

Intro:

Plants face difficult times. With climate change, intensities of many types of plant stressors have increased, creating unpredictable new disturbance regimes, and many sources of plant stress are predicted to increase further¹. Plant genomes contain many answers to these challenges, especially to environmental challenges which have acted as long-term selective pressures on plants². However, plant genomes alone may not contain sufficient existing genetic variation or plasticity to ensure the success of ecologically or socially important plants in the face of decreased climatic stability and large-scale habitat changes³, even with rigorous breeding and selection programs.

Other solutions may exist: members of the plant microbiome, with its collective abundance of microbial genetic resources, may protect their hosts through competition for resources^{4,5} or active antagonism to potential pathogens⁶⁻⁸. In general, evidence has mounted rapidly that microbiomes in general are important determinants in plant health⁹⁻¹³. Together, it is proposed that the microbiome metagenome and the plant genome sum to make up the plant “hologenome”, which is more extensive and more dynamic than the plant genome alone^{14,15}. Microbiomes may become a point of leverage in the near future, wherein humans could increase resilience in plants of interest to environmental and biotic stressors by experimental manipulations of plant-associated microbial communities¹⁶⁻¹⁹. However, microbiome engineering has yet to achieve widespread success as an agricultural method, most probably due to an underestimation of the ecological complexity that maintains key members of microbiomes²⁰. For microbiome engineering to succeed, the intricate dynamics of host-pathogen-microbiome systems must be sufficiently understood to create persistent, beneficial microbiomes.

Here we propose to examine the *Pinus sylvestris* / *Sphaeropsis sapinea* host-pathogen interaction, with a focus on the augmentation of *Pinus* disease resistance by the natural products of its microbiome. *Pinus sylvestris* is an economically important and ecologically dominant forest tree throughout many regions of northern Eurasia with a long history of management and study²¹. *Sphaeropsis sapinea* (syn. *Diplodia sapinea*) is the causative agent of *Sphaeropsis* tip blight, but is also an extremely common asymptomatic wood endophyte and saprotroph in *P. sylvestris* and numerous other conifer species, with its pathogenic state appearing mostly in otherwise stressed hosts trees.²² It is thought to be an emerging pathogen in European forests, possibly due to climate-change induced stress on its host trees^{23,24}. In two studies, the presence of endophytes have been suggested to mitigate symptoms of *Sphaeropsis* tip blight, either through antagonism or competition^{5,25}. Important work has already been conducted by host researcher Dr. Terhonen and colleagues at University of Göttingen at the proposed site that greatly enhances the feasibility of this project proposal, including:

- extensive fungal endophyte culture surveys, completely archived available for use with the work proposed below²⁶

- ITS2 metabarcoding surveys of the mycobiome of the host tree in various stages of disease severity²²
- RNAseq survey of response by host seedlings to inoculation with *S. sapinea*²⁷.

Questions, Hypothesis, and significance

Questions

Is a "mature" microbiome important to disease resistance in host plants?

If so, what are the mechanisms by which host disease resistance is augmented by the microbiome?

Hypotheses and predictions:

H1 - Plant genome function is augmented very early in life by recruitment of a microbial community.

H2 - This augmentation in plant function is imbued at least partly by chemical compounds originating from the secondary metabolome of the plant microbiome.

P1 - Seedlings with a reduced, less-diverse microbiome will show higher *Sphaeropsis* blight disease severity relative to enhanced-microbiome seedlings.

P2 - The hologenomes of enhanced-microbiome seedlings will contain numerous biosynthetic gene clusters (BSGs) that are greatly reduced or absent in the hologenome of reduced-microbiome seedlings.

P3 - After inoculation with the pathogen *S. sapinea*, a subset of transcripts originating from the non-pathogen BSGs will be up-regulated in microbiome-enhanced seedlings.

P4 - Microbiome-enhanced seedlings will show differential phenotypic response to the pathogen: disease severity will covary with the presence of important biosynthetic gene clusters within their microbiome.

Significance:

As discussed above, the microbiome of plants has been shown to be important to plant health historically, and may represent one of the great hopes for increasing climate resilience in plants in the current era of rapid change. However, the inverse of this hope must also be examined. Within each plant is an ecosystem as complex and diverse as the habitats of the host plant. While many have acknowledged the destabilizing effects of climate change on macro-ecological systems like forests, the effects of climate change on the interior ecosystem that is the microbiome are likely to be just as drastic and unpredictable.

In this way, systems such as the *Pinus sylvestris* / *Sphaeropsis* host/pathogen-system are particularly important, because they are representative of the new era of disease that will face forests, cropping systems, and other ecosystems: **with climate change, plant microbiomes will behave unpredictably**. Large, disruptive changes in ecological roles of their associated microorganisms are possible. The *Pinus/Sphaeropsis* system may serve as an example: a facultative, weak pathogen that is historically considered a typical member of the host microbiome has rather quickly elevated its status as an emerging threat to the pines of Europe and Asia, likely due to increases in stress that are ultimately attributable to climate change.

In these times of rapid change, therefore, the urgency of detailed research into the dynamics of microbiomes within plants has increased - the leverage points of the microbiome must be explored. To this end, biosynthetic gene clusters are particularly important to study, as their self-contained nature allows simplified detection of entire pathways, and relatively easier transformation into heterologous systems. Because so much of the capacity of microbial secondary metabolome resides in BGCs, they are a natural place to search for the mechanisms by which microbes interact with one another. In general, BGCs represent a low-hanging fruit in the search for helpful natural metabolic solutions for enhancement of plants and drug synthesis²⁸⁻³⁴. Their diversity is astounding, however, and here we propose to filter the search for important gene clusters by the use of transcriptomic and phenotypic approaches. This pipeline for discovery of useful microbial gene clusters may be generalizable to host-pathogen systems elsewhere.

Methods

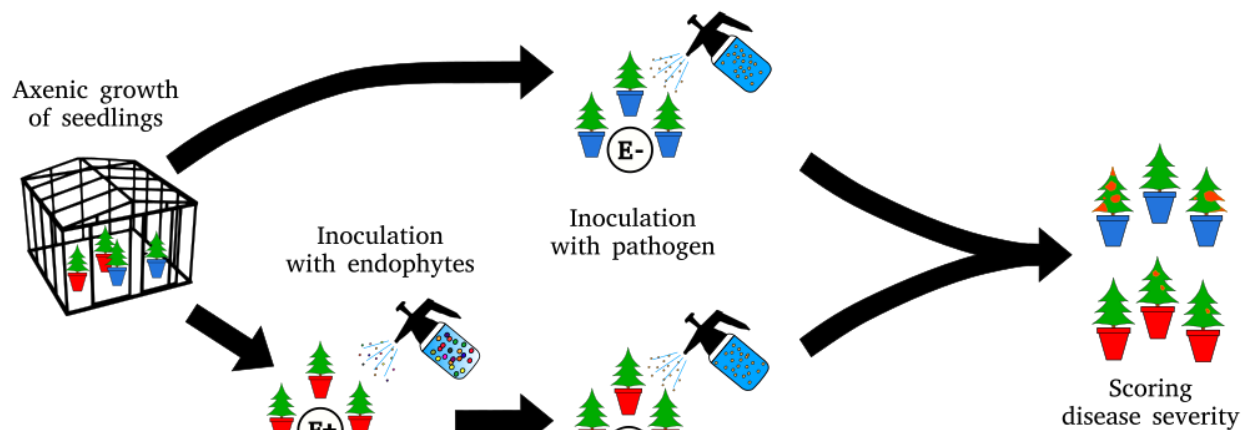
Summary:

We will experimentally reduce the microbiome of *P. sylvestris* seedlings using axenic growth methods, and restore mycobiome of some seedlings by inoculating with endophytes associated with a low-disease state. Following this, we will challenge both reduced-microbiome and regular seedlings with *S. sapinea*, and observe changes in the holo-transcriptome. Gene clusters will be sampled to estimate the capacity of secondary metabolome of the microbiome of these seedlings. The holo-transcriptome will be monitored for changes after infection with *S. sapinea*, and correlated with disease severity, to determine what portion of the microbiome meta-genome is activated by the disease.

Seedling preparation, endophyte inoculation, and pathogen inoculation

In the first year, microbiome-reduced seedlings will be grown in mostly-sterile conditions³⁵. Seedlings will be grown from seed from the research site of Blumenstein et al²²., a stand of Scots pine (52.327653 °N 11.189848 °E) close to Behnsdorf in Saxony-Anhalt, Germany. This also the site of origin for the endophyte cultures to be used for E+ seedlings²⁶. The most commonly recovered fungal endophytes observed in *P. sylvestris* from the previous study site

will be incorporated into the endophyte inoculation mixtures³⁶. Endophyte inoculation slurries will be prepared using scraped conidia from agar endophyte cultures or from using lightly-homogenized mycelium from liquid cultures where necessary. Half of seedlings of *P. sylvestris* will be misted with the endophyte inoculation slurry, and half with sterile malt controls. Successful endophyte infection will be confirmed through re-isolation of endophytes from inoculated seedling material 1-2 weeks following inoculations. Pathogen inoculation will take place 1-several weeks after this, following Vornam et al.²⁷, using a strain of *S. sapinea* isolated from the study site.



Metabarcoding-based exploration of fungal biosynthetic gene clusters:

Epiphytic and endophytic microbial communities will be sampled separately. To sample epiphytes, leaves will be submerged in tween / sterile water mixture, and vortex-ed to dislodge epiphyte biomass. This wash fluid will be centrifuged, and the pellet frozen for later DNA extraction. Leaf endophytes sampling will follow Thomas et al.³⁷, using a bleach-based surface sterilization method, followed by tissue homogenization and DNA extraction. Bulk DNA will be purified using column kits, and selectively PCR-amplified with PKS and NRPS primers (see below). Amplicon libraries will be prepped according to Illumina recommendations³⁸ and will be sequenced using a Illumina MiSeq platform sequencer, with a MiSeq V3 kit (2 x 300 bp). Metabarcoding results will be subject to standard bioinformatic pipelines to reduce sequencing artifacts and group highly similar reads³⁹. Following this, amplicon reads will be evaluated and grouped using closest-known biosynthetic gene clusters using the software package eSNaPD^{32,40} and public databases.

The biosynthetic capabilities of the microbiome will be modeled by sampling for the presence of two families of biosynthetic gene clusters. This will be accomplished using two metabarcoding surveys of type I polyketide synthases (PKS) and nonribosomal peptide synthases (NRPS). These data will paint a general picture of some broad classes of secondary metabolites that tree microbiomes are predicted to produce differentially in response to environmental challenges.

These enzymes encode backbone molecules for two of the broadest families of microbial secondary metabolites (polyketides and nonribosomal peptides)^{41,42} and exist in diverse homologs that can be used to infer medium-to-fine grain portrait of the secondary metabolome of the plant microbiome. Primer pairs for this survey will be based on two studies conducted by Charlop-Powers et al.^{32,43} with degenerate primers that target the ketosynthase (KS) region of type I polyketide synthases (PKS) and adenylation (AD) domains of nonribosomal peptide synthases (NRPS). Limited, initial exploration of these primers *in-silico* of KS-targeting primer sites has shown that they are present in both fungal and bacterial PKSes (see [jupyter notebook](#)), and AD primers are expected to perform as well in fungal NRPS searches. In soil, these primers tended to produce amplicon sizes of 350-500 bp, suitable for paired-end MiSeq platform sequencing. These primers on public databases show very few matches to plant sequences, with the vast majority of observations of NRPS and type I PKSes in public databases originating from microbial sequences (see [jupyter notebook](#)). However, the possibility exists that plants are greatly under-sampled for type I PKS gene clusters⁴⁴. Since our hypothesis focuses on the complementary role of the microbiome, we will attempt to enhance primers with plant-blocking oligonucleotides⁴⁵. The sampling depth necessary to capture the full diversity of secondary metabolites is unknown, but estimated numbers of unique PKS and NRPS types in soil samples in both studies by Charlop-Powers et al. range from 2000 to less-than-10,000 enzyme "OTUs". As both enzyme families (PKS and NRPS) are thought to occur only rarely in higher plants, and as plant-blocking nucleotides will be sought for primers, it should be possible to sample endophytic PKS and NRPS gene clusters as well as epiphytic.

We will emphasize the detection of enzymes in pathways of microbial secondary metabolites that could be "useful" to plant hosts in response to pathogen stress, including antifungal compounds and antioxidants. Our survey will broadly target all microbial gene clusters secondary metabolites with polyketide or non-ribosomal peptide backbones (and hybrids), which will likely uncover a vast array of pathways, of which only a subset will be applicable to our questions. As such, we will first examine results for:

- Fungal anti-mycotic compounds such as echinocandins (NRPS pathway)^{42,46}, polyene anti-mycotic including Nystatin and amphotericin (PKS)⁴⁷⁻⁴⁹, and strobilurins (PKS)^{50,51} in response to high pathogen pressure,
- Pigments including anthraquinones^{52,53} and melanins⁵⁴⁻⁵⁷ (PKS pathways) that may potentially act as antioxidants and UV-protectants.

RNAseq-based exploration of the host, pathogen, and microbiome transcriptome:

RNAseq survey methods will be applied using a tripartite approach: reads will be aligned to host using available genomic and transcriptomic resources^{21,58}, to pathogen using existing genomes^{59,60}, and by mining the remaining, unaligned reads for reads of fungal origins. Host and pathogen transcriptomes will be sequenced using standard Illumina platform sequencing and bioinformatic pipelines^{27,61,62}, including important transcriptomic studies already undertaken²⁷.

The latter method, mining of unaligned reads to characterize the transcriptome of the microbiome, is relatively uncommon and warrants further explanation:

RNAseq studies of large organisms very often leave 15-20% of total reads unaligned to the genome of the targeted organism. These reads are typically discarded, as RNA expression in the large organism is usually the focus of RNAseq studies. These discarded reads can originate from sequencer error and laboratory contamination, but many also originate from the transcriptome of the microbiome. Through careful curation of these “trash” read libraries, without minimum abundance cutoffs, we can draw an outline of metabolic activity in the microbiome. A similar method has recently been used successfully on the holo-transcriptome of sponges⁷⁰.

Preliminary test-of-concept:

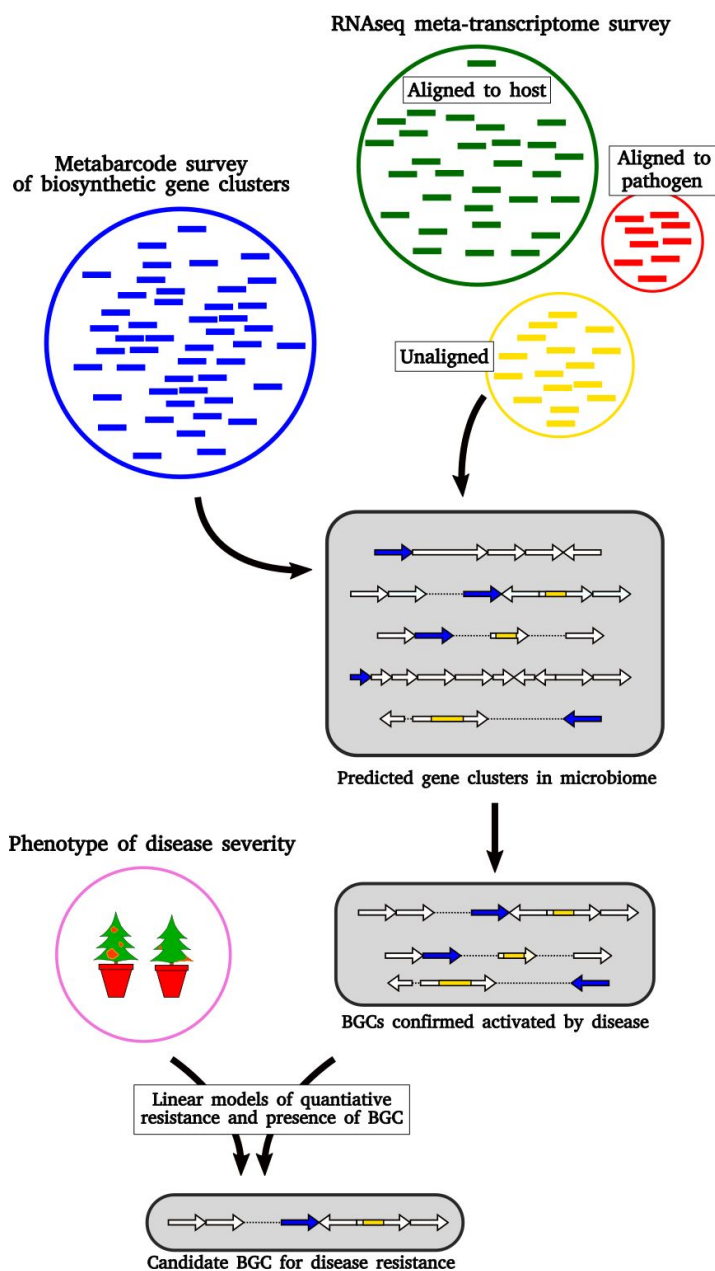
In a first exploration of this method, we aligned 11 transcriptome samples from a publicly available dataset⁶³ to host *Pseudotsuga menziesii* genome⁶⁴. For each of these samples, approximately 15% of reads are unalignable to the host. We blasted the reads not aligned to host genome against a database of ~10,000 fungal genes randomly selected from NCBI genbank. The average proportion of total reads (including those aligned to host) with high confidence matches to fungal genes in this database was 0.4%. This amounted to average of ~50,000 fungal reads per sample, with each sample containing an average of ~11,700,000 reads before alignment to host. If this rate applies to other sequencing events, in a single lane of illumina HiSeq 3000/4000 with 50bp per read, we may expect to see as many as 2,700,000 fungal reads. Some amount of these reads will be due to laboratory contamination or undigested ribosomal RNA, but presumably a large portion are reads originating from the microbiome. Prokaryotic reads were not examined but are of equal interest, and could be estimated similarly, provided RNAseq libraries were not created via poly-A enrichment methods. It is worth noting that this amount of read coverage is comparable to results from Roche 454 Pyrosequencing platforms, which have been successfully used for RNAseq studies^{65,66}. Simply expanding the reference database of fungal genes to include the large number of published fungal genomes will likely increase this number of recovered microbiome reads.

Phenotyping of plant disease

All seedlings will be photo documented immediately prior to inoculation by *Sphaeropsis* and at weekly intervals following for several weeks until mortality of all diseased seedlings and/or stabilization of disease symptoms in all living samples occurs. Camera setup will be standardized and pots will be marked to allow repeated standardized photography from several angles of all seedlings. Disease severity will be classified using machine-learning algorithms specialized for plant-phenotyping computer vision problems, using the PlantCV package in Python⁶⁷. If additional training data are required, twigs of varying disease severity will be collected from the field site, where *Sphaeropsis* tip blight is common.

Synthesis: analysis of gene cluster metabarcoding, RNAseq surveys, and disease severity phenotyping:

The two proposed sequence-based surveys will allow us to make high-confidence calls about the presence and activity of important gene clusters, wherever the two datasets coincide. There is a substantial body of literature, software and public databases cataloguing and predicting biosynthetic gene clusters from synthase-barcode^{40,43,68,69}. Dr. Terhonen and colleagues retain a substantial library of endophyte cultures isolated from *P. sylvestris* which can be examined for BGCs alongside the ecological samples to provide further information on the microbiome BGCs that are likely present, specific to the current *P. sylvestris* system. The Information from these sources will help discovery of un-aligned fungal transcripts that originate from "nearby" genes within predicted gene clusters, even if the exact PKS or NRPS match is not detected in the transcriptome. This will increase the radius of detection of active PKS and NRPS gene clusters in the RNAseq library from samples in the disease state. Taken together, these two methods will give us an estimate of the biosynthetic potential of plant microbiomes, and an estimate of the portion of this potential that is involved in pathogen response. Linear models modeling the relationship between phenotype (disease severity) and the presence/absence and activity of gene clusters can then help to filter to gene clusters that may be important to host disease resistance.



Timeline:

Year 1: Seedlings will be planted as soon as possible in year one, to allow for use of seedlings at field in year two. While seedlings are growing, primers for secondary metabolite gene clusters will be refined for use on fungal endophytes and tested *in-silico* and *in-vivo* using available culture libraries and *P. sylvestris* tissue. Bioinformatic methods will be further developed using

existing transcriptomes from *P. sylvestris*^{21,27} and available fungal genomes from confirmed endophytes of *P. sylvestris*. E+ inoculation will be prepared as seedlings mature.

Year 2: In late spring of year 2, E+ Seedlings will be inoculated with endophyte community inoculum, and the project enters the intensive sampling phase. Beginning 6-8 weeks following inoculations, bench preparation of samples and sequencing will take place. Analysis and writing phase will be in the final six months of the second year.

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