# An Epidemiological Approach to Assessing the Risk of Establishment of Karnal Bunt, *Tilletia indica* Mitra, in North America

**North American Plant Protection Organization**
**(NAPPO)**

**PEST RISK ANALYSIS PANEL**

***Canada - Mexico - United States***

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## INDEX

## EXECUTIVE SUMMARY

The Pest Risk Analysis Panel of the North American Plant Protection Organization (NAPPO) assessed the risk of Karnal bunt, *Tilletia indica* Mitra, establishment in commercial wheat production areas of North America. Critical factors of climate and host conducive to disease development were identified in conjunction with their time of occurrence, in phenological terms, and with potential disease severity to categorize areas at risk for Karnal bunt establishment. Detailed daily weather attributes of North America were analysed to develop a model to identify and characterize wheat production areas as zones of high, medium, or low risk (Sequeira 1999).

Data were stratified by the phenological window corresponding to the critical period of wheat anthesis for each county or municipio across North America. Decision rules were subsequently formulated to determine the probability of host and disease occurrence in relation to disease severity, or any index thereof, to allocate counties to a specified level of risk for establishment. Three broad categories of risk zones were formulated by building a mechanistic or process-oriented model and displaying the results spatially for North America using geographic information systems (GIS). Data that were collected, characterized, and linked to the disease triangle include: crop production features (yield and cropping regions of wheat), relevant wheat cultivation practices (planting dates), climatology (daily historical weather station records), known disease distribution (survey results), crop development (crop phenology), and historical disease dynamics and indices of damage levels, and host and environmental conditions leading to disease outbreaks.

Our assessment of the risk of establishment of Karnal bunt in wheat suggested that the majority of production regions of North America are not highly susceptible to this disease. Limited areas have been identified where risk may be considered as “medium. Analysis of prevailing weather and planting patterns during the production of winter and spring wheat shows that the susceptible period does not generally coincide with climatic conditions favorable to the disease for the majority of locations. Karnal bunt will likely remain “below levels of regulatory concern” throughout most wheat production regions of North America most of the time, with the exception of weather anomalies. Knowledge of the potential risk of establishment of this disease provides for more transparent justification of any risk management measures to be undertaken and aids in more efficient phytosanitary resource allocation.

## INTRODUCTION

Karnal bunt, *Tilletia indica* Mitra, is primarily a seed-borne fungal disease of wheat and triticale that could negatively affect the major wheat growing regions of the world. The effects of Karnal bunt on wheat yield are minor to insignificant; however, the effects on quality (objectionable fishy odors) are manifested in wheat lots with 3% or more infected grains and are undesirable. The movement of contaminated seed from infected areas poses the greatest risk for spread of Karnal bunt and is likely the main pathway worldwide. This disease is difficult to identify and control in the field (Murray and Brennan 1998).

Karnal bunt of wheat has a limited distribution worldwide and is confined to parts of Asia and North America (Murray and Brennan 1998). It was first reported from Karnal, India around 1931, where it had caused some yield damage. It has also been reported from neighboring regions in Nepal, Pakistan and Iran, as well as Iraq and Afghanistan (Warham 1986). In the late 1960's this disease spread to the major wheat growing areas of Mexico (Sinaloa and Sonora) and in 1996 was found in neighboring wheat growing regions in the southwestern United States (Arizona, California, and Texas) where it is currently under eradication (Poe 1998; Babadoost 2000). Karnal bunt is not known to occur in the northern US or Canada.

Within North America, zero-tolerance domestic and international quarantines are currently in place to prevent further spread of the disease (Babadoost 2000). At this time the disease appears to be confined to unique eco-climatic regions of Mexico and southwestern US; however, significant portions of wheat production in these regions are still considered located in pest-free areas.

In Mexico, pest free areas in the state of Sonora include the production areas of San Luis Rio Colorado. Pest free areas in the state of Baja California include production areas of Mexicali. Finally, the states of Guanajuato, Jalisco, Michoacan, and Queretaro are considered pest free. No significant evidence of disease spread outside of the southwestern US, in terms of expression of symptoms, has been observed since intensive surveys began there in 1997. Where new finds have been recorded, these have been associated with extremely low levels (0.1% or lower); much lower than those expected to have effects on quality or productivity.

Weather extremes (extremely dry and hot or very humid and cold) conditions are not conducive conditions for disease development (Sansford 1998). Karnal bunt appears to be limited to moderately cool and moist eco-climates. Such conducive conditions may also occur, but are rare, in northern parts of the US and Canada (Jhorar *et al.* 1992; Sansford 1998; Diekmann 1998). However, the disease has never been detected outside of its current distribution in the southwestern US and Mexico despite the historic movement of seed throughout much of the wheat growing regions of North America. This relatively limited distribution of Karnal bunt could be attributed to specific climatic factors impacting on the life cycle of the fungus (Diekmann 1998). Thus, the Pest Risk Analysis Panel of the North American Plant Protection Organization (NAPPO) investigated the likelihood that Karnal bunt could become established in other commercial wheat production areas of North America based on climate. We developed a mechanistic or process-oriented risk model based on daily weather data and resolved at the county or municipio scale for all of North America. Various models to estimate risk of establishment of Karnal bunt in different countries have been developed (Kehlenbeck *et al.* 1997; Diekmann 1998; Murray and Brennan 1998; Sansford 1998; Baker *et al.* 2000), but only one has been based on daily weather attributes (Sequeira 1999). We used the spatial analytical approach applied to a US-wide assessment of Karnal bunt by Sequeira (1999) for a North American scale assessment in this document.

## METHODS AND APPROACH

We adopted a mechanistic or process-oriented modelling approach to risk assessment based on epidemiological principles. The goal was to determine risk at a realistic but practical scale for risk management. Our model formulates decision rules based on information from the model developed by Jhorar *et al.* (1992) for field conditions, as well as information obtained from biological research cited here. The output from the model provides qualitative categorizations for risk of establishment based on estimates of the likelihood of establishment and the magnitude of disease severity as determined by climate (*i.e.*, the likelihood that Karnal bunt could infect wheat at a particular location to a specified degree of severity defines risk of establishment).

Our study focuses on one element of stage 2 (risk assessment) of the International Plant Protection Convention (IPPC) risk analysis process (FAO 2001); the characterization of the risk of establishment of Karnal bunt within continental North America (*i.e.*, within the NAPPO PRA area). Our analysis assumes a pathway to the wheat fields of North America. More detailed pathway analyses can be found in Warham (1986) and Babadoost (2000) and others. Despite extensive research efforts worldwide, much is still unknown about the pathway for introduction and the complex biology of this disease.

### *Production Characteristics Relevant to Karnal Bunt Establishment*

Wheat is grown extensively throughout North America with the United States having the largest acreage, followed by Canada and Mexico (Anon.1994). Wheat is a leading export crop in all NAPPO countries. Wheat-growing regions in North America are shown in figure 1. Despite the existence of several hundred cultivars, only a small proportion of the available cultivars are actually sown. Several agronomic types or varieties of wheat are grown and are categorized according to factors such as milling characteristics, where they are grown, and when they are planted. Wheat is planted in both winter and spring, and wheat types include red, white, winter, durum, *etc.* The distribution of wheat in terms of tonnage harvested is shown in figure 2. In the Yaqui Valley region of Mexico, planting has been progressively shifting to more resistant Durum wheat and this trend has significantly reduced the incidence of Karnal bunt (Nagarajan 1991).

A key risk criterion considered in this analysis is the unique property that wheat is planted during periods referred to as “sowing windows”, which vary by region. These sowing windows result in a continuous progression of wheat planting on the continent starting in the southwestern-most regions in Mexico and moving progressively north until the last of the spring wheat is planted in Canada. Cropping calendars (a summary of the trend for the timing of key phenological events) are shown in figure 3a-b (Anon. 1994). This figure emphasizes the timing of the susceptible reproductive or "heading" stage. The period of susceptibility has been described by Nagarajan (1991) as Zadok's decimal scale stages 45 to 69 (Zadoks *et al.* 1974). A detailed map of periods of similar phenology (and therefore similar susceptibility) in North America is shown in Figure 4. In the United States there is a progression of planting (and consequently, heading) from south to north. In contrast, the shorter growing season in Canada is such that a much narrower sowing (and heading) window occurs. In Mexico, wheat is planted during the fall, winter, and summer seasons providing for a continuous sowing window. The extensive research collections maintained by the International Maize and Wheat Institute (CIMMYT) along the coastal areas present nearly continuous production during some years.

Different types and cultivars vary in their response to different management practices and adaptability to different conditions. Our study considered only phenological timing. Although this timing is acknowledged to fluctuate, we used average heat unit requirements within a sowing region in order to forecast the timing of the reproductive period, which is the only wheat stage vulnerable to infection by Karnal bunt. As previously noted, moisture and temperature are the two key factors that lead to disease development in the presence of a susceptible host. In addition to the observation of weather data, the use of irrigation may increase relative humidity, especially when irrigation is applied at or near the reproductive (susceptible) period. Wheat in Mexico, as well as in the deserts of Arizona and California, is produced almost exclusively under irrigation.

We note, however, that research on the effects of irrigation on disease epidemiology were not available at the time of the analysis. Cursory data analysis did not identify trends that linked irrigation to disease occurrence. This empirical observation, if indeed valid, may be due to the fact that in dry regions the effect of irrigation on microclimates (that is, the increase in moisture) is highest immediately after irrigation but drops very quickly, especially in terms of moisture on the leaves. That is, for Karnal bunt which requires relatively high moisture (likely including leaf surface moisture) for outbreaks to occur, irrigation may not be sufficient to induce epidemics, in the absence of generally conducive rainfall and temperature patterns.

### *Host susceptibility*

Despite the identification of resistance in some non-commercial lines, there is no clear and specific reported resistance to Karnal bunt in wheat in commercial cultivars (e.g., Rajaram and Fuentes-Davila 1998), although resistant varieties with improved agronomic characteristics (e.g., high yielding) are the focus of continued breeding research. It has been noted that Durum wheat is moderately resistant (Nagarajan, 1991). Since wheat is susceptible to Karnal bunt infection only during its reproductive period, wheat phenology, specifically the vulnerable reproductive period, was determined using simple phenological projections based on planting date. Planting date information was obtained from the regulatory officials from each of the three countries participating in this analysis. We used Anon. (1994) to determine the timing of heading or wheat reproductive period and to identify the areas of the highest wheat production in each of the three countries. In addition, the models of Rickmann *et al.* (1996) and Stockle *et al.* (1994)

were used to verify data from Anon. (1994) corresponding to North America. A conservative assumption was made that all varieties grown were equally susceptible to Karnal bunt and that this period of susceptibility would be restricted to the wheat reproductive phase. We further assumed that the amount of inoculum in the soil had little to no effect on the onset of the disease (G. Fuentes, *pers.comm*, 1999). We also assumed that enough infectious inoculum was present to cause the onset of the disease under the right climatic conditions.

### *Weather records and analysis*

Coakley and McDaniel (1988) have suggested that a minimum of 8 years of historical weather data be used in plant disease forecasting. In this analysis we collected historical records anywhere from ten to one hundred and thirty-five years for each of the weather station locations used to characterize North America. Although long-term historical weather records may not be representative of actual conditions during a particular day or year (*e.g.*, Casti 1991), the scope of our study was to analyse risk in the long run.

The location of weather monitoring stations used in this analysis is presented in figure 5. Weather records from the United States from 1986 to 1997 were summarized for 9,068 monitoring stations nationwide. Weather records from Mexico from 1960 to 1995 were summarized for 5,055 stations nationwide. Canadian weather records anywhere from 1864 to 1999 for some 650 stations were summarized and mainly encompass arable regions of the country as shown in the figure.

A metafile developed for each of the countries includes geographic reference information (latitude, longitude, and elevation) for all stations. Daily averages were calculated for each station over all years for which records were available, and were the key data element used in our climatological characterization. For individual stations where more than ten years of data were unavailable, actual data were used to calculate averages. This, however, was the case for less than 1% of the stations. The "historical averages" file was used to build the Karnal bunt model of establishment risk. Data were stratified by the phenological window corresponding to the critical period of wheat anthesis for each county or municipio across North America. The spatial average of daily climatic conditions was interpolated using a standard GIS triangulation method with smoothing for each county or municipio (represented by ten or more years of weather data). A phenological model was developed to identify the window of wheat anthesis. Decision rules were subsequently formulated to determine the probability of host and disease occurrence in relation to disease severity, or any index thereof, to allocate counties to a specified level of risk for establishment. This necessitated overlaying wheat susceptibility information with climatological characteristics for the corresponding period and region (*i.e.* the phenological window of wheat flowering for each county). Three broad temperature regimes were identified as crucial to disease severity and form the basis of the decision rules to allocate risk of establishment into high, medium, and low risk categories.

The work cited previously (*e.g.*, Bonde *et al.* 1997, Jhorar *et al.* 1992 ) suggests that weather conditions appropriate for Karnal bunt development include a relatively cool temperature regime (temperature maxima between 14°C and 20°C) and an elevated humidity or repeated rainfall as detailed below. Temperatures between 16-18°C were considered optimal for this study. Temperature maxima outside this range but approaching 5°C or 20°C were considered adequate but less than optimal. Above 20°C and below 5°C temperature maxima, conditions were considered not conducive to disease development. We acknowledge the lack of consistency among authors in reports of temperature optima for Karnal bunt, and therefore tested the assumptions above including deviations of plus or minus two degrees. Factors determining etiology are detailed below. Our baseline study used only temperature factors. That is, the temperature regimes are consistent with Jhorar *et al.* (1992), but we do not use a humid-thermal index in these studies, as relative humidity data were unavailable. After examining the categorizations obtained from a temperature-determined risk categorization, we further examined the correspondence of the identified regions with rainfall patterns.

### *Integration of the Data intoRisk Zones*

The output of this study is the characterization of discrete geographical zones by varying degrees of establishment potential of Karnal bunt in the wheat production areas of North America. We used geographic information systems (GIS) software to overlay data layers. The mapping of regions with equal likelihood of pathogen establishment (hereafter, "isopathogenicity"), regions of same susceptible phenology (hereafter, "isophenology"), productivity maps, and conservative assumptions of propagule entry or survival in the pathway (*i.e.*, the assumption that the pathogen is omnipresent) provided a final determination of risk zones. We use the term "zone" to describe one characteristic of the landscape; we use the term "risk zone" to characterize an aggregated area of equal risk rating. Specifically, where an intersection in time of the host's reproductive status and range of weather conditions conducive to the disease was identified in a particular area, an estimated risk rating was allocated to the area and called a risk zone. The specific categorization of risk zones into "high", "medium", and "low" categories was made based on how close the average climatic conditions were to the field optimal for Karnal bunt given that the host was susceptible at the location and time being characterized.

It was assumed that the climatological records were related to micro-canopy conditions, an assumption that will obviously be less robust given irrigation or other agronomic practices which may dramatically alter the microenvironment. It is known that irrigation increases the susceptibility of wheat (*e.g.*, Nagarajan 1991), by modifying the microclimate (temperature and humidity). Although we initially concentrated on temperature while assuming humidity was optimum, we incorporated a decreased likelihood of pest establishment in areas with reduced moisture by examining precipitation variations (from climatological normals) during periods of wheat susceptibility.

Reports of optimum conditions for the pathogen defined by (Jhorar *et al.* 1992) were used to generate our results. The model used is reasonably robust and the assumptions as to the specific "optimal" temperature selected can easily be modified. The results and interpretations however, were found to be insensitive to changes of up to "2°C.

In summary, the specific steps for developing the categorizations into risk zones included: 1. developing geographically referenced data files on wheat planting and estimated phenology from the daily weather archive for North America, 2. developing geographically referenced data files on climatology, 3. developing geographically referenced data files on the occurrence of Karnal bunt disease, 4. producing a continuous raster grid (a continuous color map) by interpolation of climatology point data, 5. producing a series of maps representing different snapshots over time in which climatological characterizations (temperature, rainfall) were overlayed with polygons outlining areas where wheat was susceptible during specific time periods, 6. using graphical correlation to characterize geographic regions into risk zones (*i.e.,* intersection of the set of criteria defining risk of establishment).

## DISCUSSION OF RESULTS

We used multi-layered maps to communicate our findings related to zones of similar risk ("isorisk" zones). The different layers correspond to epidemiological factors: appropriate weather conditions, susceptible host, and a pathogen capable of inducing disease. Additionally, we present the geographical distribution of wheat yields to indicate key production areas and to further investigate the magnitude of risk involved.

Figure 6a-m shows maps that overlay regions of similar and susceptible phenology ("isophenology" regions, shown as black polygons with no shading) and isothermic regions where the color-coding corresponds to degree of appropriateness for pathogen development. That is, these isotherms were defined to correspond to the range of conditions (optimal to sub-optimal) relative to the ability of Karnal bunt disease to develop. These identify regions of "isopathogenicity" as specified by the color gradients. The terms *isopathogenicity* and *isophenology* are proposed for convenience and do not represent botanical or epidemiological conventions. Figure 6a-m corresponds to different periods that capture the progression of wheat phenology in North America. That is, each figure corresponds to a period during which wheat is in a phenologically susceptible state. In figures 6a-m the color yellow represents the optimal or near optimal given the assumptions previously discussed. The color blue and green represent adequate but not optimal conditions. Colors approaching red and black (on the "hot" side) and towards purple ("cold" side) are not considered susceptible to disease development. Although we analyzed establishment risk for all two-week periods during the entire growing season, only representative examples of our findings are shown. All analyses support the findings demonstrated by the figures.

### *United States*

Maps of the United States (figures 6a-d) show broad areas that cover all risk categorizations when considering temperature only. When the crop and its phenological patterns are considered however, we note that during mid-April (figure 6a) most areas of wheat (southernmost production regions of the United States) are too warm to support epidemics. There are small regions of Texas, Arizona and California that are considered of medium risk, and there are a few discrete regions of California that would be considered at high risk. For mid-May (figure 6b), conditions in areas with susceptible wheat are considered too warm to support epidemics. There are very small, discrete areas of medium risk as shown by the blue points on the map. During early to mid June (figure 6c), temperatures continue to increase countrywide, reducing the risk of Karnal bunt development. A few exceptions and discrete areas of high risk are shown as yellow points on the map, along with discrete areas of medium risk as denoted by blue and green shades. Finally (figure 6d), most of the spring wheat (northernmost production areas) enters its reproductive period (from late June to early July) when temperatures are generally too warm to support epidemics, except for small areas of medium risk shown as blue points on the map. Figure 7.1-7.2 show that low precipitation patterns prevail during wheat susceptible periods in the United States. In figure 7, polygons indicate where wheat is grown and is in a phenologically susceptible period. Consideration of the importance of areas with higher relative precipitation (figure 7.1-7.2; blue shaded regions) is necessary; although temperatures in figure 6a-d may not be conducive to Karnal bunt epidemics during average years, these areas may exhibit higher levels of risk during years that deviate significantly from the norm (*e.g.*, during El Niño events). Therefore increased vigilance (in terms of surveys) is warranted in the areas where susceptible stages overlap with higher precipitation patterns (figure 7.1, 7.2).

### *Canada*

Maps of Canada (figure 6e-f) show that spring and durum wheat production in the Canadian Prairies (which has a late June to early July reproductive period) is phenologically susceptible when it is too warm for the pathogen to develop. There are areas of suboptimal temperature along the northwestern fringes of these production areas (e.g., northwest of Alberta and westernmost production areas, as indicated by the blue shaded regions. No areas in Canada approach optimal temperatures. Karnal bunt has been reported unable to survive extreme freezing conditions (Nagarajan, *pers. comm.*). According to these reports, severe winter temperatures such as exist in Canada (figure 9) are linked to decreased propagule viability. Thus, it is unlikely that this disease would become established in the Canadian Prairies given temperatures that can dip below -27°C during the winter. In addition, rainfall in Canada during the periods of susceptibility (figure 7.4) is low in the Canadian Prairies and further reduces the level of risk. Winter wheat growing in southern Ontario and Quebec and the very few areas of Atlantic Canada are at low risk too. Results of isorisk areas are analogous to those of states in the northeastern US bordering Canada. Despite warmer winters in eastern Canada compared to the Canadian Prairies, temperatures can still get cold enough to hamper inoculum potential of Karnal bunt, thereby further reducing risk. These results are comparable to those of most of the northeastern states of the US. Clearly, in the long run and excluding anomalies, Canada is unlikely to have climatic conditions conducive to the establishment of Karnal bunt.

### *Mexico*

The map of Mexico shows temperature regimes that span all categories. Within the areas marked by the polygons corresponding to Fall-Winter production regions (reproductive period from end of January to February) there exist limited locations with optimal temperatures for Karnal bunt development (yellow shading) in the States of Baja California, Chihuahua, Sonora and Coahuila (figure 6g). The Winter wheat entering reproductive period during January and mid-February is associated with a higher incidence of areas with sub-optimal temperatures (medium) as indicated by the blue shading (figure 6 g,h).

For Winter wheat that enters reproductive stages at the beginning of March, there are areas in the Northern production regions experiencing optimal temperature conditions (yellow shading), but sub-optimal conditions (medium) predominate as indicated by blue shading (figure 6i). Most of the country experiences temperatures not conducive to establishment during May to September (figure 6g,k,m) as indicated by the red shading. There are no areas showing optimal temperatures for disease development during this period.

For Spring-Summer wheat that enters its reproductive period towards the end of July through September the temperatures are not conducive, with discrete of sub-optimal temperature indicated by the blue shading near the State of Mexico. Indeed, most of the production at the end of the season (July to September) occurs with temperatures above those considered optimal (red and dark shaded areas). An exception to the warming trend is the existence of areas of sub-optimal temperatures in the States of Mexico, Hidalgo, Tlaxcala, and Puebla (blue shading).

Figure 7.3 shows that the precipitation that occurs during Summer and Fall (June to October) does not coincide with phenological stages susceptible to disease development in the production regions of Fall and Winter wheat. The pattern of precipitation only shows coincidence with susceptible stages in the production areas corresponding to Spring and Summer. However, in these areas temperatures are moderately conducive (but still sub optimal) for disease development.

### *Occurrence of Karnal bunt in North America*

Figure 8 shows all known records for Karnal bunt in North America denoted by stars. Known positive locations (through 1999 survey reports) are located in Arizona and Texas in the United States and primarily along western coastal areas (States of Sonora and Sinaloa) in Mexico. Some known positive locations, especially in the coastal states of Sinaloa and Sonora where high levels of infestation have been reported, do not correspond to high-risk zones as predicted by our model.

Conditions in these coastal growing regions are unique in that significant precipitation does occur during the latter part of the year. Whereas most commercial wheat is not susceptible after July, the extended planting season here results in the presence of wheat year round in some years. This factor is likely to increase susceptibility because of the shift in sowing windows for any given year.

The temperatures, however, remain sub-optimal at coastal locations in Mexico (Sonora, Sinaloa, Baja California) where positive finds are reported and Karnal bunt has become prevalent. Whereas rainfall is likely a factor increasing susceptibility, the research of Rosenberg *et al.* (1983), Baker (1994), Régnière and Bolstad (1994), and others suggests that temperatures in coastal areas are commonly overestimated, as the cooling effect of coastal winds on crops is not captured by weather monitoring stations. This research suggests that a combination of lowered temperatures due to coastal effects, rainfall patterns that overlap susceptible periods, and the use of irrigation are factors conducive to Karnal bunt development in Mexico as shown in figure 8. Inland areas of Arizona and Texas where most US finds were reported would not be subject to the same coastal effects, do not share the same precipitation patterns during periods of susceptibility, and do not experience optimal temperature ranges for disease development. Further, significant infection of Karnal bunt has never been detected in the United States, which further strengthens our conclusion that coastal wheat production is subject to unique conditions that increase susceptibility. The nature of irrigation on Karnal bunt etiology, however, needs to be monitored and evaluated, especially in Mexico and the southwestern US.

A final note regarding likelihood of establishment concerns the behavior of pathogen spores under snow cover or extended cold conditions. Nagarajan (*pers. comm.*) has stated that Karnal bunt spores may rapidly decay under extreme cold. This is consistent with the response of many living organisms, but we do not have quantitative relationships available at this time. Figure 9 shows North American climatic trends for temperature minima from January to April (each subfigure represents average conditions during a one-week period). The blue shaded areas correspond to temperature minima below freezing. Figure 9 suggests that significant portions of North America including most wheat growing regions in the United States and all of Canada, would not be conducive to long term survival (and therefore permanent establishment) of Karnal bunt.

### *Interpretation of Risk Zones*

This section discusses the interpretation of risk zones produced by our model.

***High*** risk zones result from the concomitant occurrence of the following criteria impacting on Karnal bunt epidemiology in each county or municipio in North America:

1. the temperature regimes are near the optimal for the disease, 16°-18°C; and
2. the crop is subject to optimal moisture conditions, rainfall > 4 mm/day for all days; and
3. the crop is in a susceptible stage, (*i.e.*, during heading identified as Zadok's decimal scale wheat growth stages 45 to 69 for all days; or

***Medium*** risk zones result from the concomitant occurrence of the following criteria impacting on Karnal bunt epidemiology in each county or municipio in North America:

1. the temperature regimes tend to be close to the high or low temperature extremes at which epidemics do not occur (*i.e.,* temperature is not optimal to support epidemics), 5°-15°C or 19°C; and
2. moisture conditions are sub-optimal, rainfall 2-3 mm/day for all days;
3. the crop is in a susceptible stage, (*i.e.*, during heading identified as Zadok's decimal scale wheat growth stages 45 to 69 for all days; or

***Low*** risk zones result from the concomitant occurrence of the following criteria impacting on Karnal bunt epidemiology in each county or municipio in North America:

1. the temperature regimes tend to be beyond the high or low temperature extremes at which disease is observed to occur, < 5° C and >20°C; and
2. conditions are dry, rainfall < 1 mm/day for all days; and
3. the crop is <u>not</u> in a susceptible stage, (*i.e.*, heading identified as Zadok's decimal scale wheat growth stages 45 to 69 does not coincide with conducive temperature or moisture regimes on any day.

We noted that prolonged freezing has been suggested as a factor in inhibiting disease development (Nagarajan, pers.comm.). At this time, published evidence is not available to support a model based on these observations. We do note however that the existence of prolonged freezing conditions in significant areas of North America suggests a future model when the above considerations are coupled with freezing conditions. In addition to the considerations above, high risk would be linked with areas where prolonged freezing temperatures generally do <u>not</u> occur, except in unusual years, and therefore do <u>not</u> eliminate inoculum. Medium risk would be associated with prolonged freezing temperatures and snow cover generally occurring and therefore reducing or eliminating inoculum. Finally, low risk would associated with prolonged severe freezing temperatures generally occurring and therefore eliminating inoculum or drastically reduce any inoculum. At this time and given the limited evidence, we present the information on temperature minima to further support our findings of low risk in some areas (those prone to prolonged freezing) in a qualitative and empirical manner.

We note that the conditions for high risk (as per the parameters listed above) did not occur in most of North America. Medium risk is best indicated by the areas shaded blue in the maps corresponding to temperature and except for coastal areas, red and black shading indicates low risk. Our interpretation of available data suggests that coastal areas are prone to significant 'evaporative' cooling effects. However, the coastal areas of Mexico have not been characterized as to such effects. Our categorization of the risk in the production area in that states Sinaloa and Sonora is determined qualitatively as medium.

These risk categorizations were inferred from the temperature and moisture regimes affecting the severity of Karnal bunt along with wheat phenology data all based on epidemiological principles of disease expression and are communicated in (figure 6a-m), although not explicitly stated as such. Thus, our approach to analyzing risk was dependent on the layering of information using geographic information systems. This approach has been proposed earlier (*e.g.*, Nelson *et al.* 1999). In our application, the use of these spatial analytic tools is similar to the phytogeographic approach and to the multivariate analysis used by Dobesberger and MacDonald (1993). That is, we identify the key data types that explain disease etiology. Diekmann (1993) also identified the strongest explanatory variables using multivariate approaches and then uses those factors and the estimated coefficients to obtain ratings for any location, but in a non-GIS environment. In our study, we propose that epidemiology should dictate the main variables that must be studied and additional detail (in terms of sub-data types such as average maximum temperature during a given two-week period) should be suggested by biology but may be constrained by information availability (Zadoks and Schein 1979). The resulting identification of susceptible areas is dependent on the concomitant occurrence of the range of the three key factors determining disease epidemiology in both space and time (assuming sufficient time for interactions): susceptible host, virulent pathogen, and appropriate climatic conditions. These descriptions of risk are based on average conditions. Weather anomalies (e.g. those experienced in the state of Texas, USA during 2001) will make it possible for outbreaks to occur on specific years if inoculum is present.

### *Applicability of the correlative approach using geographic information systems (GIS)*

The approach used here is mechanistic in the sense that it is based on known biological causal relations of disease epidemiology (as opposed to surface or empirically-derived statistical functions to make inferences). If the spatial distribution and severity of Karnal bunt within North America were to increase, then correspondence, clustering and other statistical approaches might prove useful to derive appropriate probabilistic inferences about disease risk.

The method we used is correlative and not dissimilar in logic to many clustering and classification algorithms in existence (*e.g.*, Diekmann, 1993, Dobesberger and MacDonald, 1993). The number of variables that can be considered in a GIS-based analysis as conducted here (*i.e*., layering of untransformed biological data) however, limits this mechanistic approach. Were the study to require a large number of predictor variables (*e.g*., relative humidity, planting depth, wind speed, latitude, variety or cultivar, fertilization, soil type, rotation sequence, other pests, *etc*.), this approach would be less straightforward and likely more cumbersome. In such a case formal discriminant analysis might provide a better alternative analytical approach. Approaches such as discriminant analysis and other multivariate procedures are not incompatible with the methods outlined here. For example, discriminant analysis would help summarize many layers into a single expression, which could then be easily mapped as a single displayed layer. Examples of these applications in agriculture include Harvey (1996) and Dobesberger and McDonald (1993).

As noted, the analysis of risk presented here is based on long-term climatological averages. That is, it identifies risk zones based on historical or averaged patterns. It is well known, however, that there is no such thing as a typical or average year. Any specific year may deviate significantly from the historical average. The implication of this observation is that our findings do not imply that Karnal bunt will never occur in areas that are classified as low risk. However, it is unlikely that this disease will exist in such areas at densities that will lead to epidemics during most years since categorization as low risk implies a combination of adequate moisture, adequate temperature, susceptible hosts, and sufficient interaction time is unlikely to be realized. Whereas temperatures may be conducive in a given year, the combination of all necessary critical factors is less likely to occur. The authors, therefore, conclude that the areas characterized as low, medium, or high risk will conform to these zone classifications in the majority of years.

## CONCLUSIONS

A detailed assessment of the risk of Karnal bunt establishment in North American-grown wheat produced, in addition to the assessment itself, a geo-referenced database related to wheat production, description of production practices, daily climatology, disease distribution, and crop phenology applicable to pest risk assessments for North America, in general. The output generated by this study consists of "risk zones", which categorize wheat production regions based on the rating for risk of disease establishment in a pest risk area.

The risk model confirms that the majority of production regions in North America are not highly susceptible to development of this disease most of the time. Limited areas have been identified where risk may be considered medium or high. Analysis of prevailing weather and planting patterns during the production of winter and spring wheat shows that the susceptible period does not generally coincide with climatic conditions favorable to the disease at the majority of locations throughout North America. The majority of wheat producing areas in the United States and Canada correspond to the lowest risk category for Karnal bunt. This is true for both winter and spring planted wheat. Some areas in Mexico are in the medium risk categories.

The disease was noted to occur in areas that the model considered of medium to low risk. In Mexico, these areas were all located along the coast. It was noted that existence of the disease in Mexico followed "boom" or "bust" patterns and was not noted to occur every year even in areas generally acknowledged as infested. In the United States, the occurrence of Karnal bunt in very limited areas has been associated with climatic anomalies and was only observed to occur at very low levels of infestation.
Recommendations for future research include better characterization of microclimatic conditions at finer time scales (including the effect of irrigation and continental vs. coastal effects on humidity patterns), development of field simulation models of disease occurrence for bunts and smuts (specifically exploring the relationship between controlled chamber studies and field conditions), investigation of the effect of snow cover on *T. indica* spores and investigation of other *Tilletia*-like organisms exotic to North America. The model and approaches used here need further refinement and further validation with data from other areas of the world where Karnal bunt is known to occur.

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## CONTACTS

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## FIGURES

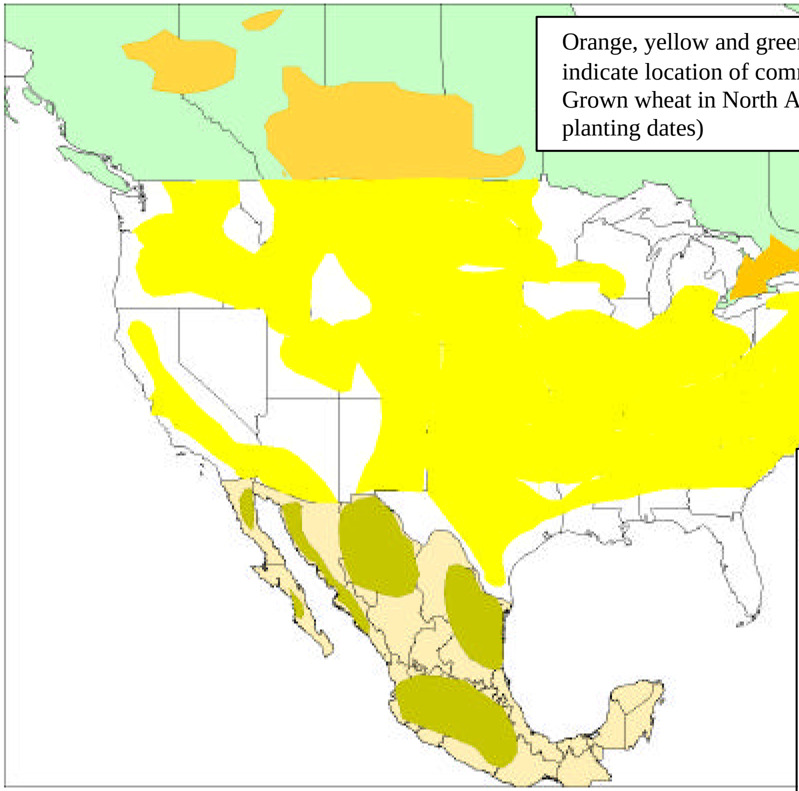


Figure1. Wheat growing regions in North America

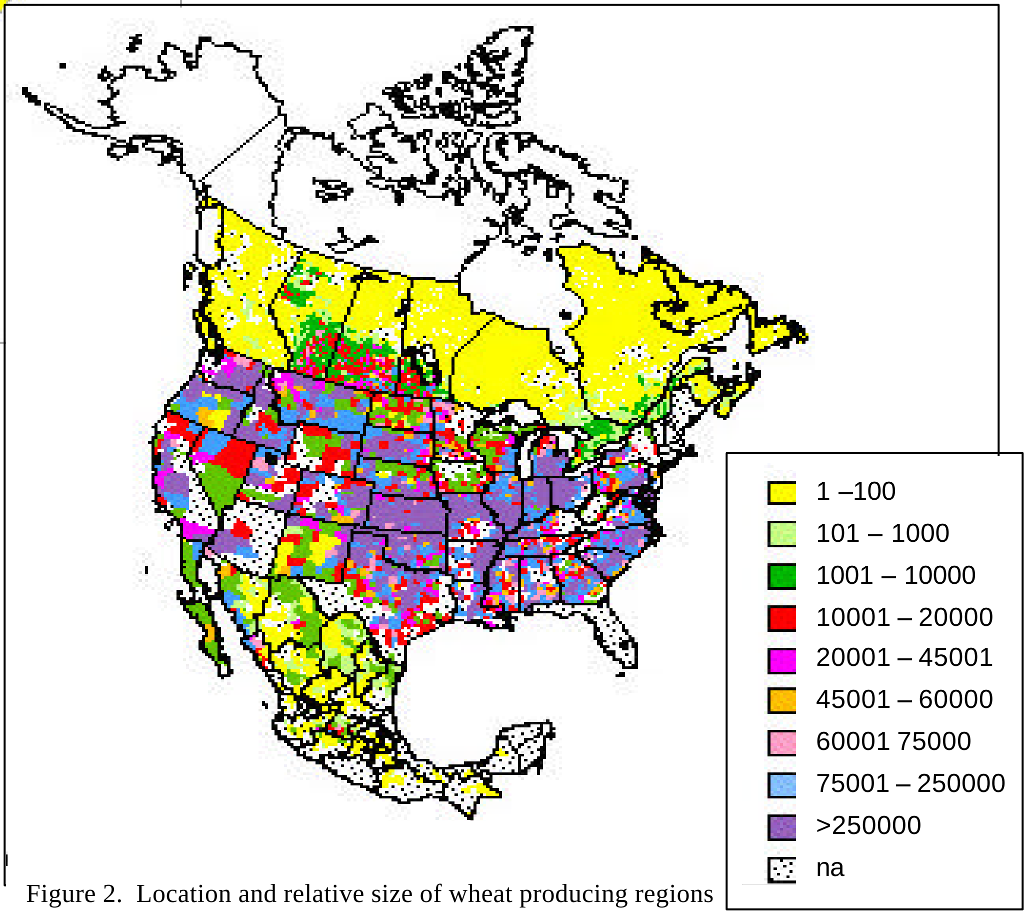


Figure 2. Location and relative size of wheat producing regions in North America, metric tons/unit area, spring and winter wheat

# Cropping Calendars for Wheat in North America

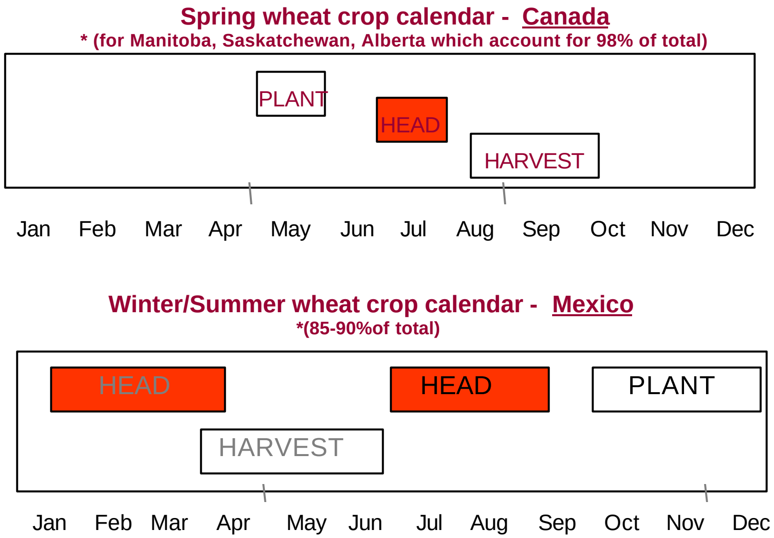


Figure 3a. Crop calendar for key wheat producing regions in North America

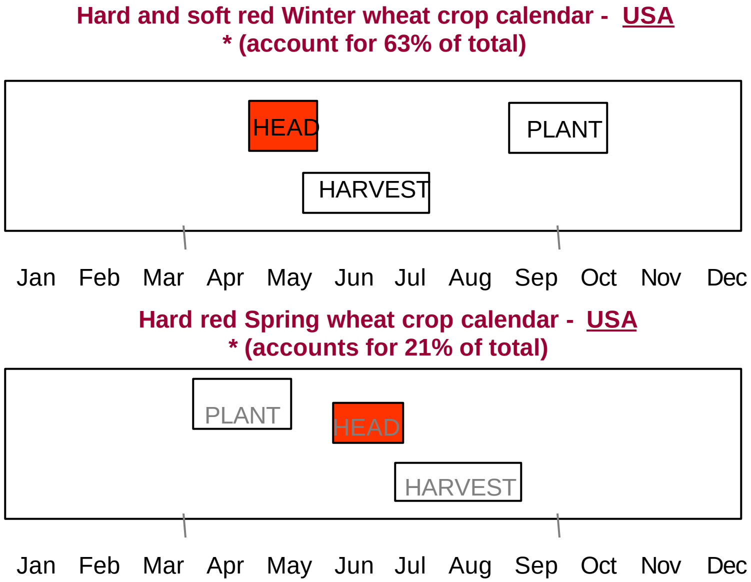
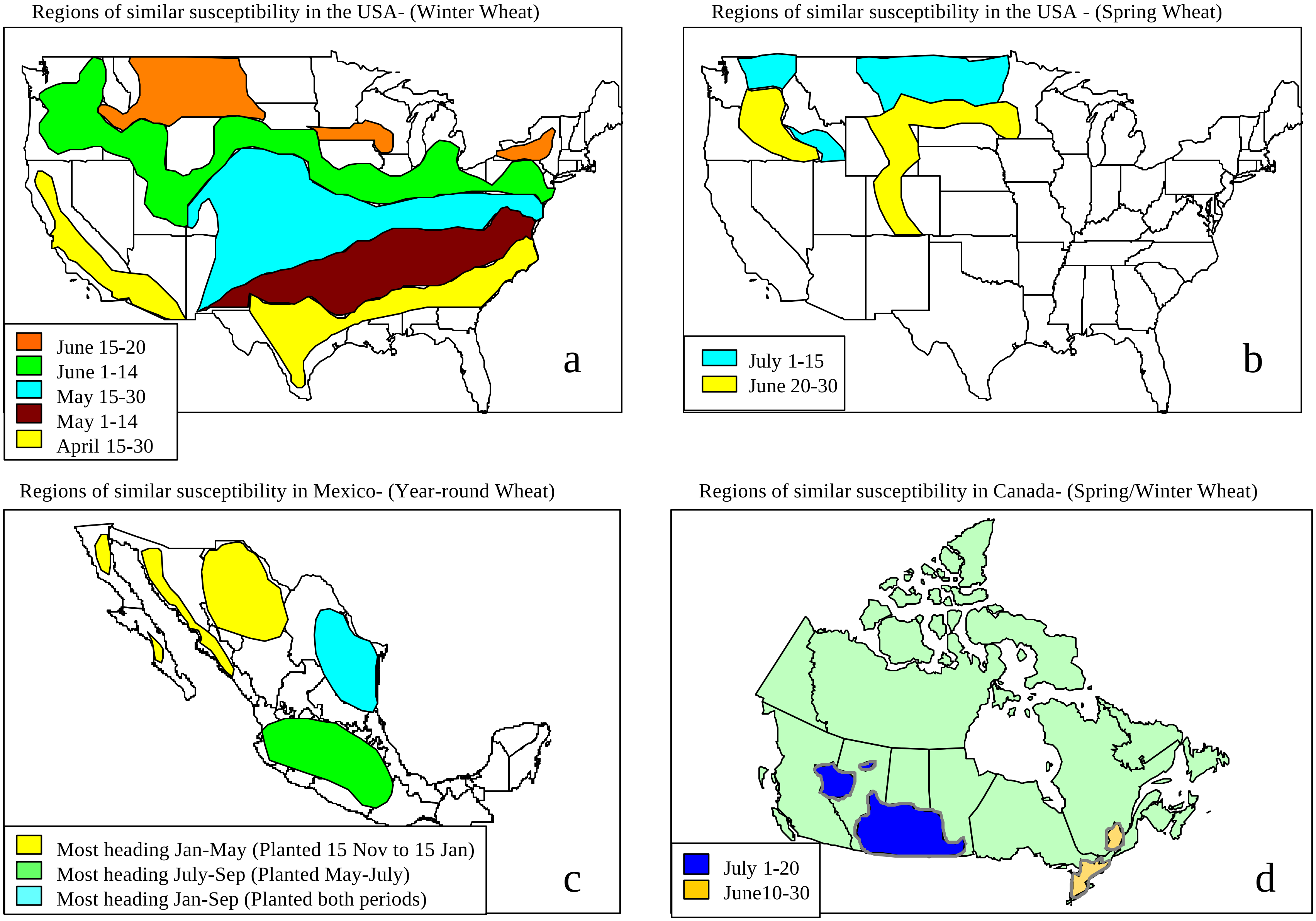


Figure3b. Crop calendar for key wheat producing regions in North America


Regions of similar susceptibility in the USA- (Winter Wheat)

Regions of similar susceptibility in the USA - (Spring Wheat)

Regions of similar susceptibility in Mexico- (Year-round Wheat)

Regions of similar susceptibility in Canada- (Spring/Winter Wheat)

Figure 4. Regions of similar phenology (specifically the reproductive period during which wheat is susceptible to Karnal bunt) in the United States (a,b), Mexico (c), and Canada (d)

Weather Records for
North America
-Station Locations-

Stars indicate exact location of
weather monitoring stations
for which historical records are
available to NAPPO
Canada: 630 Stations
Mexico: 5,300 Stations
USA9,100 Stations

Figure 5. Location of North American weather monitoring stations used in this study.