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Feasibility of Using Aeration to Cool Wheat Stored in Slovenia: A Predictive Modeling Approach Using Historical Weather Data

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Abstract: The use of aeration, which refers to cooling of a grain mass using low-volume airflow rates with ambient air, is an under-utilized component of management programs. A model simulation study was conducted for the country of Slovenia by examining historical weather data for 10 selected sites to determine if sufficient cooling hours <15 °C were available in August and September to cool stored wheat. The weather data were then coupled with a degree-day model to determine if a generation of *Sitophilus oryzae* (L.), the rice weevil, could be produced in the absence of aeration, using a start date of 1 August. The weather data for September was used to classify Slovenia into different risk zones, depending on the number hours <15 °C. Three sites from each zone, from warmest to coolest, Portorož, Novo Mesto, and Lesce, were further examined using a web-based aeration model and insect population growth model for *S. oryzae* developed by Texas A&M University Beaumont TX for cooling stored rough rice, to predict bin temperatures and population growth from 1 August to 30 November. The results show that, for most of Slovenia, in the absence of aeration, a complete generation of *S. oryzae* could occur based on an infestation beginning 1 August. The use of aeration immediately cooled stored wheat in the three selected sites, resulting in a dramatic decrease in predicted populations of *S. oryzae* in aerated wheat compared to unaerated wheat. The results show that the use of aeration may be expanded in Slovenia for management of stored commodities, and it could help alleviate dependence on insecticides for insect pest management after harvest.

Keywords: wheat; storage; insects; integrated pest management; non-chemical control

1. Introduction

Aerating stored grains may best be described as using low-volume airflow rates to cool a grain mass down to a specified temperature [1]. The airflow rates in English units are between 0.1 and 0.3 cubic feet per minute per bushel, which is equivalent to about 0.12–0.36 m^3/min/metric ton (MT). These airflow rates are distinguished from grain drying, which utilizes airflow rates that are several orders of magnitude greater than those used for aeration [1,2]. Development for most stored product insects ceases at about 15 °C [3,4], which can be used as a target temperature for utilizing aeration to cool a grain mass. Aeration can be an important component of integrated pest management (IPM) programs for stored grains, as it is a non-pesticide option that could mitigate development of insecticide resistance in stored product insects.

Throughout most of the temperate regions of the world, hard red winter wheat is planted in autumn and harvested during the summer months of the next year. One of the obvious requirements for using aeration is availability of electricity and the hours that the ambient outside air is below the 15 °C threshold necessary to cool the grain mass, for slowing or halting development of insects. Theoretical engineering calculations state that 120 h below a specified threshold are necessary to cool the grain mass to that temperature at an airflow rate of 0.12 m^3/min/MT [5]. A controller wired into the electrical system of the bin can be set to operate when ambient temperatures fall below the desired threshold [6–8]. The aeration system can be configured to bring the ambient air into the bottom of the grain mass where a cooling front is then produced that can gradually cool the grain from the bottom of the bin to the top. These hours assume that the aeration fan is properly sized to match the bin capacity and can deliver this cooling front throughout the grain mass.

Historical weather data, available from the USA National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (https://www.ncdc.noaa.gov), have been utilized to predict the hours below this insect developmental threshold temperature for corn, wheat, and rice stored in different regions of the USA [9–13]. A program written in Q-Basic, which required maximum and minimum temperatures for a given day, along with sunrise and sunset times, was utilized for these studies and published [9]. The sunrise and sunset times were obtained from the website of the USA National Weather Service (https://www.weather.gov). For most regions of the USA, the hours below 15 °C in September were best used to predict success of aeration in a given location.

The Q-Basic program [9] could predict hourly temperatures but perhaps a simpler method is necessary to further promote the concept of aeration, particularly for international use. A common method to determine degrees days was developed several decades ago [14,15] and has become widely implemented in agriculture (e.g., [15]). The model functions by approximating the temperature diurnal course using a sine wave delimited by the maximum and minimum daily temperature readings from a weather station, and then calculates degree day or hour accumulations by integrating under the sine curve. The model may subsequently be tied to key phenological events in the life history of a pest, as has been done for *Ophiomyia simplex* (Loew), the asparagus miner [15]; *Lobesia botrana* (Denis and Schiffermüller), the grape berry moth [16]; and even postharvest pests such as *Dinoderus minutus* (F.), the powderpost beetle [17]. However, to date, a degree-day calculation method has not been used to model potential efficacy of grain aeration.

There are no studies outside of the US that examine historical weather data to assess the feasibility of using aeration to cool wheat in storage. The objectives of this study were: (1) to determine hours below 15 °C in September, using the web-based climatic data and the sine wave model described above, for the country of Slovenia; (2) to develop a climate map of Slovenia for utilizing aeration in September; and (3) to predict temperatures in aerated and unaerated wheat, along with associated population growth of *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae), the rice weevil, a cosmopolitan pest of stored wheat, using a web-based system developed by Texas A&M University, Beaumont, TX, USA for cooling stored rough rice [18]. This web-based model was used for the aeration simulations and predictions for growth of *S. oryzae* because there is no currently-available web-based easy-to-use modeling program specifically for aeration and determining insect population growth in stored wheat.

2. Materials and Methods

2.1. Data Collection

Weather station data for Slovenia were obtained from USA-NOAA Climatic data website for the years 2010–2019. Weather stations were then selected from the data available from the NOAA site. Some stations were missing too much data to use, while others were geographically redundant, so ten were arbitrarily selected to provide geographic representation without excessive duplication. Data for the Novo Mesto site in Slovenia were first examined by determining the hours below 15 °C in September for each of the 10 years, using the Baskerville-Emin [14] method of calculation described above that utilizes daily maximum and minimum temperatures to delimit a sine wave, and then by calculating hourly temperatures below 15 °C. The data for each year were then combined and averaged to get the mean hours below 15 °C in September. Then, the temperature data for September for each year was combined to get a 10-year average dataset, and the process of using the sine wave model to obtain hours below 15 °C in September was repeated. The values obtained by averaging the data for each of the 10 years, versus the value obtained by using the 10-year average data, were within 20 h of each other, thus the second methodology was chosen to allow for examination of more weather stations due to the time savings from utilizing the 10-year average data. Data from 1 August to 30 November were averaged for each of the 10 stations from 2010 to 2019, except for the station in Lesce, which was missing data from 2018–2019. Thus, for each of the stations, a temperature dataset of average maximum and minimum temperatures was created for each site.

2.2. Estimating Temperature Accumulation and Constructing a Simplified Degree Day Model

Daily hours below 15 °C were calculated for each station beginning 1 August and ending 30 November. Data were used to map the country of Slovenia for hours below 15 °C in August and September, using QGIS v.3.12.3. Point source information about hours below 15 °C in Slovenia were projected onto a map derived from the NUTS 2013 dataset for political boundaries on the Geoportal of the European Commission (EuroSTAT). In the software, the SAGA processing tool was used to implement inverse distance weighted (e.g., square root) interpolation of hours between the point information using a cell raster size of $0.01° \times 0.01°$ using the projection coordinate system EPSG:4326-WGS 84. The same process was used to interpolate degree-days as calculated below 15 °C for Slovenia. The modeling assumption is that, in this scenario, aeration would be accomplished through the use of an automated controller, which would operate aeration fans when ambient temperatures were below 15 °C. The cooling pattern is best described as a cooling front, and if the cool air is drawn into the bottom of the grain mass, the front will move upwards through the grain until the entire mass is cooled. Thus, there would be no cooling when temperatures were above 15 °C. Data were then examined to predict the average date by which 120 h are accumulated below 15 °C for cooling grain in the ten selected sites, beginning on 1 August.

A simple degree day model for predicting if a generation of *S. oryzae* was completed was constructed as follows for either unaerated or aerated grain. At a standard rearing temperature of 27 °C, it takes *S. oryzae* about 6 weeks or 42 days to undergo development from egg to adult [19,20]. Thus, 27 °C multiplied by 42 days corresponds to 1134 accumulated degree days. At 32 °C, it takes about 5 weeks (or 35 days) to develop from egg to adult for *S. oryzae* [19,20], which corresponds to an accumulation of 1120 degrees. Likewise, at 22 °C, seven weeks is needed to progress from egg to adult, corresponding to 1078 degrees. Since these numbers are not absolute, a degree-day accumulation value of 1000 degrees was used to determine if a generation of *S. oryzae* could be produced, based on average daily temperature from August to September.

2.3. Model Simulations Based on Texas A&M Beaumont Rice Model

As stated above, the rice aeration and insect population model developed by Texas A&M Beaumont [18] was used because there are no comparable easy-to-use web-based models for stored wheat. The model allows the user to specify parameters for bin size, depth of grain mass, type of aeration fan, and starting grain temperature. The input values chosen were a bin height of 7.3 m, diameter of 3.7 m, depth of grain 6.1 m, 1 m of headspace, and a 30 hp Sukup (www.sukup.com) fan. The bin dimensions were chosen to represent a large farm bin or a small elevator silo, with a capacity of about 340 MT. This model, similar to previous models, assumes unlimited growth and development of the insect population from a starting value. Thus, starting values must be low otherwise the numbers are so high that they may not be biologically meaningful. The starting value of *S. oryzae* was 0.04 mixed-sex adults/27.2 kg of wheat, which equilibrates to 1.5 adult/metric ton as the starting value. These adults were assumed to enter the bins on 1 August. The temperature patterns produced through aeration, and the resulting effects on *S. oryzae* population development, Birch [21] can be used to describe the difference between unaerated and aerated wheat. The maximum and minimum datasets for each site were run through the aeration component of the model, which then outputs the temperatures in 5 levels for unaerated and aerated grain: top, $\frac{1}{4}$ down from the top, middle, $\frac{3}{4}$ from the top, bottom, and the average temperature in the bin. The insect model predicts populations in an unspecified level, and the average per kg, based on a specified starting level. Because the insect component is paired with the aeration component, only the average bin temperatures between unaerated and aerated grain are reported for the simulations.

3. Results

3.1. Temperature Threshold Results

The map of September temperatures below 15 °C shows that, for much of Slovenia, there may be sufficient hours below this threshold to begin and possibly complete aeration in August or early September (Figure 1A,B). However, aeration could not be accomplished in the coastal region until late September or possibly October. The hours below 15 °C in August and September for each of the 10 selected weather sites are shown in Table 1. Note the low number of hours below 15 °C for Portorož, chosen to represent the coastal area, because no weather data were available for the port of Koper. In addition, the mountain site of Kredarica was chosen for geographic representation for Figure 1 and is not representative of a site where wheat would typically be stored. The average date by which 120 h are accumulated below 15 °C at each of these sites and the number of temperature hours are also shown in Table 1. The degree day approach predicts that a generation could be produced, starting on 1 August, in Portorož, Murska Sobota, and Novo Mesto (Table 1 and Figure 1C). Partial generations could be completed in all other sites except Vojsko.

Table 1. Hours below 15 °C in August and September for 10 sites in Slovenia, from lowest to highest in September. The airports in Ljubljana and Maribor are well outside the city limits, so they were used. Kredarica is in the mountains and is not representative for wheat storage but was used to make the climate map [1,2].

Station	Lat.	Long.	August	September	120-h Date	Degree-Days
Portorož	45.5	13.6	0	89	3 October	1471
Murska Sobota	46.7	16.2	38	264	13 September	1091
Novo Mesto	45.8	13.2	26	272	14 September	1018
Maribor airport	46.5	13.7	67	287	8 September	953
Postojna	45.8	14.2	150	334	27 August	915
Ljubljana airport	46.2	14,5	123	356	31 August	870
Lesce	46.4	14.2	136	359	30 August	857
Kočevje	45.6	14.9	181	364	23 August	901
Vojsko	46.0	13.9	247	532	18 August	525
Kredarica [3]	46.4	13.9	720	744	5 August	

[1] 1 August was used as a starting date for wheat storage, although wheat may be loaded into a bin before or after that date, depending on the region and the climatic conditions of a given year. This date was used for standardization. [2] Most of the weather sites with data were from central and western Slovenia. There was a lack of weather station data from the northeast quadrant of the country. [3] There is no wheat storage in northern mountain region of Slovenia, and the site was chosen only for geographic representation.

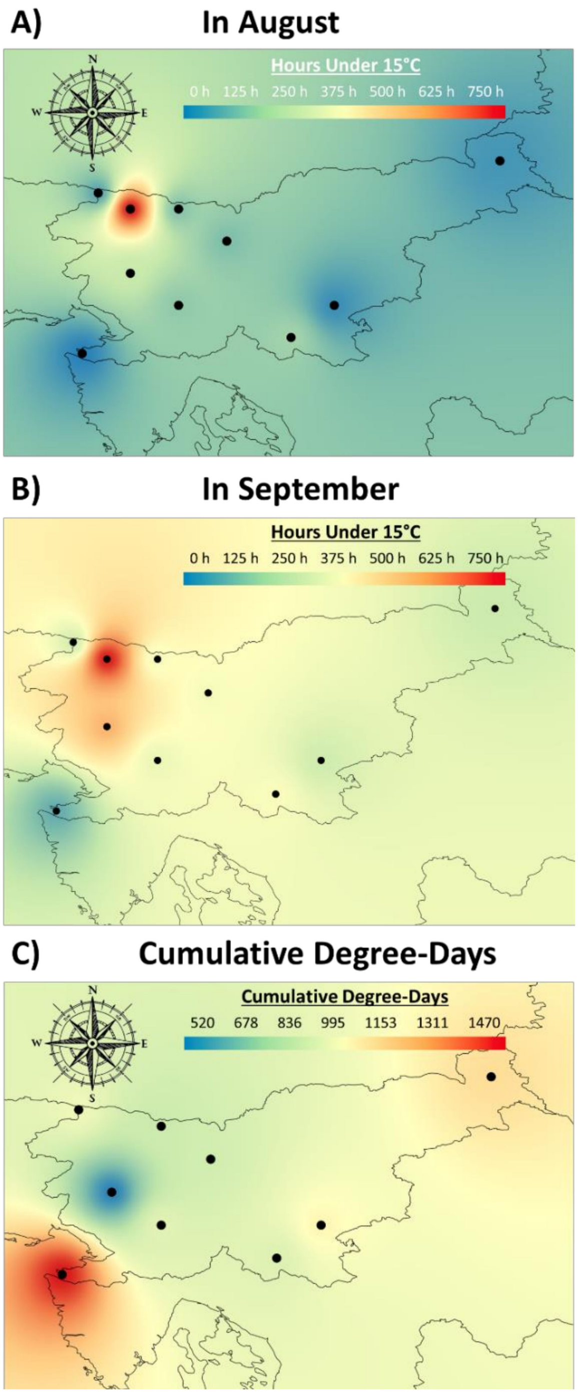
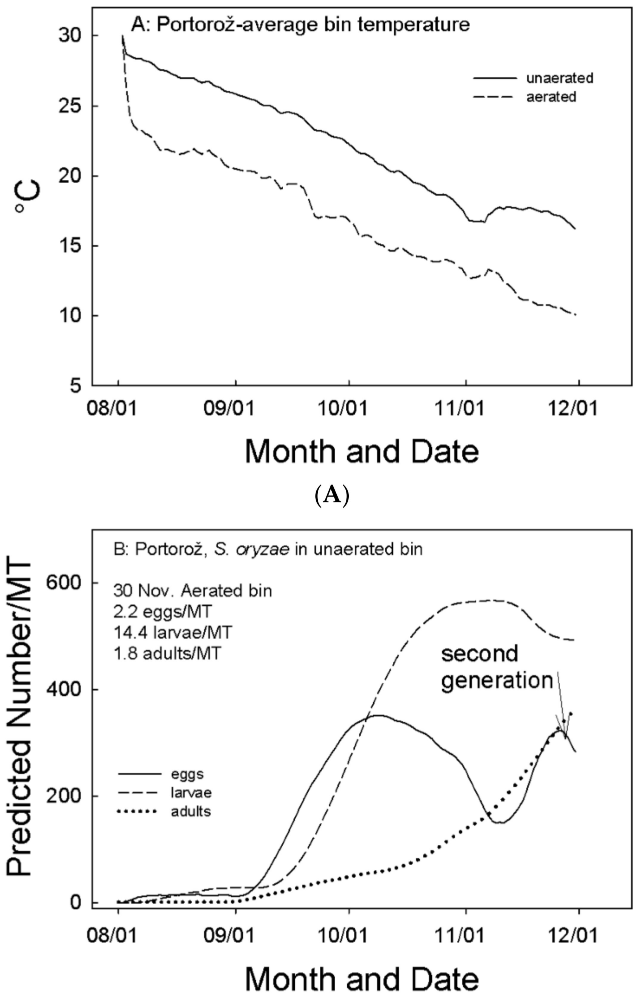


Figure 1. Spatially interpolated values among weather stations (denoted by black dots) for hours that the ambient temperature is below the threshold of 15 °C in Slovenia for: (**A**) August; (**B**) September; and (**C**) cumulative degree-days calculated using the Baskerville-Emin method, starting August 1 based on 10-year historical average values, and a lower developmental threshold of 15 °C. Most of Slovenia has at least 120 h of ambient air temperature under 15 °C, suggesting that grain aeration may be a useful additional pest management tactic for the country.

3.2. Beaumont TX Aeration Model Results

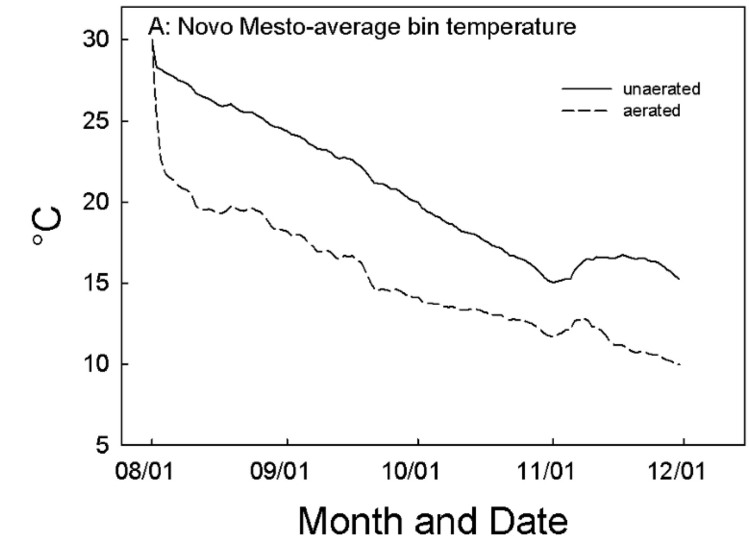
Three sites (Portorož, Novo Mesto, and Lesce) were chosen to represent areas of low, moderate, and high temperature accumulation levels below 15 °C in September, based on results in Table 1. Daily maximum and minimum temperatures from 1 August to 30 November, along with the starting level of 1.5 mixed-sex adults/MT and initial grain temperature of 30 °C, were the main inputs. The impact of aeration on bin cooling patterns in Portorož were dramatic; with aeration, the threshold temperature of 15 °C was reached on 7 October, while, in non-aerated grain, the threshold was not achieved (Figure 1A). Similarly, the predicted growth of *S. oryzae* increased to 210, 724, and 268 eggs, larvae, and adults/MT, respectively, in unaerated grain on 30 November, and, while some population growth was predicted for aerated grain, the numbers were far lower than those predicted for unaerated grain (Figure 1B). Predicted grain temperatures with and without aeration in Novo Mesto essentially followed the same pattern as those for Portorož (Figure 2A). With aeration, the threshold temperature was reached on 9 September and without aeration it was not reached until 29 November. Predicted *S. oryzae* populations in unaerated grain were lower in Novo Mesto than those predicted for Portorož, with predicted levels of 0.5, 303, and 42 egg, larvae, and adults/MT, respectively (Figure 3). However, aeration quickly reduced the bin temperatures and no growth in *S. oryzae* was predicted for aerated grain. Aeration also reduced temperatures and resulting *S. oryzae* population predictions in Lesce (Figure 4A). Temperatures in unaerated grain were lower than the other two sites, with resulting lower *S. oryzae* population predictions (Figure 4B), but aeration still had a positive effect. No *S. oryzae* population development was predicted for aerated grain.



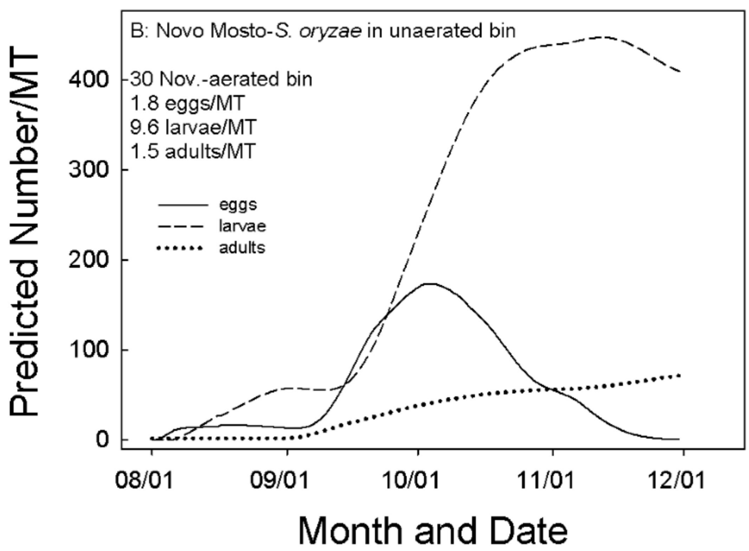
(**A**)

(**B**)

Figure 2. Predicted average bin temperatures in unaerated and aerated wheat stored in Portorož, Slovenia from 1 August to 30 November (**A**); and predicted numbers of eggs, larvae, and adults of *Sitophilus oryzae* in unaerated wheat (**B**). Predicted numbers of each life stage on November 30 in aerated wheat are listed as text (**B**). In the X-axes, date is given in Month-Day format.



(**A**)



(**B**)

Figure 3. Predicted average bin temperatures in unaerated and aerated wheat stored in Novo Mesto, Slovenia from 1 August to 30 November (**A**); and predicted numbers of eggs, larvae, and adults of *Sitophilus oryzae* in unaerated wheat (**B**). Predicted numbers of each life stage on November 30 in aerated wheat are listed as text (**B**). In the X-axes, date is given in Month-Day format.

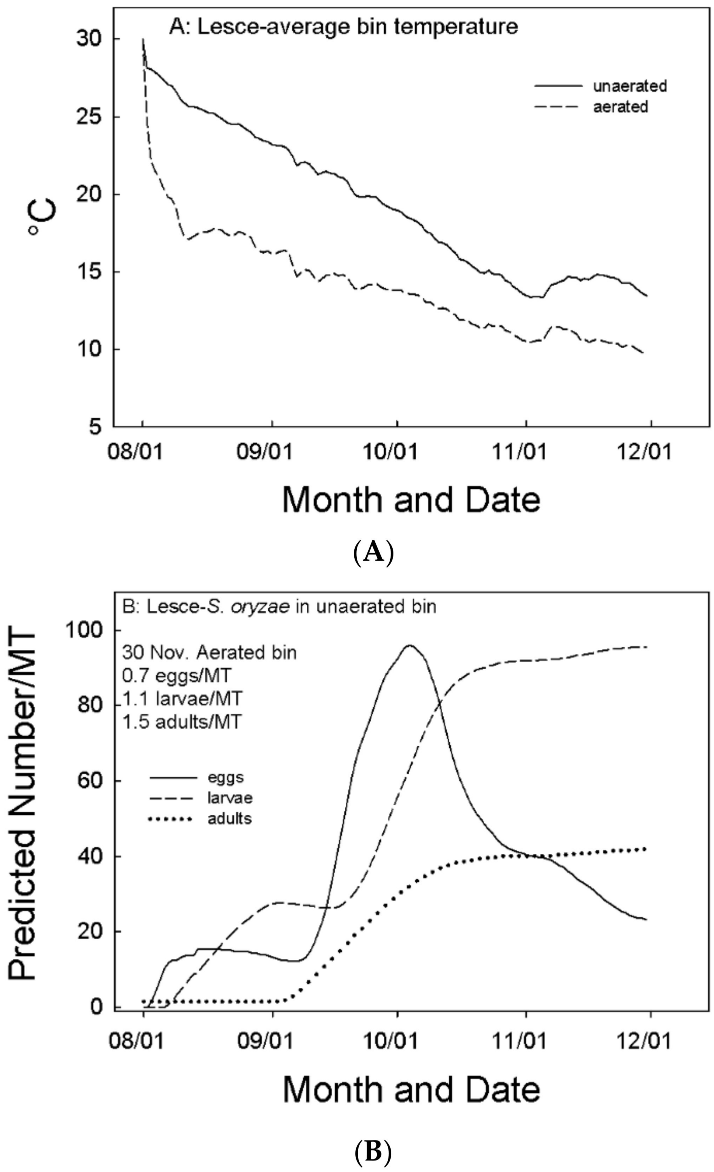


Figure 4. Predicted average bin temperatures in unaerated and aerated wheat stored in Lesce, Slovenia from 1 August to 30 November (**A**); and predicted numbers of eggs, larvae, and adults of *Sitophilus oryzae* in unaerated wheat (**B**). Predicted numbers of each life stage on November 30 in aerated wheat are listed as text (**B**). In the X-axes, date is given in Month-Day format.

4. Discussion

The start date of 1 August for the temperature accumulations and the modeling component of the study was chosen based on information in the scientific literature regarding wheat harvest times in Slovenia. In a previous experiment describing effects of *Oulema melanopus* (L.), the cereal leaf beetle, on field wheat, the wheat was planted on site at the University of Ljubljana, Slovenia, in Autumn and harvested on 19 and 25 July [22]. In a different experiment in which wheat was grown in Serbia, which is in the Balkan peninsula near Slovenia, the harvest date was also late July [23]. Thus, the start date of August 1 for the simulations was chosen to correspond to an average binning date for wheat harvested in Slovenia, regardless of location. The 10 locations for weather data were chosen to give a geographic representation of historical weather data in Slovenia.

Most of the published papers on *Sitophilus* spp. in stored products in Slovenia focus on *Sitophilus zeamais* (Motchulsky), the maize weevil [24]. However, the temperature requirements and population development of this species on wheat is similar to those for *S. oryzae*, which is a primary pest of wheat in the United States (US) [25]. *Sitophilus zeamais* is usually associated with corn (maize) in the US [25]; however, this species can readily feed on wheat as well. Thus, the predicted population development for *S. oryzae* generated by the TAMU-Beaumont model should be applicable to other *Sitophilus* species.

The first aeration methodology used a cyclical aeration approach, based on the theoretical assumption that 120 h below a given temperature threshold are needed to cool wheat to that level, using an airflow rate of 0.12 m^3/min/MT. This calculation is independent of the size of the storage bin and assumes the aeration fan motor is powerful enough to deliver the specified airflow rate through the wheat mass. This approach was used to stratify Slovenia into different aeration zones to predict feasibility of using aeration as part of pest management programs, similar to what has been done for different regions of the US [9–13]. However, this hourly time estimate is a theoretical estimate, and in actual practice more hours may be required to cool the bin. Studies conducted by Arthur and Casada [8,26], in which wheat stored in Kansas was initially cooled to 24 °C during in the summer months, showed that more than 200 h below this 24 °C threshold were required for this initial cooling. The cooling cycles to 15 °C in autumn required between 120 and 150 h.

The degree day approach described in this study, which has been used to predict generation times for crop pests [15], was used to determine if a generation of *S. oryzae* could be produced in the absence of aeration, starting on 1 August. A degree-day methodology was previously used to predict generation times for *S. oryzae* on bagged rice stored in Japan [27], but the degree-day approach outlined in this manuscript was the first time it was used to predict generation times for a stored product insect. The advantage of a degree-day approach is that it is simple to use, easy to understand, and valid for comparison purposes. A degree-day approach also fits with aeration models, because most aeration models for stored grains assume that the peripheral regions of a grain mass will cool much more slowly than the bulk mass, and temperatures on the surface of the grain mass may approximate ambient temperatures [28–30]. The results show that, in the warmer regions of Slovenia, in the absence of aeration temperature, conditions for stored wheat were sufficient to produce a complete generation of *S. oryzae*, assuming an infestation start date of 1 August. However, even if temperatures in the cooler regions of Slovenia would not support development of a complete generation, larvae feeding inside the kernels could cause potential damage and loss of milling yields.

The second aeration approach utilized the Texas A&M web-based rice model, which had to be used because there is no comparable model currently available to predict aeration patterns or insect population growth in stored wheat available from the current scientific literature or on university or governmental websites. The aeration approach utilized by this model is based on a sophisticated aeration controller that would operate whenever outside ambient temperatures were lower than a specified measuring point in the grain mass or in the aeration plenum of a bin. This same approach was used in the now outdated Stored Grain Advisor model, developed by scientists with the USDA-Agricultural Research Service in Manhattan, KS. [30]. This model was developed in the 1990s, but it was a CD-ROM Windows based model, and the last platform it would run under was Windows XP. The modeling approach of both the web-based rice model and the old Stored Grain Advisor model would show immediate cooling of the wheat mass, compared to the cyclical approach of using time accumulations below a specified temperature threshold. Rice is less dense than wheat; it occupies 0.73 kg/m^3 compared to 0.97 kg/m^3 for wheat, thus it should cool faster than wheat. While the rice model may over-predict the speed of cooling for stored wheat, the overall patterns still show a clear benefit to using aeration to cool wheat stored in Slovenia, as predicted populations were orders of magnitude less when aeration was used compared to no aeration.

The results of this simulation study show that there is potential for the expanded use of aeration in Slovenia. The use of aeration could alleviate the need for fumigation in some regions, but fumigation or additional inputs such as grain protectants could be needed for wheat stored in the coastal region.

Incorporation of aeration into management programs could alleviate development of phosphine resistance in *S. oryzae*, which is increasing in Australia and other parts of the world [31,32].

5. Conclusions

The use of aeration, which is defined as using low-volume airflow rates to cool a grain mass, is an under-utilized component of pest management programs for stored wheat. Analysis of historical weather data for the country of Slovenia shows that sufficient hours of temperature below 15 °C, the lower limit of development of most stored product insects, are available to cool stored wheat throughout most of the country. The results of modeling simulations show dramatic differences in cooling patterns of unaerated versus aerated wheat, and correspondingly low predicted population development of *Sitophilus oryzae* (L.), the rice weevil, in aerated wheat compared to unaerated wheat.

Author Contributions: F.H.A. and W.R.M.III conceived and designed the experiment and performed the analyses. F.H.A., W.R.M.III, and S.T. prepared the final manuscript. All authors have read and agreed to the published version of the manuscript.

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