Within-season effects of climate variability on leafhopper abundance and shoot growth in tea fields

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# Introduction

1. climate change is real

The years between 2010 and 2019 represent the warmest decade on record [CITATION]. There is consensus that this warming is caused primarily by anthropogenic release of CO2 into the atmosphere [CITATION]. We have also seen global changes in precipitation regimes over the past century [CITATION], with wet regions getting wetter and dry regions getting drier, and the frequency of extreme weather events such as droughts is increasing.

2. effects on insects

Climate change is predicted to have diverse effects on organisms and ecosystems that vary by species and geography [CITATION]. Increasing mean temperature is expected to increase the growth of many groups of insect herbivores (Bale et al., 2002), and to increase the latitudinal ranges and populations of some agricultural pests (Bebber et al., 2013; Porter et al., 1991). Warming has resulted in an increase in herbivory and crop damage over time (Deutsch et al., 2018; Meineke et al., 2018). Multivoltine insects, in particular are expected to benefit from warming, as longer growing seasons allow for more generations and greater potential population growth (Bale et al., 2002).

Changes in precipitation have less predictable effects on insect populations, partly due to limited research relative to the effects of temperature. In dry places, where desiccation may be a significant source of mortality for insects, increase precipitation may result in increases in herbivore populations (citation). In wet places, increases in precipitation may have negligible effects on plants, which are not water limited, and may increase mortality in herbivores due to infection by entomopathenogenic fungi (citation).

3. relative effects on plants, crops

4. effects on interactions (direct like insects/young leaf; indirect due to changes in plant chem, tritrophic interactions)

Temperature can act on relative growth rate of plants and insects to alter insect distribution and abundance. If host plant growth is too slow due to cold temperatures, or if leaf development is too fast due to high temperatures, there may not be enough young leaf tissue to support herbivores (Bale et al., 2002).

Climate change has the potential to alter species interactions (citations). The interactions between plants and herbivores are especially important for reasons… Alterations in herbivore—plant interactions can stem from or result in changes in plant chemistry at a population or even landscape level (Hunter). Climate change is predicted to affect plants and herbivores differently. For example, insect herbivores are predicted to have higher temperature optima for vital rates than their host plants (Berggren et al., 2009), which result in reduced growth of plant tissue and increased growth and activity of herbivores as temperature warm, compounding to increase herbivore density (e.g. insects per young leaf). Changes in precipitation can also alter the ability of plants to respond to herbivory with induced defenses (Scott et al., 2019).

In addition to the direct effects of climate change on plant chemistry, changes in herbivore density have quantitative and qualitative effects on plant defensive chemistry. For example, an increase in tea green leafhopper density resulted in complex, non-linear changes in induced tea plant secondary metabolites resulting in a change in metabolite blend in addition to overall increased secondary metabolite production (scott et al). Changes in metabolite blend can have important consequences for multiple trophic levels. For example, parasitoids (citations) and even hyperparasitoids (citation) can use plant metabolite blend to infer host density and parasitism status, altering their oviposition decisions. [landscape-scale example from Hunter]

Plant secondary metabolite blends are also important in some agricultural systems, where they are the prime determinants of crop quality. Tea quality, for example, is determined primarily by the concentrations and composition of volatiles, catechins, methylxanthines, and amino acids. In some tea cropping systems, metabolite blend can be more important than crop yield, resulting in farmers sacrificing yield to maximize quality in a number of ways (Ahmed et al., 2014; Cho et al., 2007; Saijo, 1980). One strategy unique to tea originates in northern Taiwan and involves farmers allowing and encouraging tea green leafhopper (*Empoasca onukii*) damage in order to induce secondary metabolite production (Cho et al., 2007). *E. onukii*, like other *Empoasca* species, feeds by rupturing cells and ingesting fluids (Backus et al., 2005; Jin et al., 2012). This causes chlorosis, stunting, thickening, and curling of leaves, and in severe infestations can cause necrosis at leaf margins and early leaf abscission—a set of symptoms collectively referred to as “hopperburn”. *E. onukii* is generally considered a pest and can reduce tea yields up to 20% (citation). However, some tea farmers encourage E. onukii infestations because of the volatiles induced uniquely by leafhopper damage (Zeng et al., 2019). E. onukii is highly multivoltine, having 9-15 generations per summer in the warmest parts of its range (citation). Previous lab studies have shown that development and generation time are reduced under warmer conditions in related species (citations). Within-season temperature was shown to have a greater impact on infestation severity than day of arrival in a related migratory leafhopper pest, *Empoasca fabae* (Baker et al., 2015). Therefore, there is the potential for within-season climate variablitiy to have an impact on leafhopper population. In addition, climate may affect shoot growth of tea plants. Young shoots are not only the unit of harvest, but also the preferred feeding sites for E. onukii (citation), so changes in shoot elongation must be considered together with E. onukii population in order to understand changes in functional density.

# Materials and Methods

The study was conducted at Shanfu Tea Company in Shaxian, Sanming Prefecture, Fujian Province, China (latlong, elevation ~ 200m) from June 5 to July 22, 2017. Two adjacent fields planted with the same tea cultivar (Tie Guan Yin) were used for this experiment. Tea plants in both fields were of similar age (~ 30 years??? Check notes for this). In each field, we labeled 10 plants chosen randomly by using a random number generator to create combinations of row number and % distance into the row from the road to the edge of the field. Each day at around 6:00am, we counted tea green leafhoppers (*Empoasca onukii*) on the undersides of the second leaf from the shoot on these plants. At the beginning of the summer, we counted leafhoppers on 30 leaves, but switched to counting 50 leaves on June 24th. The first initial of the person doing the counting was recorded to be used as a covariate. Data were collected every day from June 5 to July 24 on both fields.

Weather data was collected on site. A temperature sensor and datalogger (model, HOBO, city) was installed between the two fields on a stake at the height of the tea canopy in a shade thingy. Datapoints were taken hourly (check this). Precipitation was measured using a simple rain gauge (model, company, city) between (dates). Rain gauge data was not available before (date) and…. [still haven’t decided whether to integrate local data from Dr. Han (excel) or Li Xin (photographs of a hand-written spreadsheet in a PDF].

We allowed the tea farm to operate as usual in these fields and they were harvested several times during the experiment. Field A was harvested on June 28, July 8, and July 22. Field B was harvested on June 8, July 13, and July 24. When harvested, tea pickers pluck two leaves and a bud and pluck all tea plants in the field, including the plants we labeled. At the time of harvesting, we collected leaves by plucking in the same way as the tea pickers. These leaves were then processed as follows: For a subset of leaves (50-100 per field per harvest), the second leaf on each shoot was removed and placed underside-down on a flatbed scanner (MODEL). Images were scanned at 700dpi and saved as JPEG files. Several scans were used each harvest to collect images of around 50–100 leaves.

The remaining harvested leaves were microwaved for two minutes to denature polyphenol oxidase and other enzymes (Ahmed) and then dried by microwaving on medium power for 1 min at a time, allowing to cool between, until dry.

In addition, we obtained processed tea from each harvest from the farm manager. Processing was consistent across all harvests

## Statistics

To assess the effects of temperature and precipitation on shoot growth, we first calculated a simple linear growth rate as the daily change in shoot height in cm. Because growth measurements were taken early in the morning, the most relevant weather conditions were assumed to be from the previous day.

We used distributed lag non-linear models (DLNMs) to model quadratic, potentially delayed effects of weather on shoot growth or leafhopper densities. Because weather is likely to be autocorrelated through time, using lagged weather (e.g. temp at day 0, temp at day -1, temp at day -2, etc.) as independent variables would result in overfitting (Teller et al). ﻿DLNMs model a bi-dimensional dose-lag-response association kernel where the effect of a predictor can vary non-linearly through lag time and across predictor intensity. These bi-dimensional kernels were created as a two-dimensional smoothed term in generalized additive models (GAMs)  
 implemented using the mgcv package in R. The two-dimensional smooths used a cross-basis provided by the dlnm package. In this DLNM framework, we modeled the effect of temperature and precipitation on growth as quadratic and the effect of lag as a penalized cubic regression spline. We chose these bases because we expected a quadratic effect of temperature and precipitation on plant growth and leafhopper population growth *a priori* but had no strong predictions for the shape of the relationship to time. In addition to the two cross-basis smooths for temperature and precipitation, the shoot growth model included stem diameter and day post-harvest as smooth terms using a penalized cubic regression spline basis, with harvest ID (a combination of field and harvest number) and plant ID as a random effects. For leafhopper density, a similar GAM was built using the same cross-basis kernels for temperature and precipitation. The response was leafhopper counts with an offset of number of leaves counted using a Poisson family error distribution. Days post-harvest was included as a smoothed co-variate (maybe???) and harvest ID as a random effect (???).

# Results

Plant growth

# Discussion

# Works Cited

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