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REVIEW

The Ecosystem Approach to Grain Storage

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Abstract The progress in understanding the stored grain ecosystem is reviewed. Succession of insects, insect movement and distribution, interaction among insects and microflora, and the development of hot spots inside stored grain ecosystems are evaluated. Based on these case studies, we examined the understanding of the stored grain ecosystem from the view of ecosystem approach. To understand the storage grain ecosystem, integration of the parts (the collected data under small scale laboratory conditions) into a usable whole (the entire grain storage ecosystem) is required. To verify the synthesised whole, both small and full scale tests are required. To manage the stored grain ecosystem, understanding the ecosystem and application of ecosystem approach are the keys.

Keywords Stored grain · Management · Ecosystem · Ecosystem approach

Introduction

The stored grain bulk is an ecological system [73]. Ecosystem approach of stored grain can be defined as a strategy for the integrated management of stored grain that promotes conservation and sustainable methods to manage stored grain to deliver high quality grain and products at the end of the storage period. Application of ecosystem approach is to use the concept of ecosystem to thoroughly understand and manage the stored grain ecosystem. Essentially, it requires considering the effects of actions on every factor or element of the ecosystem, based on the recognition that all factors are linked [14, 15]. The ecosystem approach to stored grain can aim for short- or long-term economic gains by optimizing the use of the stored ecosystem without damaging the other ecosystems [25]. Application of the ecosystem approach will help us reach an environmental friendly and sustainable solution of storage grain management.

The ecosystem concept was introduced by Tansley [80]. Before the 1970s; however, the study of the grain storage ecosystem had not often been the practice among scientists, economists, and grain management personnel involved with the grain storage problem [73]. Therefore, several grain storage scientists [73, 84] strongly urged the research community to devote great effort to study the whole grain storage ecosystem and make a proper synthesis of the interaction of variables before individual control and management decisions are taken. In the last 40 years, interactions of the grain storage ecosystem were studied by several multidisciplinary research teams in the world. An “International Symposium of Stored Grain Ecosystem” was held in Winnipeg, Manitoba, Canada, 1992, and the multidisciplinary approach is well documented [32], and the need for an interdisciplinary approach is generally recognized. Entomologists, mycologists, chemists, engineers, and food scientists are commonly involved in research, but effective integration of technical solutions is often lacking. The concept of the ecosystem approach has not been properly integrated into the stored grain management under most situations.

Practice of grain storage management impacts on stored grain ecosystems. The source of the impacts mostly is the

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application of pesticides, fungicides, fumigants, and dusts. These impacts have been abundantly described and reviewed [4, 11]. Our purpose in this study was not to present an exhaustive list of references on the research of stored grain ecosystem and impact on the environments; rather, we focused on the progress which has been made in understanding the ecosystem in the following research areas: succession of insects, insect movement and distribution, interaction of insect and fungi, and the development of hot spots. The reason for choosing these research areas is that researches related to these areas require large grain bulks and they mirror the complex interactions among factors. Also, it reflects the chronological research progress in the understanding of the stored grain ecosystem. Based on these case studies, we examine the interaction between factors and application requirement from the view of ecosystem approach. This treatment of the subject should serve to enhance the growing awareness of storage as a system within a system and to develop sound management program using the ecosystem approach rather than the conventional management.

Interaction Among Factors in Stored-Grain Ecosystem

A bulk of grain is not homogeneous because it contains gradients of oxygen, carbon dioxide, nitrogen, moisture, temperature, and quantities of dockage and has distinct physical and biological properties. A stored grain ecosystem consists of non-living and living factors. The interactions among these factors could be simplified as shown in Fig. 1. Sinha et al. [78] analyzed the interrelations among 32 variables including the living and non-living factors in two 13.6-t wheat bulks stored for 8 years. Eleven of the 32 variables accounted for 65.6% of the total variability influencing the quality of the stored wheat. The most important living factors in this 8-year study were grain determinations along with storage time due to fungal and insect infestations. The most important nonliving factors are the temperature and grain moisture content [79].

The result of the interaction among factors in stored-grain ecosystem is the consumption and decomposition in stored-grain ecosystem (Fig. 2). During this transformation of stored-grain ecosystems, volatiles, insects or their body fragments, and fungal metabolite might be present. Gas concentration, and grain temperature and moisture content might change. These physical, chemical, and biological changes are used to control and monitor the quality of the

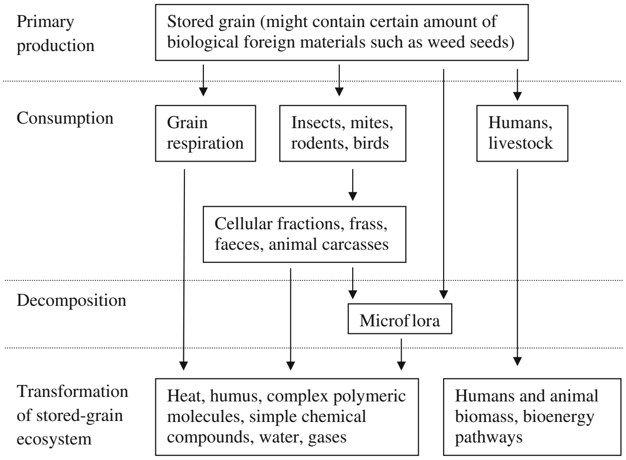

Fig. 2 Transformation of stored-grain ecosystem (modified from Sinha [74])

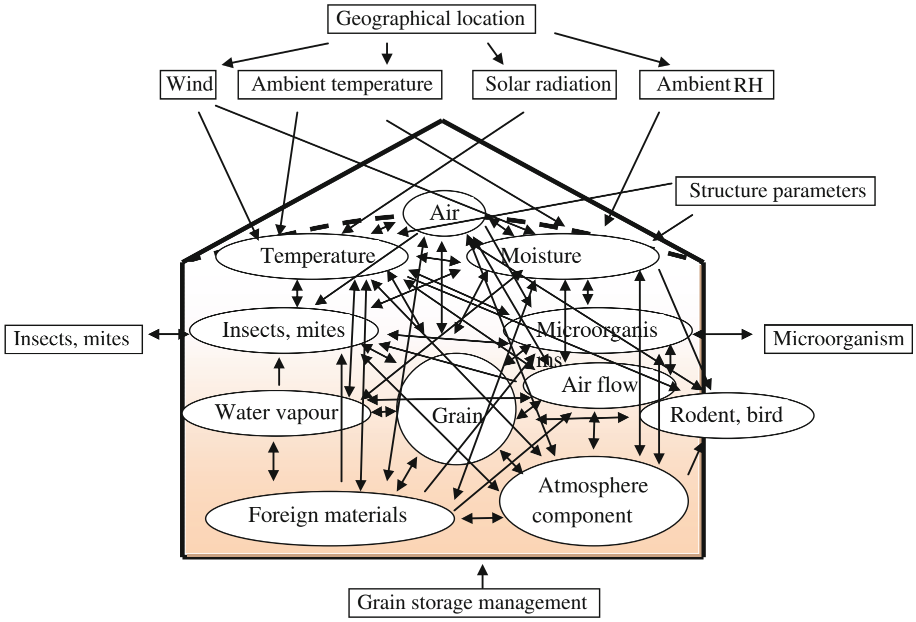

Fig. 1 Factors in a stored grain ecosystem and the interactions among factors in non-aerated and unsealed bulk grain (modified from Jayas [31])

stored grain [12, 34, 53, 57, 60]. Even though some volatiles produced by insects [67], fungi, and grain [12] are detected under controlled laboratory condition, it is not very clear as to which and how many chemicals are produced inside stored grain bins.

Insect Succession in Stored Grain Ecosystem

More than 500 insect species are reported to be associated with grain [26], and 150 species of insects and mites are listed as grain and its product pests, but only 10–15 species occur frequently and most are beetles [89]. Even though a lot of species could become dominant under certain environmental conditions or storage time, several species (such as *Oryzaephilus surinamensis*, *Cryptolestes ferrugineus*) have a higher frequency of occurrence and abundance (Table 1). The dominant species in a series of succession communities often exist at very low levels in a grain bulk long before conditions favor their dominance. In the extreme case, all the dominant species are present at the time of storage. Sinha and Wallace [76] found that a series of arthropod communities developed and replaced one another at short intervals (less than half years) as the hot spots developed and then cooled.

The composition of insect species changes as the grain deteriorates, and dominance by certain species is associated with the grain quality [2, 7]. Even though insects might modify their environment during the succession [8–10], the entire environment of the ecosystem might be the drive force for the insect succession [3]. For example, the species composition in grain residues differed from that in the wheat stored in bins [27]. Insect population follows the grain temperature which is mainly influenced by seasonal weather temperature and the predominant species changes during the year [24]. Insect population might increase or decrease when grain is moved through transportation system [44, 64].

The species composition of succession differs from one climatic region to another and from commodity to commodity. Succession of insect species is not as strictly regulated by the moisture content of the grain but depends on whether the insect is a parasitoid, predator, primary grain feeder, or scavenger [17, 18]. The species involved in succession at a particular site depend on which species are present in the area. This difference reflects the fact that insects arrive at different times and, once established, they alter the environmental conditions, benefiting some and forcing others into local decline and extinction. Despite this difference, there are similarities and parallels in the

Table 1 Species of dominant insect and mite species during succession

Species	Time when dominant (source)
Acarus siro L.	First year (Sinha and Wallace [76])
Anisoperomalus calandrae (Howard)	Third year (Arbogast and Mullen [2])
Carpophilus dimididatus complex	Entire experimental period (Arbogast and Throne [3])
Cryptolestes ferrugineus (Stephens)	First 4 year (Arbogast and Mullen [2]), first half year (Sinha and Wallace [76])
Cryptolestes pusillus (Schönherr)	Entire experimental period (Arbogast and Throne [3])
Cheletomorpha lepidopterorum (Shaw)	First year (Sinha and Wallace [76])
Cheyletus eruditus (Schr.)	First year (Sinha and Wallace [76])
Cynaeus angustus (LeConte)	Eighth year (Arbogast and Mullen [2])
Glycyphagus destructor (Schr)	First year (Sinha and Wallace [76])
Haemolaelaps casalis (Berl.)	First year (Sinha and Wallace [76])
KLeemannia plumosus (Oud.)	First year (Sinha and Wallace [76])
Latheticus oryzae Waterhouse	Fourth year (Arbogast and Mullen [2])
Oryzaephilus surinamensis (L.)	First 3 year (Arbogast and Mullen [2]), first half year (Sinha and Wallace [76]), Entire experimental period (Arbogast and Throne [3])
Sitotroga cerealella (Olivier)	Beginning of the storage (Arbogast and Mullen [2])
Sitophilus zeamais (Motschulsky)	Second and third year (Arbogast and Mullen [2]), Entire experimental period (Arbogast and Throne [3])
Sitophilus cerealella (Olivier)	Entire experimental period (Arbogast and Throne [3])
Tribolium castaneum (Herbst)	Third through fifth year (Arbogast and Mullen [2])
Trogoderma inclusum leconte	Eighth year (Arbogast and Mullen [2])
Tydeus interruplus Thor	First year (Sinha and Wallace [76])
Xylocoris flavipes (Reuter)	Entire experimental period (Arbogast and Throne [3])

succession [2]. This similarity could be explained that each species has its unique biological behavior and ecological condition for survival and multiplication. Some species produce hormones or chemicals to regulate reproductive behavior and insect population [30, 54, 81]. For example, without the development of primary insects, grain can still be infested by the secondary pests because almost any grain bulk contains enough broken kernels to permit infestation by secondary pests. However, population growth of secondary pest insects is enhanced by the damage from primary pests [5, 48, 49].

Several studies based on laboratory experiments have suggested that interspecific associations are important when examining stored-grain insect communities, and most of these studies have focused on competition/predation [48]. The presence of other species usually slows down the increase in numbers of most species [45]. Lefkovitch [50] reported that *C. ferrugineus* reduced populations of *T. castaneum*. In wheat samples collected from 129 grain silos in Kansas, the number of *T. castaneum* in a grain sample increased as the number of *R. dominica* increased, while the number of *C. ferrugineus* did not correlate with the number increasing of *Rhyzopertha dominica* [58]. However, the densities of both *T. castaneum* and *R. dominica* decreased as the number of *C. ferrugineus* increased [27].

During the large scale study (e.g., inside storage silos) of insect succession, all of the insect species presented in the study might not be recovered or identified. Therefore, information related to some species might be missed. For example, psocids were usually considered as nuisance pests rather than serious pests [62]. Over the last decade, markets increasingly view psocids as contaminants, and they have become the most frequently encountered storage pests in the world [62, 63]. However, little is known about their succession and interaction with other species inside stored grain bulks.

Most of the researches on insect succession were completed before the 1990s. These researches were usually conducted under high insect densities [12] because succession usually occurs at high insect densities. In recent years, zero tolerance of insect infestation is being enforced in the world with the requirement of food security and safety. This requires the information on insect infestation at low density. This results in the renewal of the research on insect movement and distribution in the latest decade.

Insect Movement and Distribution

Understanding of insect movement and distribution at the very beginning of grain storage or at low insect density is important because their movement and distribution will influence their further multiplication and succession at different locations. This information will provide information on sampling, trapping, and grain storage management. It was found that adults of *C. ferrugineus* move inside a grain bulk in response to temperature gradients [21, 35], moisture differences [36, 51], and CO_2 gradients [88]. Dockage percentage [36], insect densities [35], and males and females at different ages [35] are minor factors influencing their movement and distribution. These studies are usually conducted in small containers or columns because of the difficulty of counting insects in all of the tested grain bulks. These studies demonstrate some behavior of the tested insects inside stored grain bulks and explain some of the results found inside stored grain bins. For example, distribution and dispersal of the *C. ferrugineus* adults in 1.0 × 1.0 × 0.1 m chambers follow a diffusion pattern under constant environmental conditions [38]. This diffusion pattern is successfully modeled, and their diffusivity is calculated. Jian et al. [37] found that adults of *C. ferrugineus* introduced in a 0.6-m diameter and 1.12-m high wheat column had a similar distribution with those introduced in 0.1 × 0.1 × 1.0 m columns. Inside elevator in the USA, the numbers of insects generally tended to decrease with the depth below the grain surface [23, 24, 52]. This suggests that insects infest wheat stored at the elevator after it has been loaded into bins and then disperse down into the grain [23].

The behavior characterized in small scale experiments might not explain all of the phenomena found in stored grain bins. For example, *Ahasverus advena* and *Typhasea stercorea* were mainly found in the central core of farm-stored grain even when there were no significant differences in temperature and relative humidity between the core and periphery [82]. Each species of insects follow a pattern of distribution under small scale experimental set up [40–43]. These patterns could not explain that species composition changes with grain depth inside stored grain bins [24]. These differences might be explained by the difference between the small scale experiments and the tested bins, such as temperature and moisture gradients, different fungi present, convection currents and chemical flow with the convection currents, and their ability of cue orienting and detecting [33, 39]. Also, time of their movement might also play a role.

The behavior of movement and distribution of insects might be related to their adaption to the grain storage ecosystem. Stored grain beetles are negatively phototaxic and seek out refuges providing close physical contact with the insect's body [13]. There will be an advantage to insect that commence dispersion before condition deteriorate too far (temperature too high or too low, moisture too high or too low, density too low or too high), thus improving their chances of finding more suitable conditions. Dense populations of *T. castaneum* release benzoquinones causing the beetles to migrate from the crowded area [20]. Movement of grain results upward movement of *Sitophilus oryzae* [6, 42]. Therefore, the interaction between the stored grain ecosystem, the survival requirement, and their adaption to this environment should be considered during their movement.

Interaction of Insect and Fungi

Storage fungi usually accompany or follow insect infestation [68–72, 75, 77]. Therefore, succession of insect species and microflora are usually mixed together [2, 17, 76, 78, 79]. Evidence indicates some insect species are disseminators of storage fungi, and some are exterminators [1, 17], and some storage fungi attract insects and promote their population increases and other repel and secrete toxins (include mycotoxins) harmful to insects. The close relationship between insect and fungi has been well documented [17, 47].

Even though the relationship between insects and microflora is complex and there are different results under different situations, certain species of both fungi and insects often are intimately associated, and there are certain connections among the two and other factors of the stored grain ecosystem. For instance, 21 species of fungi are found associated with *R. dominica* and *T. castaneum* [28]. High bacteria counts are associated with high FAV levels [87]. *Alternaria* and seed germinations are negatively related to FAV, bacteria, and grain damage; the number of insects is related to the presence of *Aspergillus* and negatively related to the presence of bacteria. Seed germination and *Alternaria* infestation often decreased rapidly, presumably because of infestation by fungi of the *Aspergillus glaucus*. The combined action of *R. dominica* and *Aspergillus* spp. enhanced seed damage and increased grain moisture content, thus promoting bacterial growth which in turn inhibits insect and mould growth. Fat acidity values increase with time, unless seed damage and bacterial infestation are extensive [87]. There are association and synergistic interactions between mycotoxigenic fungi and *T. castaneum* [1].

More adults of *C. ferrugineus* are attracted to spoiled grain with infested by *Penicillium corymbiferum* and *Fusarium* sp. [16]. This behavior may be synergized with the response to volatile chemicals and moisture content because insect also tend to move to damp grain [51]. Stored grain and their products release hundreds of trace amount of volatile chemicals [12]. These volatile chemicals can induce insect movement, feeding, and sexual activity [12]. The situation is more complicated by the gases and volatiles released by microorganisms, grain, and insects. There has been a steady increase in the efforts to use these semiochemicals to monitor and control insect pests. Pheromones are successfully and commercially used to detect insects. More studies should be done on how and when these volatile chemicals influence insect movement, dispersion, and succession in this ecosystem.

Hot Spot

Hot spot is a good example for the study of grain storage ecosystem because the stored grain or oilseeds inside a hot spot experience fast environmental change (such as temperature, relative humidity, and gas and volatile concentration) and insect and microflora species composition change (Fig. 3). Both insect and microflora can initiate hot spots [75]. Hot spot initiated by insects is usually also infested by microflora because heat and water produced by insects benefit the development of microflora. In an insect-initiated hot spot, the combined effect of increased activity of *Penicilium* and that of the insect *C. ferrugineus* seems to be responsible for the high temperature in the hot spot [76]. It is expected that insects move away from the hot spot when temperature is >42 °C and stay at the boundary of the hot spot where temperature is warmer [35]. Heavily insect-infested zones are delimited by 14.1–34.4 °C in an oat bin with two hot spots, and a few isolated adult insects are found in the area outside these zones [76]. After the hot spot is initiated, succession of insects occurs in the 14.1–34.4 °C zones [76]. Succession of microflora occurs around and inside the hot spot. High respiration rate of microflora induces the temperature of the hot spot further go up to 65 °C and enlarge the hot spot [76]. For very few situations, oxidation of the grain makes the hot spot temperature go further up to 400 °C [56] and ignite fire if enough O_2 is provided. Hot spot usually dies after it reaches less than 65 °C (Fig. 3).

It is not known exactly why the initiated hot spot is enlarged or dies out. Ambient temperature might play an important role in the further development of the initiated hot spot [85]. It is suggested that the convection currents and moisture diffusion due to the moisture and temperature differentials in the bulk can quickly dry out the small hot spot [75]. These convection currents and diffusion could be influenced by grain porosity, location of the hot spot inside the bin, temperature, and moisture differences between the hot spot and its boundary, thermo-physical property of grain, storage structure, meteorological variable, and biological factors. Moisture diffusion and migration from a hot spot to its surroundings was recorded by Wallace et al. [85]. As the hot spots develop, the grain moisture at the top of the hot spot increases, while the grain below is dried [76]. During the hot spot development, grain experiences a sharp increase of temperature and moisture content. The

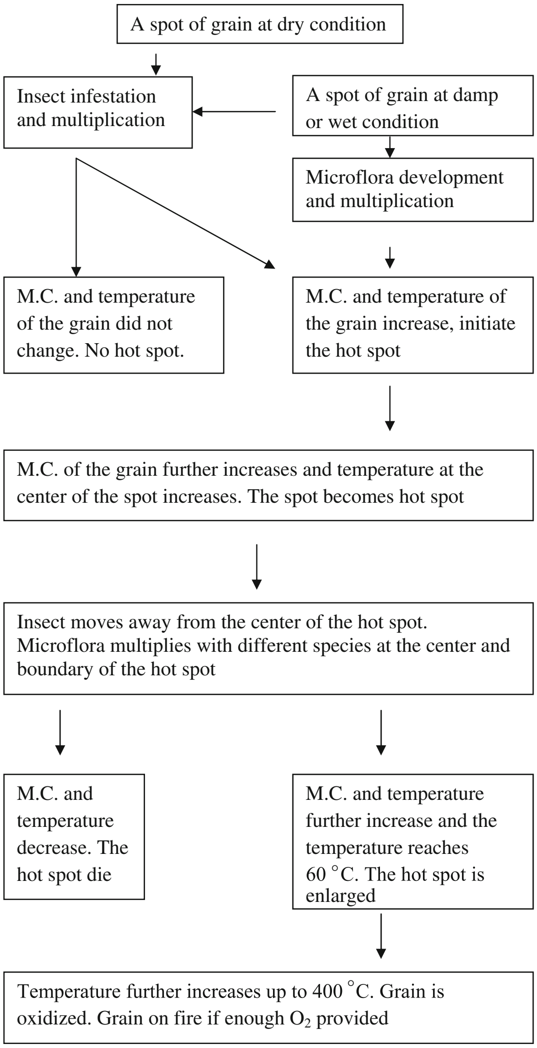

Fig. 3 Schematic of the development of a hot spot

grain should produce volatile chemicals [12]. If there are convection currents around the hot spot, then these volatile chemicals should be detected if reliable sensor is located at the top of the hot spot. It is not known whether this chemical currents influence insect movement and distribution inside the bin.

Ecosystem Approach

Understanding the Stored Grain Ecosystem

To develop a program of grain storage management, thorough understanding of the grain storage ecosystem is the key [73, 86]. For example, to understand the development of hot spots and succession of insects and microflora, the relationship between two or among a few factors has to be studied under controlled laboratory conditions. However, no matter how carefully collected, these collated data under laboratory conditions have limited use in granaries where variables are at transient condition and influence each other [40, 73, 86]. For instance, granaries at different places and time might have different succession of insects and microflora [18, 72]. The development of hot spots inside whole scale granaries might be induced by different factors at different conditions [69, 75, 76]. The insect movement and distribution might be triggered by different factors [33]. The interaction of these factors in turn influences the stored grain ecosystem [73]. Therefore, even though it is often logically difficult to conduct replicated research in whole scale granaries for long periods, studies are required to find the interaction relationship between variables under full scale conditions [86]. Integrating the parts (the collected data under small scale controlled conditions) into a usable whole (the entire grain storage ecosystem) and comparing the synthesized whole with the collected data under the full scale conditions will help us understand the development of hot spots and succession of insects and microflora, and further our understanding of the entire stored grain ecosystem [86].

Compared with the experiments of whole scale granaries, mathematical modeling might be an inexpensive tool [29, 46, 55] to understand the stored grain ecosystem. The advantage of the mathematical modeling is that the developed model could couple all the non-living and living factors, simulate the interaction among the factors, and predict the results based on the simulated environments of the stored grain ecosystem [31]. The interaction between two or a few factors could be fully studied under laboratory conditions and the determined relationship between a few factors could be combined into developed models. The developed models must be calibrated and validated using the data collected in full scale granaries [29, 46, 55]. This calibration and validation includes the process of the revision of the relationship between the factors found under controlled conditions. Calibrating and validating models can verify and improve their accuracies [29, 46, 55]. Therefore, a well-developed and validated mathematical model will help us understand the stored grain ecosystem [31].

Grain storage expert systems are computer programs that solve problems related to grain storage management [22]. The expert systems can store both qualitative and quantitative information and act as storehouses of information that can be continually added to and improved over time [22]. Expert systems coupled with mathematical models can suggest alternative strategies to prevent problems from developing. An expert system might be used as a tool to understand the grain storage ecosystem if the ecosystem approach is applied.

Management of the Stored Grain Ecosystem Using Ecosystem Approach

The concept of ecosystem approach is not the same as already used concept of the Integrated Management (IM) such as the widely used Integrated Pest Management (IPM) [14, 15, 19, 25]. The main difference between ecosystem approach and the IM is that the ecosystem approach uses the ecosystem concept to manage the stored grain and IM uses the ecosystem concept as an option [19]. A program developed based on IM might be adapted and improved using ecosystem approach because many recommendations developed in IM program are also based on the concept of the stored grain ecosystem. Therefore, compared with IM, ecosystem approach adds complexity to management, but brings additional tools for the task.

Solutions that are developed to address the problems in a stored grain ecosystem may be different if the ecosystem is not thoroughly understood, interaction of stored grain ecosystems within the preharvest agroecosystem is not considered, and the ecosystem approach is not used. For example, the initial grain condition influences the stored grain ecosystem [56]. Grain harvest time and duration are always influenced by other ecosystems and weather conditions. Both insects and fungi might infest the grain before it is loaded into bins [66]. These factors influence the initial grain condition, such as temperature, moisture content, and insect and fungi infestation rate.

One of the concepts of ecosystem approach is to inspire farmers and managers to use the relationship between the stored grain ecosystem and agroecosystems, among factors, and between factors inside granaries and climate change [14, 15, 19, 25]. During the development of storage grain management program, human needs and impacts on environment should be considered. The strong relationships between weather condition and insect and microorganism succession, insect movement, and development of hot spots indicate that a sound program of management of the stored grain ecosystem should take advantage of the local weather condition and available information. For instance, to limit pest reproduction and growth and stop the succession of the insect species and microflora, with the limited tools available, temperature, moisture content control, or management (such as drying grain using hot or natural air, cooling grain by aeration or chilled aeration, and turning grain) are probably the most widely accepted methods [59]. These methods could be used in most places of the world if local weather data are intelligently applied and chilled aeration is integrated in the process [59].

Politics play an important role in the management of the stored grain ecosystem [61, 65, 83]. In any country, management of stored grain bulks can change due to changes in regulations established by their government. Government rules, such as price subsidies, grade standard, and mycotoxins tolerances, have an impact on how the system is managed [61, 65, 83]. Policies can guide the practice of stored grain management to conservation and sustainable direction [61]. Therefore, ecosystem approach should be considered during the development of regulations related to grain storage because grain storage is the key link of the grain demand–supply chain and farming ecosystems. Ecosystem approach should be also used in the global scale because storage ecosystems are connected by transportation and commerce.

Outlook for Future Research

Multidisciplinary research should be strengthened and research projects should be conducted by coordinated team with specialists in different research areas because the stored grain ecosystem is a system in systems [86]. The challenge that remains is to integrate the parts into a usable whole and to fill in areas of research that still need to be addressed. To verify the synthesized whole, large scale, and multi-factor tests (such as inside stored silos) should be conducted. The research scope needs to be broadened to cover the range of ecosystem and agroecosystem components and toward the geography, climate, and agricultural sequence of regions.

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