions are very important in determining the distribution and survival of any species, both plants and animals, and the same applies to the Dubas bug. Understanding the distribution and affinity of the bug to variables can play a key role in mapping, control and management, including resource allocation (spray teams, field personnel, etc.).

This research will use tools and techniques available in modern spatial analysis packages, such as Geographic Information Systems and Remote Sensing, to model and develop spatial links and correlations between presence/absence/density of Dubas bugs with climatological, environmental and human factors and conditions. We will develop GIS layers that give the density and distribution of the bug infestation levels and the stress observed in the date palms, and link them with rainfall patterns, humidity, wind direction, temperature, soil salinity, irrigation practices, farming practices, etc. to investigate correlates. We will also investigate whether soil types, geology, aspect, slope, elevation and available solar radiation play any part in enhancing the development, survival and spread of the Dubas bug. Solar radiation models, such as the one developed by Kumar *et al.* (1997) have been used extensively to study presence/absence and density of various animals. We will also use combinations of some of these variables, such as the humid-thermal index (HTI) (Jhorar *et al*. 1992, 1997) to gain an understanding of preferred environments of the Dubas bug. This research will start off by using single variables to develop correlations and then move onto more complicated predictive models and regression analysis where we incorporate all factors to investigate what combinations of factors are the most conducive to the survival and spread of the bugs.

This project will also look at issues such as:

1. Human-related factors, such as aerial spraying. It will be of value to gather aerial and ground insecticide spraying data for the past 10 to 20 years and correlate these with current bug densities and densities of key natural enemies.

2. Cultural practices such as planting distance, irrigation, fertilization, pruning and sanitation should be also considered in any model to explain distribution and density of the Dubas bug.

3. Biotic factors such as species and densities of natural enemies (predators, parasitoids, parasites, and pathogens). Even if the environment and climate is conducive, but there is significant mortality due to natural enemies then Dubas bug densities will effectively be lower.

We will use modern geostatistical techniques and statistics such as Geary's Index, Morans *I*, Getis-Ord Gi*, Ripley's K-Function, etc. to look at hot spots and clustering of the bugs and investigate why they are clustered in certain regions/conditions. These techniques will help us identify the most important variables or combinations of variables that help the Dubas bug develop, prosper and migrate.

Once the factors and combinations of factors have been identified we will then use these to develop predictive models that will be able to give us the probability of occurrence, spatial distribution and densities under different environmental, climatological and resource availability conditions. These models then could be used to forecast the spatial distribution and densities of the bugs under prevailing conditions at the beginning of each bug season. These results in-turn could be used for management purposes and for decision making as to where to direct resources for preventive action.

A second, but linked, part of this project will use remote sensing tools and satellite images to develop early detection techniques for Dubas bug at broad scales. We will use images such as Quickbird (both panchromatic and multispectral) and/or the new 8-band WorldView images to map the spatial distribution of the bug, and possibly do this on a temporal scale as well to see the directions and speed of spread. We intend to use the new hyperspectral remote sensing techniques to develop early pre-visual detection of the Dubas bug. The output, especially the spatial distribution and spread images, will be used as inputs to the GIS-based predictive models.

To ensure that the project has local benefits and ongoing support, we will incorporate 2 PhD candidates from Oman as part of this research. One will concentrate on the remote sensing side, looking at pre-visual detection and mapping, while the other will work on the GIS side looking at geostatistics, correlation and identification of variables and developing predictive models. One of the candidates has already been identified and is interested in being part of the team. Mr Khalifa Alkindi has just completed a Masters in GIS at the University of New England in Australia, working with the PI and has expressed interest in a PhD. The project will also have 2 Masters students who will enrol at Sultan Qaboos University. One of the Masters students will develop a prototype webserver (*eDubas*) for management and serving of spatial data related to Dubas bugs while the second Masters student will study the spatial patterns of Dubas bug migration in northern Oman and the climatological factors affecting dispersal of this pest. The postdoc will research the relevance of the humid-thermal index for Dubas bug ecological niche modelling and development of hyperspectral techniques for early detection of stress due to Dubas bug infestation.

We bring together a team from both Oman and Australia with expertise in spatial modelling, GIS, Remote Sensing, horticulture, climatology and entomology. Dr Lalit Kumar, the principal investigator, is a Senior Lecturer at the University of New England and is an expert in remote sensing, spatial analysis and GIS-based modelling. He currently is working on a project with a PhD student in Jeddah, Saudi Arabia applying similar GIS techniques described in this proposal to dengue fever and its vector to describe the density and distribution and linking them to environmental, climatological and economic variables. Dr Ali Al-Wahaibi is an Assistant Professor of entomology at SQU and has been involved in Dubas bug research in Oman for 14 years. Dr Om Jhorar, a consultant and adjunct Senior Lecturer at the University of New England, is an agro-climatologist and has consulted in the agronomy (Plant Protection) field for the last 26 years. He developed the widely used humid-thermal index for karnal bund of wheat modelling in 1992 and applied it on a different crop (chickpea) during his PhD study that earned national level recognition from the Government of India. Dr Babu Madhavan, a remote sensing expert, is a Senior Research Scientist with the Remote Sensing and GIS Centre at SQU. Dr Talal Al-Awadhi, a GIS specialist, is an Assistant Professor with the Geography Department at SQU. Dr Rashid Al-Yahyai, an expert in horticulture, is an Assistant Professor in the Crop Science Department at SQU. Associate Professor Onisimo Mutanga, from the University of KwaZulu Natal in South Africa, is an expert in hyperspectral remote sensing and development of early detection techniques of pest stress, having undertaken similar work in pine plantations in South Africa.

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2. Literature Review and Analysis of Related Work

Introduction

The date palm (*Phoenix dactylifera*) is one of the oldest cultivated fruit trees in the world and is an important crop in arid and semi-arid countries. It is an important economic crop in the Sultanate of Oman (Mani *et al.* 2005) as well as most Arab countries (El-Juhany 2010). Its fruits have high nutritional value and the people in the Middle East depend on it for their livelihood. The date palm does well in the Gulf area since the weather is dry, with long summers and short winters. Its optimum temperature for growth is 32^{o}C (Moustafa *et al*. 2004) but can tolerate temperature ranges of 0^{o}C to 50^{o}C. It can also tolerate high levels of salinity (Al-Yahyai 2006). The Sultanate of Oman is the 8th largest producer of dates in the world, with a production of 238,000 metric tons in 2005 (Al-Yahyai 2010). Most of the production is in the northern part of the country, with Al Batinah (42%), Al Sharqiah (19%), Al-Dhahirah (17%) and Al-Dakhliah (14%) being the dominant provinces (Al-Yahyai 2010). There are many cultivars of date palms grown in Oman, with some important ones being Khalas, Fardh, Naghal, Kinaizi, Khasab and UmmAssilla. In total there are about 180 female and 48 male varieties among the 7.8 million date palms in Oman (Al-Yahyai and Al-Khanjari 2008). The long production season, extending from May to November, coupled with the diversity of date varieties, makes Oman one of the counties with the longest date production seasons in the world (Al-Yahyai 2010).

Date production in Oman is not without its share of problems. A variety of insect pests cause major damage to this crop resulting in plant deaths, reduced yield and production loss (Howard 2001). One such species, the Dubas bug (*Ommatissus lybicus* Bergevin), has been identified as being of major economic importance in the Sultanate of Oman (Al-Zadjali *et al*. 2006). Indeed the Dubas bug has been identified as one of the reasons for the decline in date production in Oman (Al-Yahyai and Al-Khanjari 2008). It is also seen as a pest of date palms in several countries in the Near East, North Africa and southeast Russia (Klein and Venezian 1985). It is said to have originated in the Tigris-Euphrates River Valley from where it has spread to other areas in recent decades (Blumberg 2008).

Dubas bug impacts are severe in Oman, Southern Iraq and Southern Iran, while not so severe in the United Arab Emirates, Saudi Arabia, Egypt, Tunisia, Libya, Algeria and Morocco. In Oman, the infestation seems more severe in mountain wadi biomes and less in open plains and coastal areas away from mountains. Preliminary data collected by Ali Al-Wahaibi (personal communication) shows different levels of infestation in different localities within Oman. Both Hussain (1963) and Gharib (1966) stated that heavy infestations mostly occur along rivers. In these areas both male and female trees and the different date varieties were damaged equally (Gharib 1966).

The Dubas bug is a planthopper belonging to the family Tropiduchidae (Hemiptera: Fulgoroidea).

It is a sap feeding insect and both adults and nymphs suck the sap from the date palm, causing chlorosis and repeated heavy infestations cause desiccation of leaves and the weakening and death of some of the palms (Hussain 1963; Howard 2001). There is also an indirect effect whereby the honeydew produced by this species can lead to growth of black sooty mould on the foliage and consequently a reduction in photosynthetic rates of the date palm (Mokhtar and Al-Mjeni 1999; Blumberg 2008). The female of this species ranges in size from 5-6 mm while the males are 3-3.5 mm. The colour is yellowish white (cream-colored) and the main distinguishing feature between males and females is the presence of spots on females while the males have a more tapered abdomen and larger wings relative to the abdomen. The nymphs have 5 instars and each instar has white waxy filaments (Hussain 1963).

Biology and Life History

Various studies have investigated the biology of this species (Hussain 1963; Klein and Venezian 1985). In Oman, it has two generations per year with the spring generation of young nymphs appearing in late February - early March and the autumn generation appearing in late August - early September (Alam *et al*. 1981; Thacker *et al*. 2003). In Iran, nymphs were active from April to May in the first generation and August to October in the second generation. Adults of the first and second generations were active from May to June and September to November, respectively (Payandeh *et al*. 2010). Each female can lay from 100 up to 130 eggs (Elwan and Al-Tamiemi 1999). At the end of each generation the female lays its eggs by inserting them singly into holes it pierces in the tissue of the rachis and in the leaflets of the date palm frond. The eggs remain dormant for about 3 months and when they hatch the resulting nymphs continue living on the fronds of the same palm – drawing the sap and excreting large amounts of honeydew which covers the fronds leading to the growth of black sooty mould. In extreme cases the mould can block the stomata of the leaves. The black sooty mould, in combination with the loss of sap or the physiological changes resulting from the loss of so much sap, may disrupt the growth and reproduction of the date palm which in turn reduces its crop. The honeydew secretion may also make the date fruits to be unpalatable (Gassouma 2010). It typically takes 2-4 months for eggs to hatch. The developmental time of eggs was studied under three temperatures, 25°C, 30°C and 35°C and the results showed that 30°C appeared to be the optimum temperature for the biological activities of this species (Payandeh *et al*. 2009). At 35°C the biological processes of the bugs were disrupted, leading to high mortality, particularly in females. Research into the spatial distribution and population fluctuation of two generations of Dubas bug in the Bam region of Iran showed that this pest had an aggregated spatial distribution pattern (Payandeh *et al.* 2010). Blumberg (2008) has reported that low temperatures below 0°C adversely affect the ability of adults to survive. The Dubas bug avoids direct sunlight (Klein and Venezian 1985) and it is spread by transfer of infested offshoots and by wind (Blumberg 2008).

Biological Control

Some research has also been conducted on the natural predators and parasites of the Dubas bug. Early results show a variety of natural enemies that could be used as biological control agents and among these are *Aprostocetus sp., Oligosita sp. and Runcinia sp.* (Biennial Agricultural Report 2006). Hussain (1963) has also reported that the eggs of the Dubas bug are parasitized by a small Chalcidoid (same as aforementioned *Oligosita*) while the nymphs and adults were preyed upon by the larvae of the lace wing (*Chrysopa carnea* Steph.). He also reported three adult species of Coccinellids as preying upon nymphs and adults of the Dubas bug. However, further research is needed to determine the distributions of these natural enemies in Oman as well as their effectiveness in controlling Dubas bug populations. Some measure of success was also achieved with pathogenic bacteria as microbiological control agents although their toxicological aspects need further research to assess the safety of their implementation on a large scale (Biennial Agricultural Report 2006).

Chemical Control

Given the significant economic impact of this pest, research into effective management strategies is of high priority. Several insecticides have been evaluated for Dubas bug control in Oman with SUMI-ALPHA® 5 EC being effective as a ground spray and KARATE® 2 ULV, TREBON® 30 ULV and SUMICOMBI® 50 ULV achieving some measure of success as aerial sprays (Anonymous 2006; Biennial Agricultural Report) . KARATE-ZEON was also found to be very effective as it gave 100% reduction in number of Dubas bug instars and adults 3 and 7 days after application (Anonymous 2008). However, the use of this particular pesticide is restricted due to its side effects such as irritation. In Israel, systemic carbamates such as aldicarb and butocarboxim have been successful while in Iraq dichlorvos (DDVP) injected directly into the infected palms were also successful at suppressing the pest population (Blumberg 2008). Managing the Dubas bug with insecticides is expensive and has negative impacts on the environment, non-target species (particularly natural enemies of Dubas bug) as well as human health. Research has shown that some pesticide residues persist in the fruit up to sixty days after application (Khan *et al.* 2001). In addition, chemical control has achieved limited success and this pest continues to pose a major challenge to Omani agriculture.

Further Research

While a lot of work has been carried out on the biology and ecology of the Dubas bug, limited research has been carried out into the current and potential distribution of the Dubas bug (Al-Zadjali *et al*. 2006). In fact, there is no focused research on the spatial and temporal distribution of this pest insect and its relationship with environmental, climatological and human related factors. The climatic factors that influence the survival and distribution of the Dubas bug merits further study since this information may be useful in determining its current and future potential distribution, particularly in light of climate change. In a review of the effects of climate change on pest populations, Cammell and Knight (1992) suggest that increases in mean global temperatures as well as changes in rainfall and wind patterns could have profound impacts on the population dynamics, abundance and distribution of insect pests of crops. More recent research (Cannon 1998; Bale *et al.* 2002; Gevrey and Worner 2006) has supported this hypothesis. A key issue in ecology and conservation is the mapping of pest species distributions as this information can be used to devise more effective management strategies for their control. Spatial analysis techniques, remote sensing and species distribution modelling are useful tools for carrying out such analyses. Such studies require information on the current distribution of Dubas bug which can be obtained by detailed sampling as well as literature searches and searches on databases such as the global biodiversity information facility (GBIF). Once sites of known occurrences are identified, the environmental conditions at these sites can be used to make projections to other regions to identify potentially suitable areas that can be colonized by the species of interest. An assessment can also be made to see whether areas will continue to be climatically suitable under future climate scenarios. Once suitable climatic variables have been identified, other environmental variables such as soil types, slope, aspect, geology and elevation can be incorporated in a Geographical Information System (GIS) to evaluate which variables or combinations of variables play a role in enhancing the development, survival and spread of the Dubas bug. Remote sensing imagery can also be used to study the health of date palms. High spatial resolution imagery such as IKONOS and Quickbird can be useful in the early detection and extent of date palms infested with the Dubas bug. Such analyses can be carried out on a broad scale much more cheaply and effectively using remotely sensed imagery compared to extensive field based surveys. Early detection can play a crucial role in the management and control of infestations and further research into techniques for early detection merits urgent attention.

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3. Objectives

To date, most of the global research on the Dubas bug has focussed on its ecology, biology, or control mechanisms. There has been limited or no research on linking the presence, density and spatial and temporal distributions of the Dubas bug with environmental, meteorological and human (cultural) factors that promote the development and prevalence of this pest. Dubas bugs develop and inhabit certain areas because those areas have suitable environmental, meteorological and cultural conditions. This is true for every single plant and animal species: organisms inhabit those sites that are most suitable to their needs.

To understand the distribution and prevalence of the Dubas bug, highly detailed and sophisticated information about the environment, climate and human (cultural) practices is needed in order to understand current biogeographical patterns and predict future ones. This is where spatial information technologies such as Geographic Information Systems (GIS) and Remote Sensing (RS), with their emphasis on geo-referenced data (location-based data) and related spatial analysis methodologies for organising and understanding the suitable conditions, can play a significant role.

The main objectives of this research are:

1. Develop correlations between various environmental, meteorological and human factors related to date farming and the distribution and density of Dubas bugs, through the use of spatial analysis and modelling techniques.

2. Develop early detection and map infestation levels using remote sensing technology.

3. Map hot-spots and cold-spots of Dubas bug infestations.

4. Use the Humid-Thermal Index (also called the Humid-Thermal Ratio) to predict the occurrence and non-occurrence of the Dubas bug.

5. Develop a GIS model of Dubas bug risk areas using a combination of suitable environmental and meteorological factors and human practices. Models that map and predict the spatio-temporal risks of Dubas bugs will be demonstrated.

6. Develop a prototype webserver (*eDubas*) to help the decision makers at different management levels in Oman to make more informed decisions about Dubas bug management and control

7. Study the spatial patterns of Dubas bug migration in northern Oman and the climatological factors affecting dispersal of this pest.

The main aim of this research is to gain an understanding of the correlations between various environmental, meteorological and human factors related to date farming and the distribution and density of the Dubas bug, through the use of spatial analysis and modelling techniques. In this project, remote-sensing tools and satellite images will be used to develop early detection techniques for the Dubas bug at broad scales. High-resolution images such as Quickbird and the new 8-band WorldView images will be classified to map the spatial distribution and levels of infestation of the bug. Temporal images, covering a 10 year period, will be classified as well to see the directions and speed of spread of the Dubas bug.

Image segmentation techniques will be used to extract individual palm canopies. These will give us density information for the date palm plantations in Oman. These images will be classified or used to determine row spacing for the date palm plantations. These data will be fed into our GIS models as row spacing between palms has been mentioned as a critical factor in Dubas bug infestations. The new hyperspectral remote sensing techniques will be used to develop early pre-visual detection of the stress levels caused by the Dubas bug. The output, especially the spatial distribution and spread images, will be used as inputs to the GIS-based predictive models.

Dubas bugs infested and damaged palm tree hotspots, cold spots, direction (e.g., north) and spatial patterns (dispersed or clustered) will be identified and visualised. This research will use tools and techniques that are available in modern spatial analysis packages, such as GIS and RS, to map, model and develop spatial links and correlations between the presence/absence/density of bugs with environmental, meteorological and human factors.

GIS layers will be developed to give the density and distribution of the Dubas bugs and link these with meteorological variables such as rainfall, maximum and minimum relative humidity, wind directions, maximum and minimum temperature and available solar radiation to investigate the correlations between them.

Biological systems are highly dependent on two most important elements of climate i.e. temperature (thermal) and humidity (moisture). Temperature is the derivative of solar radiation and thermal emission, while humidity is the derivative of dry or wet conditions associated with various forms of precipitations. These factors are specifically important in the regions where extreme temperature and humidity conditions are prevalent with large fluctuations within seasons causing predisposition of plants and aggravation of insect pests and diseases. Humid-Thermal Index has successfully been demonstrated in developing and testing relationships between several plant diseases in varied climatic conditions including the Indian subcontinent, Australia, Europe and North America. This method holds high potential in the study of insect pests and diseases with possibility of highly accurate predictability of their occurrence and non-occurrence and under specific climatic and weather conditions. Such predictions can help reduce human efforts when conditions are expected to be unfavourable and help in preparedness in advance to meet the challenge in the event of threat that could result in heavy crop loss.

The correlations between such environmental factors as soil types, aspect, slope and elevation that play any part in enhancing the development, survival and spread of the bugs will also be investigated.

The human (cultural) practices such as the use of insecticides, method of spraying, planting, fertilising and others will be investigated and analysed to illustrate their impacts on the presence and density of the Dubas bug and find the correlations between them. The most important variables or combinations of variables that help the Dubas bug develop, prosper and migrate will be identified. The spatial patterns and relationships (in both space and time) will be analysed to develop a better understanding of factors related to Dubas bug development and spread.

A GIS model of Dubas bug risk areas will be created using a combination of suitable environmental and meteorological factors and human practices. Models that map and predict the spatio-temporal risks of Dubas bugs will be demonstrated.

Once the factors and combinations of factors have been identified, we will then use these to develop predictive models that will be able to give us the probability of occurrence, spatial distributions and densities under different environmental, meteorological and resource availability conditions. These models can then be used to forecast the spatial distributions and densities of the bug under prevailing conditions at the beginning of the bug season. These results, in turn, could be used for management purposes and for decision making as to where to direct resources for preventive action.

We will also develop a prototype webserver (*eDubas*) to help the decision makers at different management levels in Oman to make more informed decisions. The aim is to enable the precise deployment of resources and insecticide spraying schedules. This can lead to saving on spray use, which is better for the environment and reduces costs. A comprehensive ongoing database and scheme for recording of Dubas bug infestations (location, date, intensity, etc.) will be established. *eDubas* will be a web-based reporting and a management system to help all the stakeholders in the date palm industry.

4. Benefits to Oman

In this project, spatial information technologies and methods will be used to extract intensive details about spatial patterns, spatial correlations and other factors regarding the Dubas bug and different environmental, climatic and cultural variables that can help to understand, control and manage the impact of these insects on palms across Oman. This will be the first study worldwide to use these technologies and methods to study the Dubas bug and their impacts, in contrast to previous studies, which concentrated on the ecological and entomological aspects. Therefore, this project will place Oman at the forefront of applying new cutting-edge technology to the study of the Dubas bug and its impacts on date palms. Similar techniques are routinely used in the medical field to study the presence of disease clusters and then investigate why those clusters occur at those geographic locations. Our proposal applies those same techniques to the study of the presence, density and distribution of the Dubas bug.

This project is also very strong on capacity building in Dubas bug research for Oman. We propose to train 2 PhD and 2 Masters students (all from Oman). This is important as we want the benefits to flow back to Oman. The 2 PhD students will be enrolled and trained at the University of New England (UNE) in Australia, one of the leading universities in the field of natural resources management and environmental science. The 2 Masters students will enrol at Sultan Qaboos University (SQU) in Oman but will have the opportunity to spend part of their candidature at UNE. This will enable them to gain exposure to research methods and expert analytical help. All 4 students will be supervised by a team of experts comprising academics from both UNE and SQU.

Upon completion of the project, Oman will have a larger pool of experts in Dubas bug research. It will enable Oman to take a leading role in Dubas bug research and become a Centre of Excellence in this field in the Middle East. This gives Oman an opportunity to attract research funding and to train people from the region. The PI and the climate consultant from Australia will both be willing to be part of this Centre of Excellence and contribute to research and training.

There is also the benefit of recommendations to the government and farmers of Oman as to the best locations and optimum cultural practices for planting date palms, prediction of future infestations, etc.

This project will generate at least 12 papers in international peer reviewed journals (2 PhD's publish 3 papers each, 2 Masters students publish 1 paper each and the postdoc publishes 4 papers over the 3 years). A search of the literature shows that most of the current research on Dubas bug in Oman is published in workshop and conference proceedings that do not have as wide a readership as journal articles, nor do they have the same impact. Twelve papers in international journals over three years will certainly place Dubas bug research in Oman on the world map.

This study will generate data at fine scales covering much larger areas of Oman than any of the previous studies. We will locate at least 40 rain gauges in areas that do not have one and will install at least 120 temperature and humidity data loggers. We will measure soil salinity in at least 120 plots spread over the landscape in northern Oman. This data will be recorded over 5 seasons (2.5 years), so the project will result in an extensive dataset covering a number of years and over a wide area. Upon completion of the project, the data will be made available to all researchers in Oman. The data will become a property of the Sultanate of Oman. All data will be formatted to the UTM 1882 format, the standard used in Oman, before delivery.

Our *eDubas* web-based delivery and inspection system will enable future researchers to see what research has been conducted, where this research has been conducted and what data layers are available.

5. **Outline of proposed activities/Research Methodology [Describe your implementation plan, time-lines and milestones]**

(i) Determining infestation levels, tree spacings and density (Remote Sensing)

Classify satellite images to extract palm crowns, then remove the centre and concentrate on the outer part of the crown. The centre of the crown remains green and is not affected by the Dubas bug. By removing the centre and concentrating on the outer part of the crown we have a higher probability of comparing impacts of Dubas bug and categorising infestation levels. The images will then be classified using unsupervised classification technique as at this stage we will not have ground truth data. Once unsupervised classification has been achieved, the Dubas bug infested crowns will be grouped into different categories based on infestation (stress) levels as detected by the satellite image. The infestation levels will later be calibrated with ground-truth data.

30 random samples from each infestation level (no/very low, low, medium, high) will be identified for collecting detailed ground truth data. Using ground truth data, we will perform supervised classification as we will know the infestation levels at the sites. The ground truth data will be used to train the algorithm and then classify the whole image. Further 50 points from each class from this supervised classification image will be used to verify the accuracy of our classification scheme. This is important as it will tell stakeholders how much confidence they can have in using satellite imagery and the methodology for broad-scale mapping and modelling of Dubas bug infestation levels.

Infestation levels will be determined by direct assessment of the insects. The most convenient way to do this is by collection of frond samples and distinguishing between newly laid eggs (this season) from those of previous seasons which did not hatch. Per-season (June; January) per farm and per tree, 3 fronds at 3 different heights (frond ages) (bottom, middle, and top will be cut, making sure the 3 fronds are from different compass directions, from each of 4 palms per each of the 4 major cultivars of the farms (e.g. Khalas, Fardh, Khasab, Naghal). This will amount to a maximum of 48 frond samples per farm. Unhatched, unparasitized new eggs (white with greenish tissues around) will be counted to determine current season densities (which predict next season infestation) in a subsample of 10 randomly selected leaflets and 10 inter-leaflet areas from each of the base, middle, and apex of each frond. Old eggs (hatched, unhatched, parasitized) on bottom fronds will be counted (based on same subsamples indicated above) once at the beginning of the sampling program to get an idea of past infestations (accumulated for past 3-5+years).

The crown information extracted will be used to calculate the density of palms per unit area; to be used as part of the GIS based spatial analysis to answer the question whether infestation levels are linked to the density of palms. The crown information will also be used to determine random systematic nature of farms. This information will be used in the GIS analysis to answer the question whether the random plants have a higher risk of infestations.

The crown information will also be used to determine row spacings. Literature mentions that those plantations that have wide row spacings have lesser likelihood of high Dubas bug infestations. The row spacings data extracted from the satellite image will help us correlate infestation levels with row spacings.

Data generated:

- Tree density
- Tree spacing
- Infestation levels
- Accuracy of infestation level
- Type of plantation (random or systematically planted)

Image fusion techniques will be used to merge the 2.5m multispectral image with the 0.7m panchromatic image to utilise the advantages of both image sets. The panchromatic image has a very good spatial resolution but lacks the multiband information that the 2.5m multispectral image provides. By using various image fusion techniques we will be able to use the strengths of both the image sets. We will compare the accuracy and distortion levels of 4 image fusion techniques: HSV, Brovey, Gram-Schmidt and Principal Component. The selected technique will then be used for the fusion of all Worldview images and all classification (both supervised and unsupervised) will be carried out using this image.

(ii) Change detection sensitivity levels over a longer time frame (Remote Sensing)

Based on the classifications of all areas covered by the images in the first part of the project, a number of different areas will be selected for more intensive spatio-temporal risk assessment studies. We will obtain as much historical images as possible for these areas and will supplement this by the following 2 years of data. We aim to build a picture over a 10 year period of infestations (say from 2004 to 2014). These multi-year images will be classified as in the first part of the project. Change detection will be analysed by standard change detection algorithms. The change detection will tell us the degree of change in the infestation levels that needs to occur before they are detected by the satellites. This is important for the development of a management and surveillance system for Dubas bug monitoring.

(iii) Visualizing and identifying hotspots (spatial patterns) (GIS)

We will use clustering techniques such as Getis Ord Gi*, Moran’s I and Ripley’s K function to identify and visualize the hotspots of Dubas bug infestation. For hotspot analysis we will need locations and levels of infestations of the Dubas bug. This information will be extracted from the classified satellite image. All infested levels as detected by the satellite image will be extracted and coded for different levels of infestation. The raster data will be polygonised to give polygon data as an input to the cluster analysis algorithms. Where point data is required we will use the centres of these polygons.

The hotspot analysis will give us information about those regions that have a higher risk of infestation. Based on the hotspot analysis, different layers will be created for each level of infestation. This will then be used to determine the spatial direction for each infestation level. Direction distribution (ellipsoid) method will be used to identify the direction of each risk level.

(iv) Determining spatial correlations with meteorological variables (GIS)

Based on the satellite image classification results, we will select 120 plots for more intensive studies. 30 plots will be selected from each of no, low, medium, and high infestation classes. In each of the plots we will measure the minimum/ maximum temperature and relative humidity every half an hour every day over 2.5 years. We will mount dataloggers that record data at set intervals and can be downloaded via a USB device once every 3 months. The plots will be selected based on stratification, so that we cover different soil types, rainfall regions, elevations, etc. 40 rain gauges will be installed to cover the region and data from these will be integrated to give a continuous rainfall surface over the study region. At present most of the weather stations in Oman are along the coastal regions and are not suitably located to be used for interpolation purposes.

We will use Geographically Weighted Regression (GWR) to model correlations between Dubas bug infestations and meteorological variables. The meteorological variables tested will include temperature (max, min), relative humidity (max, min), and rainfall. Relative humidity and rainfall data recorded in the field will be supplemented by data obtained from the Bureau of Meteorology and derived from satellite imagery (NOAA or Meteosat). We will correlate each infestation level with each individual meteorological variable to determine the suitable meteorological variables and range that suits the development of Dubas bugs. Then, an overall model will be created to include those variables with the highest correlations with infestation levels.

We will use the humidity and temperature measurements from each of the plots and the densities of the Dubas bug to test the significance and predictability of the Humid-Thermal index for Dubas bug distribution. Daily minimum and maximum relative humidity and temperature data will be collected and averaged on a weekly basis. Humid thermal index (HTI) will be calculated by dividing values of humidity by the corresponding values of temperature. The correlations will be worked-out between peak values of Dubas bug infestation and weekly calculated HTI. This in turn will give most favourable and least favourable windows of conditions during seasons. Conditions during those periods will provide input in the form of HTI for developing predictive models. Other than current, this study will use available historical data of Dubas bug and HTI to strengthen predictability of the model.

(v) Modelling solar radiation on monthly basis

We will use Kumar’s 1997 model to calculate the potential solar radiation at each location for 12 months and will then correlate these with different infestation levels to examine if solar radiation plays a determinant role for different infestation levels in different locations during the infestation periods. A digital elevation model (DEM) for Oman will be used in this modelling. The solar radiation modelling will be done on a per pixel basis and will incorporate the effects of slope, aspect, day of the year, sun position in the sky and the impacts of shading by adjacent terrain. We believe shading will be an important factor due to the rugged terrain surrounding most of the date plantations in the wadis.

(vi) Determining spatial correlations with environmental variables

We will use GWR to model correlations between Dubas bug infestations and the environmental variables such as soil types and salinity. We will measure soil salinity in each of the 120 plots, with at least 3 readings per plot. The soil types layer will be obtained from the Ministry of Agriculture. After collecting the data of environmental variables, suitable types of soils and suitable salinity levels will be determined, and then an overall model will be created to include those variables with the highest correlations with infestation levels.

(vii) Determining spatial correlations with human relative practices

GWR will be used to model the correlations between Dubas bugs and human related practices that include irrigation practices, row spacing, density and management in terms of undercover vegetation. Firstly, row spacing and density will be extracted from the satellite images. Secondly, irrigation practices and management in terms of undercover vegetation data will be collected using a simple questionnaire. The questionnaire will be divided into 2 sections. The first section will be about irrigation practices and the second about management in terms of undercover vegetation.

(viii) WebGIS server system (eDubas)

A prototype WebGIS-based information system will be developed incorporating all the spatial and non-spatial details pertaining to Dubas bug issues. Our proposed *eDubas* bugs-clearinghouse will be a repository physical structure, which collects, stores, and disseminates information, data and metadata. Using this application, GIS layers will be dynamically added and/or removed during runtime and it will have basic functionalities like Zoom In, Zoom out & Pan in order to view the map with clarity. It will have options for displaying attributes like area, type of species, population and other relevant information. The query window options will help to select the theme, attribute table, and attribute values. When the query is executed, the features in the themes (e.g., *wadi*) that satisfy the condition will be highlighted in the Map Window. The saved queries will be used to execute the classified output based on the client's requirements. An administrator in each zone will help to maintain the server as well as the data.

A proper integration of spatial data in the GIS and the non-spatial data residing in the RDBMS will be achieved in the GIS environment through Open Database Connectivity. Care will be taken to ensure that the linkage of maps to the attribute database remains dynamic, in the sense that whenever there is a change in the attribute database, it gets reflected in the GIS. A GIS interface will be customized with ESRI ArcView® as the base, the customization environment being Avenue with Dialog Designer and ArcView Network Analyst extensions. A comprehensive custom query shell, specific to the pest-science requirement, will be built across different species attributes in the attribute database, and incorporated in the menu based graphic user interface. This will be a prototype to show proof of concept. A more detailed system can be set up later, building on the lessons and expertise of this prototype.

Roles and Responsibilities

PhD 1 Remote Sensing – Image classification, segmentation, infestation levels and distributions, extraction of single crown information and densities, row spacing determination, etc.

PhD 2 GIS – Hotspot and cluster analysis, regression analysis, correlation of infestation levels with environmental and climatological variables, etc.

***MSc 1* –** GIS – Webserver development (*eDubas*).

***MSc 2* –** Spatial patterns of Dubas bug migration in northern Oman and the climatological factors affecting dispersal of this pest.

***Postdoc* –** Humid-Thermal Index related work, advanced image classification, image fusion techniques, etc. Support for PhD and MSc students, fieldwork organisation and supervision.

***PI (Dr Kumar)* –** Overall in-charge of project, principal supervisor of 2 PhD, co-supervisor of 2 MSc, supervisor of post-doc, With Asso. Prof. Mutanga will research hyperspectral and spectroscopy to develop algorithms for early detection of stress levels from hyperspectral signatures. Solar radiation modelling for input to predictive model, advanced spatial analysis techniques.

***CI (Dr Al-Wahaibi)* –** Principal supervisor of 1 MSc, co-supervisor of 2 PhD. Research on the spatial patterns of Dubas bug migration in northern Oman and the climatological factors affecting dispersal of this pest.

***CI (Dr Madhavan)* –** Principal supervisor of 1 MSc (*eDubas*), co-supervisor of 2 PhD. Research on predictive modelling of Dubas bugs hazard and mitigation involving Bayesian statistics and WOFE modelling.

***CI (Dr Al-Awadhi)* –** Co-supervisor 2 MSc, 2 PhD. Research on database development for *eDubas*, linking various sources of information, authorisation levels, etc.

***CI (Dr Al-Yahyai)* –** Co-supervisor 2 MSc, 2 PhD. Study effects of management aspects of dates, mainly fertilizer, irrigation, pruning and thinning of infested palms on date production & quality; physiological effects of date palm (in terms of photosynthesis and chlorophyll) due to Dubas infestation.

Milestones

Month 1: Kickoff and planning workshop, including field visits and site selection; Advertise for postdoc, 2 PhD and 2 MSc students, shortlist and interview.

Month 2: PhD and MSc students enrol and commence research

Month 12: PhD students submit first papers to international peer reviewed journals for publication

Month 18: PhD students submit second papers to international peer reviewed journals for publication

Month 24: PhD students submit third papers to international peer reviewed journals for publication

Month 26: Masters students submit thesis for examination; MSc students submit one paper each for publication

Month 30: PhD students submit fourth papers to international peer reviewed journals for publication

Month 36: PhD students submit thesis for examination (if enrolled in a 3 yr PhD). Final workshop in Muscat. All stakeholders and interested personnel invited. Submission of final report.

6. Academic, scientific and/or innovation significance :

In this project, spatial information technologies will be used to extract intensive details about spatial patterns, spatial correlations and other factors regarding Dubas bugs and different environmental, climatic and cultural variables that can help to understand, control and manage the impact of these insects on palms across Oman. This will be the first study worldwide to use these methods to study Dubas bugs and their impacts, in contrast to previous studies, which concentrated on ecology and entomology. An exhaustive search of literature has shown that there is no study linking location-based infestation levels of Dubas bugs with climate, environmental or human-related variables in the Middle East. This is an innovative research for the Middle East and Oman.

This will be the first time humid-thermal index (HTI) has been used to describe the ecological niche of the Dubas bug. This index has been used successfully in the study of pest problems, such as karnal bunt (caused by *Tilletia indica* Mitra) in wheat (Jhorar *et al*., 1992; Allen *et al*., 2009) and Ascochyta blight of chickpea (Jhorar *et al*., 1997). This index was developed by Dr Jhorar and he has agreed to be a consultant on this project.

This project should also lead to more refined and targeted research in the biology/ecology fields for the Dubas bug as relationships with environmental/ climatological/ human variables will be better understood. Ad-hoc projects waste valuable resources.

The Dubas bug hazard maps prepared will help to compose an Integrated Palm Management plan. This study would enhance the building capacity and skill in farmers to apply Integrated Palm Management (IPM) for control of pests.

This study will also develop models for egg hatching and the size of population of the Dubas bug. It will also show dispersal patterns of Dubas bug.

This project will result in the publication of at least 12 papers in international peer reviewed journals. Twelve papers in international journals over three years will certainly place Dubas bug research in Oman on the world map.

The results and data developed as part of this project will play a key role in future Dubas bug research that could form phase two of this project, namely:

1. Impact of climate change on the distribution and productivity of date palms in Oman and the Middle East.

2. Impact of climate change on Dubas bug population and distribution patterns.

3. Fully operational, whole of Oman webserver system; i.e. a full *eDubas* system.

This study is a new concept and for the statistical methodology mentioned here, there is no documentation in the scientific community (entomology/ biology/ agriculture). This project will help Omani entomologists/biologists/agriculturists to become leaders in advanced analytical methods. The statistical modelling system developed during this project will largely promote advanced research among biologists in Oman and subsequently in the entire Middle East.

One of the issues of concern identified from literature and talking to experts on the ground in Oman is the lack of data on Dubas bug research covering wider areas. Most of the ecological and entomological research has been conducted on local or field scale. This study will generate data at fine scales covering larger areas of Oman than any of the previous studies.

Allen, T.W., Jones, D.C., Boratynski, T.N., Ykema, R.E., Rush, C.M. (2009) Application of the Humid Thermal Index for Relating Bunted Kernel Incidence to Soilborne *Tilletia indica* Teliospores in an Arizona Durum Wheat Field. *Plant Dis.*, 93:713-719.

Jhorar, O. P., Mavi, H. S., Sharma, I., Mahi, G.S., Mathauda, S. S., Singh, G. (1992) A biometeorological model for forecasting Karnal bunt disease of wheat. *Plant Dis. Res.*, 7:204-209.

Jhorar, O.P., Mathauda, S.S., Singh, G., Butler, D.R., Mavi, H.S (1997) Relationships between climatic variables and Ascochyta blight of chickpea in Punjab, India. *Agr. and For. Met.*, 87: 171:177.

7. **Potential economic impacts of the proposal :**

Date palms are important in Oman because large amounts of money have been invested in this area through the government and local people. Therefore, they are related to the lives of Omanis and Oman's economy. Also, many Omanis are employed in farms or date-processing factories, what we call 'the value adding chain'. This project will save money because it will find the best way to avoid the impact of these insects by reducing the use of pesticides, which are very expensive. Also, it will reduce the impact of the pesticides on the natural enemies of Dubas bug, and on the environment and humans.

The benefits of this project are also in terms of better planning of date palm orchard locations and better design and management of farms, what cultivars to plant, spacings of rows, etc. There will also be savings on monitoring costs since remote sensing based methods developed as part of this project will provide a more efficient and cost-effective means of large scale monitoring of infestations and stress on date palms.

Models for predicting egg hatching and the size of populations in the future will lead to better preparation and less costly mistakes, resulting in a reduction of overall cost of management.

Once we know the hot spots of Dubas bug infestations, we can have more targeted insecticide applications. This will save on insecticide use, so lower expenses for farmers and the government. This will in turn result in better quality fruits, so higher income for farmers. Also, if the fruits are free from insecticides, the prices fetched on the markets will be higher as many countries do not allow importation of fruits that have traces of insecticides.

As a result of this research, farmers will be better informed about risks and impacts of the Dubas bug and are likely to take action earlier, thus reducing insecticide use. Through spatial analysis, hot spot analysis and distribution patterns, there will be a better understanding of Dubas bug distribution and risk areas, so can take early intervention to limit damage.

Based on the Humid-Thermal Index, advance pest outbreak warning systems will assist administrators, planners and farmers to manage the risk of crop loss when conditions are favourable for prolific growth of the bug while avoiding unnecessary use of resources when the pest is unlikely to damage the crop. This will minimise the resistance in the pest against existing chemicals used to control the bug.

8. **Expected social, cultural, educational and welfare benefits :**

Through this project farmers and other stakeholders who have date palms impacted by Dubas bugs will be appraised of the levels of risk and infestation levels and the best methods to avoid the dangers of this type of insect on the palms. This will lead to higher quality and productivity of dates, resulting in higher incomes for the farmers and the country.

The project should save the date palms by raising awareness of locations where date palms are unhealthy, and the human related factors leading to decline/ neglect. This should improve date palm cultivation throughout Oman.

Date palms are especially important in Oman because large amounts of money have been invested in this area through the government and local people. Therefore, they are related to the lives of Omanis and Oman’s economy. Also, many Omanis are employed in farms or date-processing factories. This project will save money because it will find the best way to avoid the impact of these insects by reducing the use of pesticides, which are very expensive. Also, it will reduce the impact of the pesticides on the natural enemies of Dubas bug, and on the environment and humans.

Through the *eDubas* webserver, farmers will have better and more timely access to information and will be kept informed of what actions and research projects are being undertaken. Farmers and other stakeholders are likely to be more cooperative if they can see what is happening and are kept informed of developments.

The *eDubas* system will also be of benefit for researchers and Ministry of Agriculture staff. It will contain metadata for all data layers. It means researchers do not have to waste money duplicating data capture. It will have historical and average rainfall, minimum and maximum temperature, relative humidity, soil salinity, soil types, date species at each plantation, age, row spacings, productivity (if available), history of pesticide use, etc. Staff from the Ministry of Agriculture based in different regions will be able to add data and be able to query the database to obtain information about infestation levels in different areas and make informed decisions about management and pesticide spraying needs. This will mean that there will be better and more efficient use of chemicals, leading to less impact on the environment and the natural enemies of the Dubas bug. Infestation breakouts will be more easily reported and acted upon and the ministry will have a more efficient use of the resources at its disposal.

Some other benefits are:

1. Human capacity development through building up the know-how in entomology, biology and

agriculture.

2. This research will also greatly extend the strategic goals of the Ministry of Agriculture for pests' control.

3. It will develop a well-educated workforce that can sustain and improve the educational infrastructure as well as economic growth (in export grade date palm farming) in the Sultanate of Oman.

4. The research will produce Omani researchers who will become experts in planning and conducting Integrated Palm Management in Oman.

5. Local Omani researchers/management officers will be an integral part of this research project to ensure the integrity of the data collected and validate the results for practical use.