Introduction

Wheat under pathogen pressure

Wheat (*Triticum aestivum* L.) was domesticated more than 10,000 years ago, making it one of the world's oldest crops [1]. With a cultivated area of 219 million hectares, it is also the world's most widely grown crop and is threatened by a variety of diseases that, according to simulations, will further increase in the future [2–4].
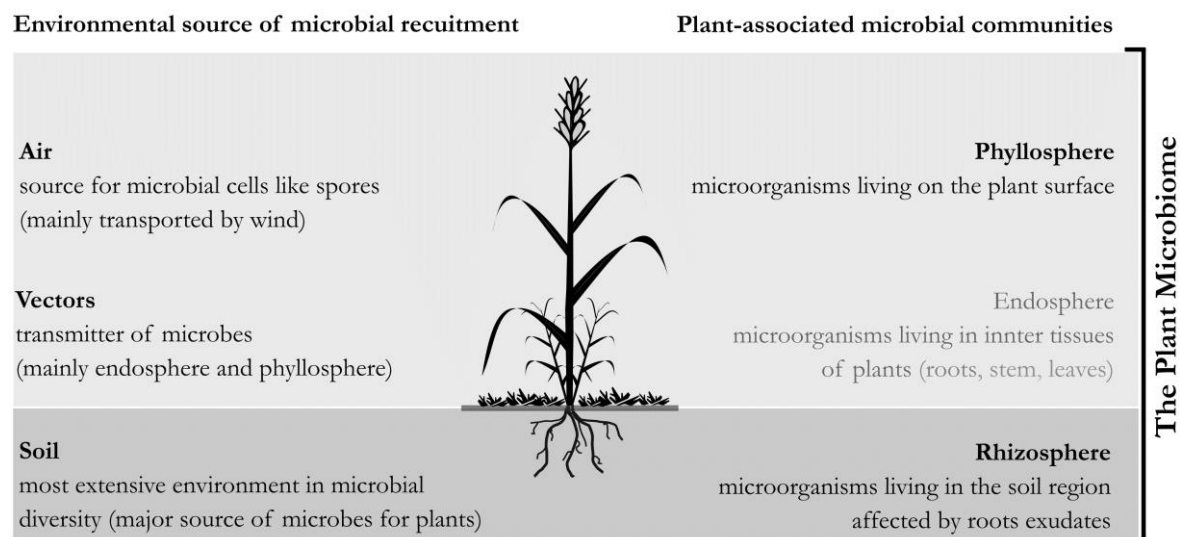
Hundreds of fungal, bacterial, and viral pathogens infect wheat worldwide and are directly affected by environmental conditions. These include serious diseases such as Fusarium head blight (*Fusarium* spp.), Powdery mildew (*Blumeria graminis*), Spot blotch (*Cochliobolus sativus*), Stripe rust (*Puccinia striiformis*), and Loose smut (*Ustilago tritici*), as future climate conditions favor these pathogens [3]. In 2006, Oerke already summarized that the potential loss from wheat diseases without appropriate actions is about 50 %. However, even with current crop protection practices, the possible loss could be reduced to only 29 %, with pathogens accounting for 10 to 20 % [5,6].

In general, developing resistant varieties remains one of the most effective and sustainable strategies for wheat disease control [7]. Nevertheless, corresponding wheat varieties are not available for every disease. For example, cultivars with high resistance to *Fusarium* have yet to be made available. In addition, weather models are currently being used to predict diseases to respond quickly with appropriate management strategies [8]. Yet these management strategies usually involve the application of synthetic-chemical pesticides. As part of the Green Deal, the EU Commission's Sustainable Use Regulation sets a target to reduce the use of chemical pesticides by 50 % by 2030 and demands an immediate reconsideration of pest management [9].

Biological disease control is becoming increasingly important in this regard. The search for antagonists as biological control agents is currently receiving much attention. It is one reason for me to examine antagonistic influences through priority effects in Chapter 3. Many knowledge gaps still need to be addressed due to recent sustainable and biological crop protection advancements. Therefore, integrating multiple approaches based on knowledge of pest epidemiology appears purposeful and efficient [3]. Thus, the focus of my studies is on pathogen dispersal (Chapter 1), the impact of regional characteristics in microbial community formation (Chapter 2) and concrete microbial interactions (Chapter 3), particularly considering temporal influences.

The plant microbiome

Plant tissues are colonized by various microorganisms, collectively known as the plant microbiome, which influences plant, soil, and agroecosystem conditions in a variety of ways, as well as being affected by these conditions themselves [10–12]. The areas of the plant colonized by microorganisms are generally divided into two categories: the rhizosphere and the phyllosphere, with microorganisms (endophytes) also present in the inner parts of the whole plant (Figure I 1) [10,13]. The rhizosphere describes the belowground regions and has been described by Lynch and Leij (2012) as "the field of action or influence of a root" [14]. Releasing root secretions creates a nutrient-rich environment that favors colonization by many bacteria, fungi, protists, and nematodes [10]. In contrast, the phyllosphere describes the aboveground microbial habitat of the plant, including the stem, leaves, flowers, and fruits [15]. Molecular identification methods have detected various coexisting bacteria, archaea, fungi, algae and viruses on the plant surface, with less protozoa. [15]. In contrast to the rhizosphere, the phyllosphere is poorer in nutrients and more exposed to environmental

Environmental source of microbial recuitment   **Plant-associated microbial communities**

Air
source for microbial cells like spores
(mainly transported by wind)

Phyllosphere
microorganisms living on the plant surface

Vectors
transmitter of microbes
(mainly endosphere and phyllosphere)

Endosphere
microorganisms living in innter tissues
of plants (roots, stem, leaves)

Soil
most extensive environment in microbial
diversity (major source of microbes for plants)

Rhizosphere
microorganisms living in the soil region
affected by roots exudates

The Plant Microbiome

stresses such as rain and drought, as well as UV radiation, which poses further challenges for microorganisms.

Figure I 1   The plant microbiome - schematic illustration of the key sources of microbes that build the plant-associated communities in the Rhizosphere, Endosphere, and Phyllosphere. Adapted from Andreote et al. (2014) [16].

The rhizosphere has received much more attention, focusing on microorganism-plant interactions and intermicrobial relationships [11]. In contrast, most phyllosphere research has focused on the detection of plant pathogens and consisted mainly of biogeographic pattern of fungal pathogens [11,15,17]. These observations often focused only on the occurrence of a single species and neglected the phyllosphere as a habitat of microbial communities. There still needs to be a greater understanding of the influences of microbial community formation on the plant surface. This reinforced my decision to focus my work on the phyllosphere and examine both the interactions in this habitat (Chapter 3) and the microbial community composition under different site characteristics (Chapter 2).

Wheat has been extensively studied for the microbiota in the rhizosphere and phyllosphere using mainly culture-dependent methods [18–21]. In recent years, through the progressive development of genetic and molecular techniques, it has become possible to obtain a more accurate picture of the microbiome by also detecting microorganisms that are difficult to

culture. Most studies in the rhizosphere have focused on responses to changes in agricultural practices and the use of different wheat varieties [22–25].

A few studies have already addressed the microbiome of aboveground wheat parts [26–29]. The so-called "core microbiome," which describes the indigenous species always associated with a particular host genotype, has not yet been ultimately defined for wheat. In the phyllosphere of wheat, bacteria such as *Agrobacterium*, *Arthrobacter*, *Bradyrhizobium*, *Bacillus*, *Enterobacter*, *Burkholderia*, and *Pseudomonas* were found to be common species that also have the potential to act against pathogens [25,30–32].

Besides bacteria, various coexisting filamentous fungi and yeasts are also found on wheat leaves and ears. The following fungal taxa are consistently among the most detected: *Acremonium*, *Alternaria*, *Bionectria*, *Chaetomium*, *Exophiala*, *Fusarium*, *Kendrickiella*, *Magnaporthiopsis*, *Microdochium*, *Morteriella*, *Nectriaceae*, *Penicillium*, *Purpureocillium*, *Staphylotrichum*, *Trichoderma*, and *Ulocladium* [33]. I will focus on *Fusarium* and *Alternaria* from this network due to their increased occurrence and economic importance.

Fusarium and *Alternaria*, two phytopathogenic fungi on wheat

In addition to the considerable yield losses caused by pathogens, a fungal infestation of wheat poses another danger: toxic metabolic products. The chemical compounds produced by some fungal strains, known as mycotoxins, can contaminate grains and stay stable for years in stored grain. Mycotoxins can cause serious health problems for humans and animals when processed as food and/or feed. Most mycotoxins are stable during food processing and are usually resistant to thermal and chemical changes [34]. Thresholds for mycotoxin contamination of market cereals have been established to ensure food safety, as defined in Europe by Commission Regulation No 1881/2006 [35]. The two mycotoxin-producing fungal pathogens that most commonly affect wheat are *Fusarium* and *Alternaria*. Due to their worldwide distribution and the economic damage, they cause through yield losses, and the additional threat of mycotoxins, they are of paramount importance. Current management strategies can rarely be implemented successfully, requiring further research to control the pathogens.

Fusarium as the causal pathogen of Fusarium head blight

Since the early 1990s, Fusarium head blight (FHB) has become one of the most critical cereal diseases in Canada (central and prairie regions), America (Midwest region) [36], Western Europe [37], and affects areas in Argentina and Russia [38]. FHB leads to yield losses and reduces the quality of harvested grains due to mycotoxin contamination. The increase in FHB over the last few years is believed to be a result of climate change, conservation agriculture, and the increasing implementation of wheat-maize rotations [2]. In many wheat-growing areas, destructive outbreaks are often occasional and influenced by climatic (frequent rainfall, high humidity, heavy dew) and management factors (reduced tillage, high proportion of host plants, short rotation intervals of susceptible varieties) [38,39].

Two pathogenic fungal genera can lead to FHB: *Fusarium* and *Microdochium* (formerly known as *Fusarium nivale*). Certain species predominate depending on the world's region and climatic conditions. For example, there are up to 19 *Fusarium* species [40,41] and two *Microdochium* subspecies (*M. nivale nivale* and *M. nivale majus*) [42] that cause FHB in Europe. *Fusarium* is widely represented by *F. graminearum*, *F. culmorum*, *F. poae*, and *F. avenaceum*, all of which are also associated with rot diseases of roots, stems, and ears of

wheat and maize [2,43,44]. *Fusarium* species form a disease complex, with multiple species usually found simultaneously on infected grain [45].

Fusarium diseases can be initiated in the rhizosphere by soilborne inoculum or in the phyllosphere by air or water [46]. Within the diversity of *Fusarium* species, both sexual spores (ascospores) and up to three types of asexual spores (macroconidia, microconidia, chlamydospores) are formed [47]. However, not all types of spores are found among all species. For example, less than 20 % of *Fusarium* species have a known sexual cycle, as does *F. graminearum* [46]. However, most species form macroconidia, which are characteristic of this species with their slightly curved, transparent, multiseptated shape. *Fusarium* species differ in their epidemiology, pathogenicity, fungicide sensitivity, and ability to produce mycotoxins, with most species producing multiple mycotoxins with varying degrees of toxicity [48].

Fusarium can produce mycotoxins of the three most relevant groups [34]:

1. Trichothecenes: type A trichothecenes, including T-2 and HT-2 toxins,
   type B trichothecenes, including nivalenol (NIV)
   and deoxynivalenol (DON))

2. Zearalenone   (ZEN)

3. Fumonisins   (FUM)

In humans and animals, these mycotoxins can damage the digestive tract, the liver, the endocrine system, the blood circulatory system, and alters the immune response in addition to cause several acute and chronic diseases. DON belongs to the most comprehensively studied mycotoxins and is formed, among others, by *F. graminearum* and *F. culmorum*, two species considered particularly relevant to FHB in temperate regions. The DSM World Mycotoxin Survey 2021 [49], which analyzed more than 24.000 samples of agricultural products from 75 countries, showed that DON contamination presents a high risk. In Europe, DON is still the main threat and was most prevalent in cereals (46 % of the contaminated samples), followed by T-2 (42 %) and ZEN (26 %) [49]. The formation of mycotoxins leads to the downgrading of contaminated wheat and severe price reductions or rejection of entire wheat batches if their concentration exceeds the maximum levels set by the European Commission [35].

Fusarium overwinters as a saprophyte on poorly decaying plant material such as corn stalks and wheat straw. Hence, infection rates are higher in cropping systems with little or no tillage [50]. Other sources of inoculation may include other crops or weeds, seeds, insects, or, less commonly, contaminated soil [42,51,52]. The fungus begins sporulating on the infested plant debris as soon as conditions become warm, moist, and wet in the spring (Figure I 2). *Fusarium* species, such as *F. graminearum*, can produce sexual spores and form dark, flask-shaped perithecia within a few weeks. These contain tubular sacs, also called asci, with many ascospores [53]. Ascospores are actively discharged from perithecia into the atmosphere and subsequently passed on by the wind [54,55]. During the asexual life cycle, common to most *Fusarium* species, conidia are produced in sporodochia on the infected residues [56].

In contrast to the ascospores, the conidia are assumed to be used primarily for short-distance dispersal and usually reach the plant via rain splash [56,57]. However, distribution of conidiospores by wind is not ruled out, as indicated by different studies [57–60]. Nevertheless, there are no comprehensive studies on the exclusive wind dispersal of conidiospores, especially considering different *Fusarium* species. Thus, an assessment of the extent to which conidiospores are involved in the large-scale distribution of *Fusarium* is

lacking. For this reason, I address the dispersal of conidiospores of various fusaria under controlled wind velocities in the Chapter 1.

FHB infection occurs when spores land on susceptible wheat-ears, especially during anthesis (flowering) of the wheat. Temperatures between 15 and 30 °C and humidity above 90 % for prolonged periods favor FHB infection by increasing inoculum production [61]. *Fusarium* invades the inflorescence and can spread through the shoots to uninfected flowers, damaging the developing seeds.
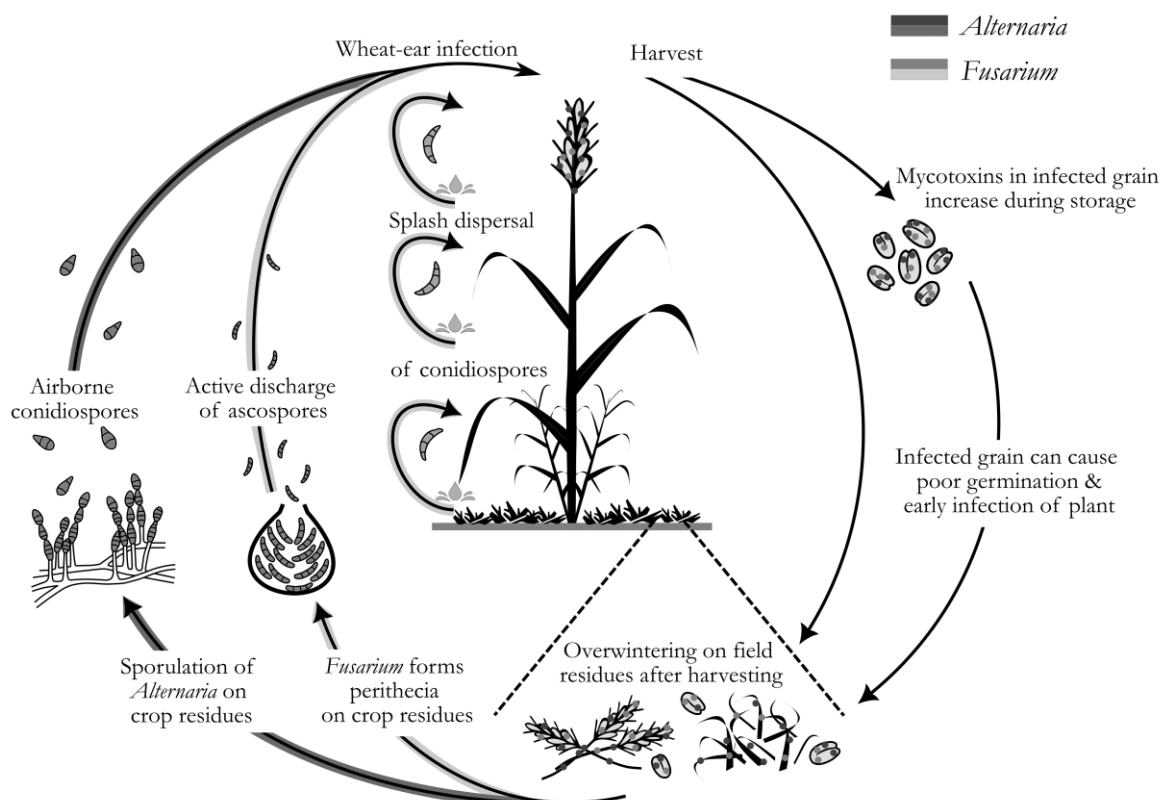
Figure I 2   The life cycles of *F. graminearum* (sexual phase, *Gibberella zeae*), causal agent of Fusarium head blight on wheat and *Alternaria* spp. causing black spot disease on wheat (adapted from Trail (2009) [56] and AHDB [227]). Details of specific aspects of the cycles are discussed in the text.

In the process, mycotoxins are produced, which *Fusarium* uses for infection and defense against other microorganisms [46]. The naked eye can often recognize infected wheat-ears after two to three weeks by bleaching the upper ear tip. If the fungus penetrates as far as the rachis, the nutrient supply to the part of the wheat-ear above is cut off, which can lead to the bleaching and the formation of shriveled grains. The symptom is, therefore, also referred to as partial white or dew blight. The shriveled and smaller kernels are typically covered in pink, orange, crimson, or white down [62]. Other symptoms might include a brown coloration on the back of the grains or the outer side of the glumes [42].

Crop rotation with small grains and corn with a two-year crop break is recommended for FHB control to allow the infested residues to decompose fully [42,63,64]. Complete plowing of crop residues will reduce infestation for the following year, and appropriate seed treatment controls seedling damage but may not prevent FHB development [64,65]. Fungicide spraying of the crop suppresses FHB but is insufficient to control the disease completely [65,66]. Hence, there is still no complete prevention and control against *Fusarium* infestation.

Alternaria as the causal pathogen of black spot disease

The genus *Alternaria* was first described by Nees in 1816 with the species *A. tenuis* [67] and has since expanded to nearly 300 species [68]. *Alternaria* is also among the most detected taxa on wheat-ears worldwide, with *A. alternata*, *A. tenuissima*, *A. arborescens*, and *A. infectoria* being the most common species groups [69–71]. *Alternaria*, together with the fungi *Cladosporium*, and *Ulocladium* causes the "black spot" disease in small cereals. Black spot disease was considered only a qualitative and commercial problem for a long time [72]. However, studies also suggest a 60 - 80 % reduction in germination rates, depending on the degree of infestation of the wheat kernels [73,74]. And with the reassessment of the importance of *Alternaria* mycotoxins, black spot disease is coming into focus.

Alternaria species produce a wide range of secondary metabolites, such as phytotoxins that play a role in plant pathogenesis and mycotoxins that contaminate various agricultural products. Based on their chemical structure, the comparatively understudied *Alternaria* mycotoxins can be divided into five categories [75]:

1. dibenzo-α-pyrones: alternariol (AOH), alternariol monomethyl ether (AME), Altenuene (ALT)

2. perylene quinones: Altertoxin I (ATX-I), ATX-II, ATX-III

3. tetramic acids: tenuazonic acid (TeA)

4. AAL toxins (AAL-TA 1- 2, AAL-TB 1- 2)

5. various structures: tentoxin (TEN, a cyclic tetrapeptide)

AOH, AME, ALT, and TeA are commonly found in high amounts in wheat [68]. Although some *Alternaria* mycotoxins (AOH, AME, ALT, and ATX-I) are not considered acutely toxic, several studies have reported that AOH and AME have mutagenic and genotoxic effects [76–80]. TeA harms several animal species, including mice, chickens, and dogs [68,71,81]. With the increasing importance and visibility of *Alternaria* mycotoxins, the EU Commission issued a recommendation to monitor the presence of *Alternaria* toxins in food at the beginning of this year [82].

The taxonomy of species is not fully defined, and species identification is usually based on a multistep approach using morphological characters, phylogeny, and toxin profiles [71,83]. Nevertheless, neither taxonomy based on morphology using conidial characteristics and pattern of catenation (started by Simmons and Roberts (1993) [84]) nor molecular phylogenetic relationships among *Alternaria* species groups could provide a precise method for species classification [71,81,83].

The spores of *Alternaria*, as with *Fusarium*, are among the most characteristic taxonomic features and differ considerably from other fungal spores. The spores are multicellular and contain melanin, which gives them strong UV resistance and favors colonization of the phyllosphere of many plant surfaces [68]. Club-shaped spores are formed on elongate conidiophores and are septate both longitudinally and transversely, with a more expanded base and a smaller and elongate tip. *Alternaria* species are hardy fungi that can overwinter in the form of mycelia or conidia in soil, seeds, and infected crop residues [85]. The life cycle is like that of *Fusarium* and begins with the formation of mycelium and spores on crop residues in spring (Figure I 2). The inoculum builds slowly as most spores are produced on dying or dead leaves. Therefore, *Alternaria* epidemics generally begin during flowering and reach their highest intensity when plants are in senescence [86]. Optimal temperatures for *Alternaria* growth range from 22 to 30 °C, but minimum temperatures can be as low as 2 to

6 °C [87,88]. At the same time, high temperatures and humidity correlate with the highest contamination of *Alternaria* species [72]. *Alternaria* spore release is favored by rainfall and sudden changes in humidity [89]. The spores of *A. alternata* are actively released into the air during a rapid increase in humidity and are further wind-dispersed [86]. *Alternaria* spreads well through the air and often has high spore concentrations, hence it is often studied in connection with its property as an allergen [90–92]. *Alternaria* can cause one of the most severe forms of asthma when airborne fungal spore concentrations are high and individuals are susceptible [90]. Therefore, many European studies are concerned with *Alternaria's* allergenic potential and atmospheric distribution rather than with the direct relationship between *Alternaria* contamination and wheat.

Wheat infested by *Alternaria* shows an apparent dark discoloration of the wheat-ear due to the mycelium and dark sporodochia [67]. When infested, wheat kernels show dark discoloration at the embryonic end of the kernel [93], which leads to a decrease in flour quality, as black spots are formed in the flour and baked goods made from it. Due to the low economic importance given to the disease so far and that the infestation occurs so late in the maturity and senescence stage of the crop, there are barely any management and control strategies for *Alternaria* infestations available [74,94]. However, due to its ability to produce mycotoxins, *Alternaria* is attracting increasing attention and the need for a more detailed characterization of the genus is growing.

Community assembly - Fusarium and Alternaria colonize the same local niche

The diversity and abundance of the phyllosphere community are determined primarily by abiotic factors such as relative humidity, season, water content, ultraviolet light, and age of leaves, as well as biotic factors such as insects, nematodes, pathogens, and the genotype of the host plant and other plants in the environment [95]. Based on the theory of community assembly and the modern coexistence theory, a basic framework for understanding local and regional diversity and its ongoing changes can be developed [96]. Theoretically, local communities form out of a global species pool that passes stepwise three main sorting processes (Figure I 3). First, dispersal limitation determines how far a species can spread and reach a new site, forming the regional species pool (dispersal limitation). At the new site, abiotic environmental conditions dictate whether the species will find the environmental conditions necessary to survive and reproduce (environmental filter). Finally, biotic interactions with existing species at the new site influence the success of the new species and its coexistence in the community (biotic filter) [96].
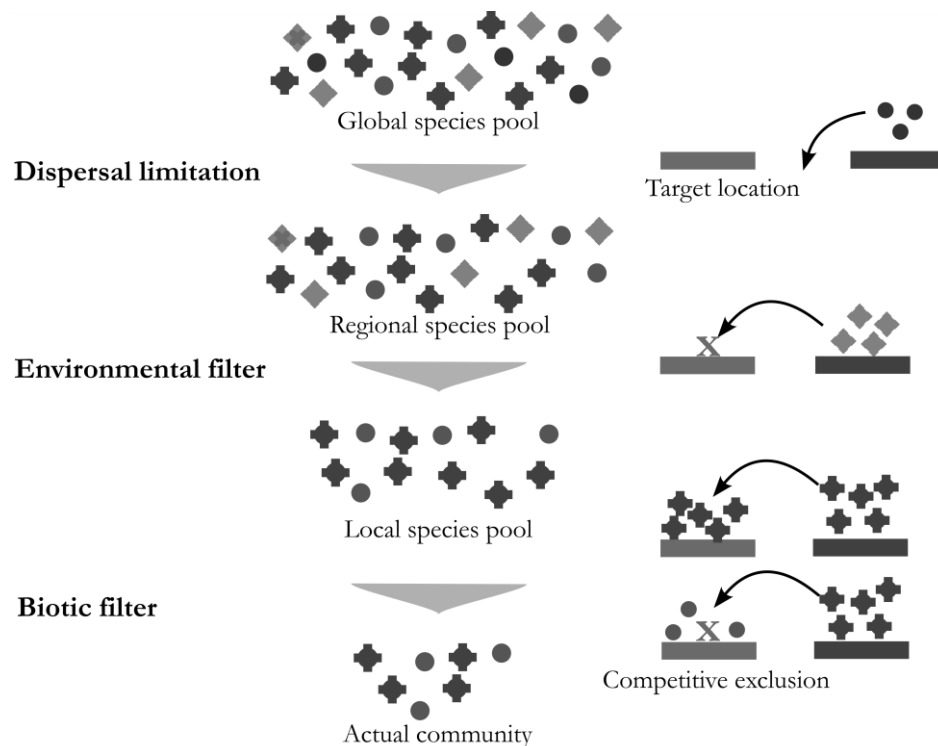
Figure I 3   Filter processes during community assembly. First, species composition is determined by their dispersal ability and potential to reach a new site (dispersal limitation). Next, the environmental conditions prevailing at the new site determine whether a species can survive (environmental filtering). Finally, competition with species already present at the new site determines whether the incoming species can establish itself (biotic filtering). The resulting community composition is the result of the action of all three filters. Combined and adapted from Kraft et al. (2015) [97] and Funk (2021) [98].

The distribution patterns of the two genera, *Fusarium* and *Alternaria*, differ considerably. Many studies on *Alternaria* fungi have examined the presence of spores in the air. *Alternaria* spores have been detected in the atmosphere worldwide [91,99–101], even at altitudes of several kilometers and in remote locations such as the Arctic [102]. In addition, long-range transport of alternaria over more than 600 km has been tracked over Europe [103]. In contrast, *Fusarium* transport mechanisms are often limited to raindrop dispersal [57,58,104], with studies on conidiospores dispersal via wind being minimal. Exceptions are fusaria which produce ascospores that may also be transported over several hundred meters in the atmosphere [105–107].

Regional distribution is often related to environmental factors for both genera. Aira et al. (2013) summarized the spatial and temporal distribution of *Alternaria* spores and found that biogeographic factors and local weather conditions determine their concentration [99]. The strongest positive correlation appeared between airborne *Alternaria* spores and temperature (especially average temperature). In contrast, spore occurrence was negatively correlated with precipitation and relative humidity [99]. In addition, a cross-regional study by Skjøth et al. (2016) showed that local climate, vegetation patterns, and landscape management were the most important factors influencing spore concentrations, while annual weather fluctuations were of lesser importance [91].

In relation to *Fusarium* incidences, Romero et al. (2022) provided a clear summary of the influence of humidity and high temperature on fungal disease outbreaks and confirm that these two factors positively affect the occurrence and abundance of fusaria [108]. As for *Alternaria*, it was also found for *Fusarium* that long-term average weather conditions (especially average precipitation values) could have a much stronger influence on the occurrence of *Fusarium* ssp. than annual fluctuations [109]. Most of the available studies on regional distribution often refer only to single *Fusarium* species such as *F. graminearum* and *F. culmorum*. Of these species and their chemotypes, it was shown that their occurrence is distributed differently in Europe [110]. Kelly et al. (2015) was able to show for specifically *F. graminearum* that their occurrence is primarily directed by complex adaptive landscapes with varying regional selection pressures [111]. Nevertheless, no specific determinant could be identified. Instead, it appeared to be a result of the combination of climatic differences, site-specific undefined characteristics, and host prevalence at the various sites [111]. There still needs to be more studies on the composition of *Fusarium* in different regions and an accounting of the site-specific characteristics that shape the community. The few studies on general mycotic phyllosphere composition usually focus on species composition and lose sight of the regional context [15,29,112]. This raises the question of the extent to which the fungal community and the *Fusarium* and *Alternaria* populations in the phyllosphere of wheat differ in different regions. This formed the basis for the study in Chapter 2, in which we investigated three regions in North-East Germany with different wheat yield potentials, soil composition, and climatic conditions for their fungal composition.

At the field level, studies have identified distribution patterns of phytopathogenic fungi *Fusarium* and *Alternaria* and one of their most prominent bacterial antagonist groups, the fluorescent pseudomonads [29,113]. The occurrence and abundance of both fungi correlated with microclimates but differed depending on the fungal genus. *Fusarium* fungi grew in places with increased humidity with distinct temporal variations, which was also evident in spore incidence. In contrast, *Alternaria* fungi were homogeneously distributed within the wheat field. Yet they were found to favor higher temperatures and lower moistures [113]. Fluorescent pseudomonads were detected in high abundances in all sites of the wheat fields, but the proportion of antagonistically active pseudomonads fluctuated in space. This is an indication that other interactions are taking place at the intermicrobial level in addition to dissemination and environmental influences.

The genus *Alternaria* is highly competitive due to its tolerance to water stress, hydrolytic enzyme production, and mycotoxins [68,92]. Damialis et al. (2015) tested several fungal species in vitro under different temperatures and nutrient availability and determined *A. alternata* as the most competitive species in these climate change scenarios [92]. In various studies, *Alternaria* successfully competed with *Fusarium* species, which had a much lower frequency as a result [68,114]. This contrasts with results by Gannibal (2018), who observed that the species *F. langsethiae*, *F. tricinctum*, and *F. graminearum* grew faster while suppressing the growth of *Alternaria* [115]. This suggests that the interactions between the different species are more complex and depend on additional parameters. In most cases, significantly elevated mycotoxin levels are found when *Alternaria* and *Fusarium* infections occur simultaneously [116–118]. In contrast to the interactions between these two phytopathogenic fungi are the pseudomonads, which have antibiotic activity through the production of inhibitory or lethal metabolites [31,119,120]. Strains of *P. fluorescence* and *P. simiae* showed promising results in reducing *Fusarium* and *Alternaria* mycotoxins in the field [32,121].

However, more consideration of the temporal component is needed in studies, which can have a strong influence on the severity of the interactions. As described earlier, dispersal capabilities not only play a role in the distance a species can overcome, but also determine

how quickly, and thus in what order, it arrives at the new location. This temporal aspect and its consequences for community structure are called priority effects. The species arriving first can use the resources in the shared habitat earlier and thus has a competitive advantage over species arriving later. In addition, there is the possibility that the release of secondary metabolites, such as mycotoxins, may hinder the colonization of the habitat for subsequent species. Therefore, in Chapter 3, we investigated not only the antagonistic effect of fusaria, alternaria, and pseudomonads against each other, but also the temporal influence of colonization of the wheat-ear.

Objectives

This project addresses the competitive coexistence of microorganisms colonizing the wheat-ear. It will elucidate the relationships between dispersal ability, local interactions within the plant microbiota, and region-specific environmental factors. Competition for spatial and temporal niches and exclusion of competition through chemical aggression may act as stabilizing or equalizing mechanisms that contribute to the coviability of organisms. The expected trade-offs between these dispersal processes and niche competition will help to better explain infection processes by phytopathogenic fungi and the importance of antagonists in suppressing phytopathogens at different spatial and temporal scales.

Abiotic and biotic vectors influence the dispersal of microorganisms in the atmosphere and, thus, microbial diversity in the phyllosphere. Phytopathogenic and mycotoxin-producing fungi of the genera *Fusarium* and *Alternaria* live in competitive coexistence on wheat-ears and exhibit great heterogeneity at field and landscape scales. The distribution pattern is designated by their dispersal ability, which is strongly related to the spore shape and its traits. The influence of different *Fusarium* species with different their spore shapes is investigated in Chapter 1 for their dispersal ability. However, their distribution patterns are also partly determined by potentially available habitat, which depends on region-specific characteristics such as temperature and precipitation, which I address in Chapter 2. In addition, sporulation and the ability of spores to establish themselves in a new habitat depend on the assertiveness of the fungi and competition with already established bacteria and fungi. For example, fluorescent pseudomonads in the microbiome of crop plants have been described as antagonistic to *Fusarium* and *Alternaria*. They may limit the distribution of phytopathogens and the production of their toxins. Accordingly, in Chapter 3, I examine the interactions among *Fusarium*, *Alternaria*, and *Pseudomonas* and emphasize the temporal influence.

Since a direct relationship between spore dispersal, fungal and bacterial abundance, and antagonistic activities remains to be found. I ask which of two characteristics is more important for the successful infection of wheat plants by phytopathogenic fungi: a high dispersal ability or a strong competitive ability? Experiments in a wind tunnel (Chapter 1), agricultural wheat fields in North-East Germany (Chapter 2), and climate chamber (Chapter 3) will reveal the distribution of phytopathogenic fungi in space and time and how this is influenced by the interactions between bacteria and fungi in the phyllosphere of wheat plants.