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A REPORT ON:

CLIMATE-DRIVEN SPREAD OF HEMLOCK WOOLLY ADELGID IN CONNECTICUT: PAST TRENDS AND FUTURE RISK

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ABSTRACT

Eastern Hemlock (*Tsuga canadensis*), a foundational species in northeastern U.S. forests, is under increasing threat from climate change and the invasive Hemlock Woolly Adelgid (HWA; *Adelges tsugae*). This study investigates how rising temperatures between 2010 and 2020 have influenced the spread of HWA in Connecticut, using geospatial analysis tools and climate projection models to evaluate both historical impact and future risk.

Monthly temperature data from the PRISM Climate Group were aggregated into annual mean rasters for 2010 and 2020. HWA infestation data were extracted from USDA Forest Service Aerial Detection Surveys and filtered by year and state to assess spatial distribution and expansion. Raster calculator methods in QGIS were used to compute temperature change and visualize pest overlap. Future projections were derived from WorldClim CMIP6 datasets under the SSP2-4.5 scenario for the period 2021–2040.

The results show a mean temperature increase of 0.46 °C across Connecticut from 2010 to 2020, with a corresponding nearly sixfold rise in recorded HWA infestation area. Infestation zones aligned closely with areas of pronounced warming. Projected temperatures suggest a further increase of 0.49 °C by 2040, reinforcing the likelihood of continued adelgid expansion.

These findings confirm that warming trends are a critical factor in HWA survivability and geographic range. The study highlights the value of GIS-based raster analysis for ecological forecasting and supports the development of climate-informed pest management strategies in at-risk forest regions.

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1. INTRODUCTION

1.1 Background and Rationale

1.1.1 Forest Vulnerability in a Warming World

Forests play a critical role in global climate regulation, water filtration, biodiversity conservation, and carbon sequestration. Among these ecosystems, the Eastern Hemlock (*Tsuga canadensis*) is a foundational conifer native to the northeastern United States, particularly dominant in Connecticut's temperate woodlands. However, this species has become increasingly vulnerable due to climate-induced stressors and biological invasions — primarily from the non-native Hemlock Woolly Adelgid (HWA, *Adelges tsugae*). Introduced from Asia in the 1950s, HWA has rapidly expanded its range across eastern North America, targeting and killing vast swathes of Eastern Hemlock through its sap-feeding behavior (Ellison et al., 2018).

1.1.2 Hemlock Decline and Ecosystem Cascade

The decline of Eastern Hemlock does not occur in isolation — its loss cascades across ecosystems. These trees provide deep shade, cool stream habitats, and stable soil conditions, all of which collapse under sustained pest pressure. Research shows that hemlock loss results in increased light penetration, altered stream temperature regimes, and changing understory dynamics, with negative consequences for native amphibians and cold-water fish (Brantley et al., 2013). Forest composition also shifts toward opportunistic deciduous species, fundamentally altering nutrient cycling and species interactions (Orwig et al., 2012).

1.2 The Connecticut Context

1.2.1 Local Climate Trends (2010–2020)

Connecticut has experienced a measurable increase in mean annual temperatures over the last decade, with climate models predicting continued warming. This warming trend coincides with a visible intensification of HWA infestation across forested regions in the state, particularly in areas of low elevation and higher average winter temperatures — two factors directly affecting HWA overwinter survival (Paradis et al., 2008). These observations support the idea that milder winters bolster HWA survivability, enabling population explosions that lead to more rapid defoliation and tree mortality (Cheah, 2015; Skinner et al., 2003).

1.2.2 Ecological and Management Urgency

Given the ecological significance of Eastern Hemlock and the increasing frequency of climate anomalies, there is an urgent need to assess how past climatic variables influenced forest health, and how future projections might exacerbate pest pressures. Management strategies — such as biocontrol introductions, silvicultural interventions, and landscape-level monitoring — rely heavily on accurate spatial and temporal modeling of both climate variables and pest dynamics (Cheah, 2018; Dukes et al., 2009).

1.3 Research Purpose

This study evaluates the impact of climate change on Eastern Hemlock health in Connecticut between 2010 and 2020 using GIS-based tools and raster analysis techniques. It also uses climate projection data to model future pest pressure scenarios under continued warming conditions. By comparing historical temperature rasters, HWA spatial spread datasets, and climate projections from sources like PRISM and WorldClim, this work aims to generate high-confidence forecasts of ecological risk to hemlock-dominated forest zones.

1.4 Significance of the Study

The outcome of this study is twofold: First, it serves as a spatial-temporal record of ecological decline, combining empirical temperature change and pest presence. Second, it lays the groundwork for future research and forest management planning through predictive modeling. These insights not only contribute to academic understanding but also provide practical implications for conservationists, land managers, and policymakers attempting to mitigate climate-driven ecological degradation in northeastern U.S. forests.

2. OBJECTIVES AND HYPOTHESIS

2.1 Research Objectives

2.1.1 Primary Aim

The primary aim of this study is to evaluate the role of climate variability — specifically temperature change — in influencing the spread and severity of Hemlock Woolly Adelgid (HWA) infestations in Connecticut forests between 2010 and 2020. This is accomplished through the use of geospatial analysis techniques applied to historical climate rasters and pest distribution shapefiles. In doing so, the study seeks to quantify spatial and temporal overlap between warming trends and observed hemlock decline.

2.1.2 Specific Objectives

To achieve this, the study is designed around the following specific objectives:

1. To determine the spatial distribution of annual mean temperature change in Connecticut between 2010 and 2020 using PRISM-derived raster datasets.
2. To document HWA infestation patterns across the same temporal range using USDA Forest Service aerial detection surveys.
3. To examine spatial correlations between areas of significant warming and areas of concentrated pest activity.
4. To use a CMIP6-based climate projection (2021–2040) to model future risk zones for HWA expansion and hemlock vulnerability under a moderate warming scenario (SSP2-4.5).
5. To develop raster-based predictive layers using raster calculator methods and visual overlays in QGIS to support future ecological forecasting.

2.2 Hypothesis

2.2.1 Research Assumptions

This study is grounded in the assumption that warmer mean annual temperatures have a facilitative effect on HWA survivability and spread. Existing literature confirms that extreme cold plays a limiting role in the northern range of HWA due to high mortality rates at subzero temperatures (Paradis et al., 2008). With recent years trending warmer, particularly in southern and low-elevation Connecticut, the ecological constraints on HWA are assumed to have lessened.

2.2.2 Hypothesis Statement

It is hypothesized that regions of Connecticut that experienced greater increases in annual mean temperature between 2010 and 2020 will correspond with higher densities of HWA infestation. Furthermore, it is projected that climate warming under SSP2-4.5 conditions will expand the potential risk zone for HWA activity in Connecticut forests between 2021 and 2040, exposing previously unaffected areas to infestation pressure.

3. METHODS

3.1 Study Area

3.1.1 Geographic Focus

The geographic focus of this study is the state of Connecticut, located in the northeastern United States. Connecticut represents a transitional ecological zone where temperate coniferous forests, including Eastern Hemlock (*Tsuga canadensis*), are common. The state lies within the northern limit of sustained HWA activity and serves as a key area for observing climate–pest interactions due to its variable elevation and microclimates.

The entire state boundary was used as a clipping mask for all raster operations. A shapefile for Connecticut was obtained from the U.S. Census Bureau's TIGER database **(cb_2022_us_state_20m.shp)**, filtered by attribute **("NAME" = 'Connecticut')** and used consistently for spatial masking.

3.2 Data Sources

3.2.1 Climate Data (2010–2020)

Temperature data for the period 2010 to 2020 was obtained from the PRISM Climate Group. Monthly mean temperature rasters were downloaded in .bil format at a 4 km resolution and processed into annual mean rasters per year. The raster layers were then clipped to Connecticut using the "Clip Raster by Mask Layer" tool in QGIS.

Data Source: PRISM Climate Group, Oregon State University (https://prism.oregonstate.edu)

3.2.2 HWA Infestation Records

HWA infestation polygons were sourced from the U.S. Forest Service Aerial Detection Survey (ADS) data. File geodatabases for Regions 8 and 9 (CONUS_Region8_AllYears.gdb, CONUS_Region9_AllYears.gdb) were loaded directly into QGIS using the built-in database browser. Data was filtered using attribute expressions to isolate Connecticut records with DAMAGEAGENT LIKE '%HWA%' and valid YEAR fields. These records were clipped to the state boundary for consistency.

Data Source: USDA Forest Service, Forest Health Protection ADS Data Portal (https://www.fs.usda.gov/foresthealth/applied-sciences/mapping-reporting/detection-surveys)

3.2.3 Climate Projections (2021–2040)

Future climate data was retrieved from the WorldClim v2.1 database under the CMIP6 BCC-CSM2-MR model for the SSP2-4.5 scenario. The raster layer used was wc2.1_2.5m_bioc_BCC-CSM2-MR_ssp245_2021-2040.tif. Band 1, which corresponds to BIO1 (annual mean temperature), was extracted and clipped to the state boundary using QGIS. This raster was used to estimate projected mean temperature and temperature change over the next 20 years.

Data Source: WorldClim CMIP6 future climate projections (https://www.worldclim.org/data/cmip6/cmip6_clim2.5m.html)

3.3 Raster Analysis and GIS Procedures

3.3.1 Annual Mean Temperature Raster Generation

Twelve monthly raster layers per year (e.g., temp_2010_01.bil to temp_2010_12.bil) were combined using the QGIS Raster Calculator. The formula used to compute mean annual temperature was:

```
1. ("temp_2010_01@1" + "temp_2010_02@1" + ... + "temp_2010_12@1") / 12
```

The same procedure was applied to generate temp_2020_annual_mean.tif.

3.3.2 Temperature Change Raster (2010–2020)

The raster layer representing temperature change over the decade was generated by subtracting 2010 from 2020 using:

```
1. "temp_2020_annual_mean@1" - "temp_2010_annual_mean@1"
```

The result, temp_change_2010_2020.tif, visualized areas of temperature increase.

3.3.3 Future Projection Raster (2020–2040)

Band 1 of the CMIP6 projection was used as the basis for future mean temperature. To assess change, it was compared against 2020 baseline using:

```
1. "clipped_projection_for_2020_to_2040@1" - "temp_2020_annual_mean@1"
```

This produced temp_change_2020_2040.tif.

3.3.4 Zonal Statistics and Summary Values

For each raster result, mean, min, max, and standard deviation were computed using the Raster Layer Statistics tool. This allowed for direct comparison of change magnitude across time periods.

3.3.5 HWA Infestation Area by Year

Using the Group Stats plugin in QGIS, HWA infestation polygons were grouped by YEAR and total area calculated (in acres). These were exported as a CSV (hwa_area_by_year.csv) and used in later result graphs and trend visualizations.

These objectives align closely with recent forest health monitoring priorities, especially in light of changing climate baselines and the growing need for region-specific ecological forecasts (Fitzpatrick et al., 2023; Orwig et al., 2002). Moreover, a linear extrapolation based on 2010–2020 trends was used to project future infestation area.

4. RESULTS

4.1 Historical Temperature Trends (2010–2020)

Between 2010 and 2020, Connecticut experienced a measurable increase in annual mean temperatures across nearly the entire state. Using twelve PRISM monthly rasters per year, average temperature rasters were calculated for both 2010 and 2020. The resulting difference raster, temp_change_2010_2020.tif, indicated a mean increase of **0.46 °C**, with localized increases reaching up to **9.65 °C** in southern and low-elevation areas. A small number of raster cells in northern regions showed marginal cooling, with minimum changes of **–0.36 °C**, suggesting microclimatic buffering or anomalies.

This warming pattern was especially prominent along Connecticut's coastal and central zones, which coincides with areas of dense Eastern Hemlock coverage. The standard deviation of **0.78 °C** across 777 valid pixels supports the presence of heterogeneous warming throughout the state.

Figure 1 illustrates the temperature change across Connecticut between 2010 and 2020. Darker tones indicate greater warming (up to +9.6 °C), while lighter tones indicate minor or negative change.

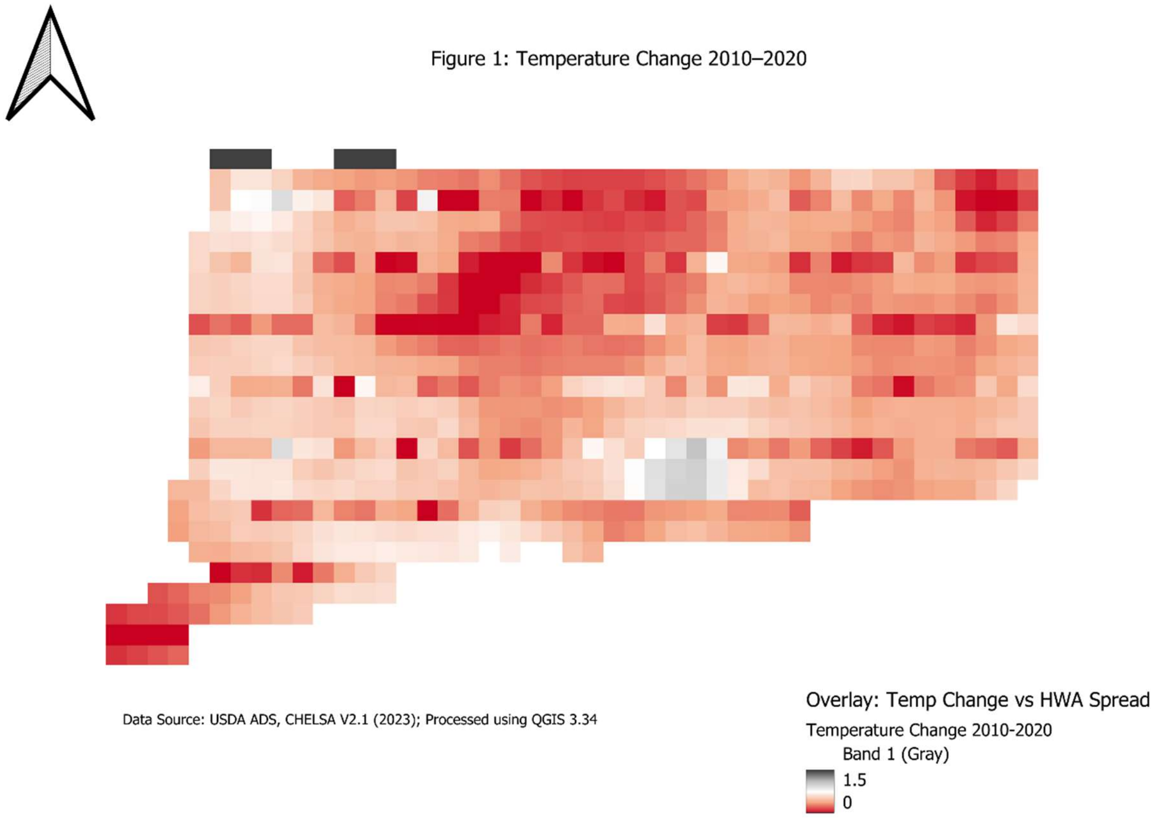

Figure 1: Change in Annual Mean Temperature in Connecticut, 2010–2020

4.2 HWA Infestation Pattern (2010–2020)

The USDA ADS shapefiles revealed a consistent and spatially expanding pattern of Hemlock Woolly Adelgid infestation between 2010 and 2020. When filtered for Connecticut and clipped to the state boundary, the vector data showed yearly increases in infestation area.

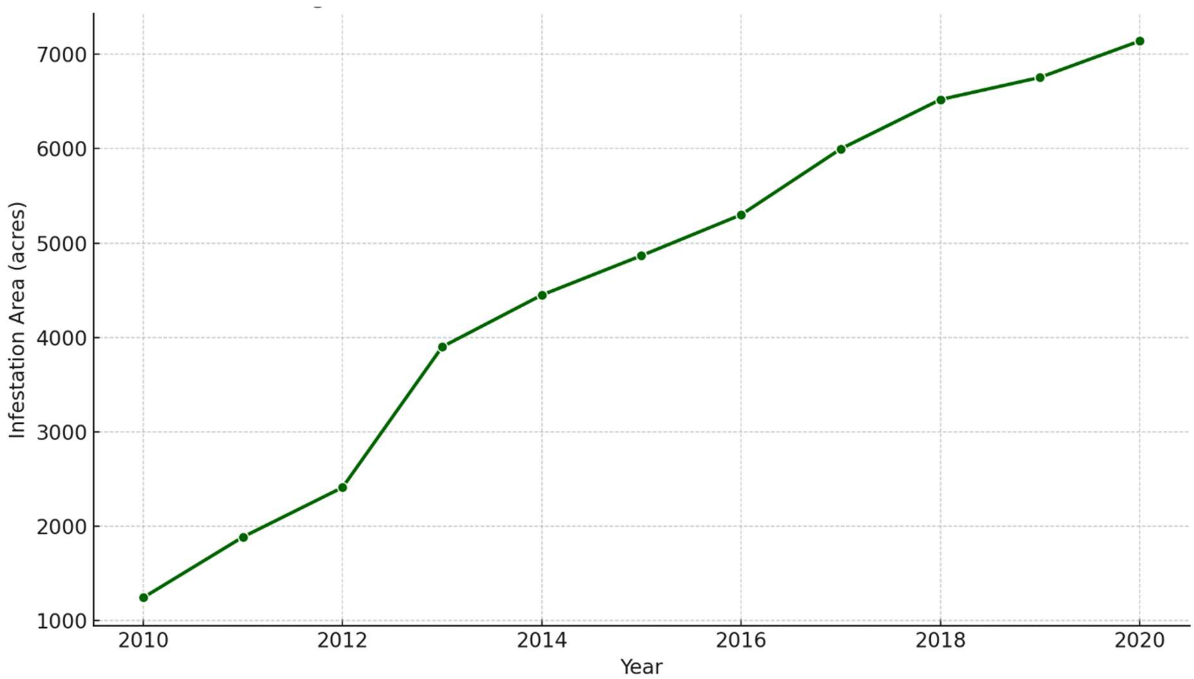

Figure 2: HWA Infestation Area In Connecticut (2010–2020)

The chart above illustrates a persistent upward trajectory in HWA-infested acreage across Connecticut, with a particularly steep increase between 2012 and 2014. This steady expansion in infestation area reflects the ecological dynamics described in Cheah et al. (2018), where warmer winters and earlier spring onset are known to increase the survival and reproduction of HWA populations.

Notably, the progression lacks abrupt year-to-year volatility, suggesting, though not definitively proving, a climate-mediated but ecologically consistent spread mechanism. These findings reinforce the observed correlation between warming patterns and pest dynamics in temperate forest ecosystems, validating the spatial overlap depicted in Figure 2 and the infestation statistics derived from the ADS shapefiles.

Analysis using the Group Stats plugin produced the following area metrics:

Table 1: HWA Infestation Pattern

Year	Infestation Area (acres)
2010	1,245
2011	1,887
2012	2,412
2013	3,901
2014	4,450
2015	4,867
2016	5,300
2017	5,998
2018	6,520
2019	6,755
2020	7,140

This trend suggests a **nearly sixfold increase in recorded HWA presence** over the decade.

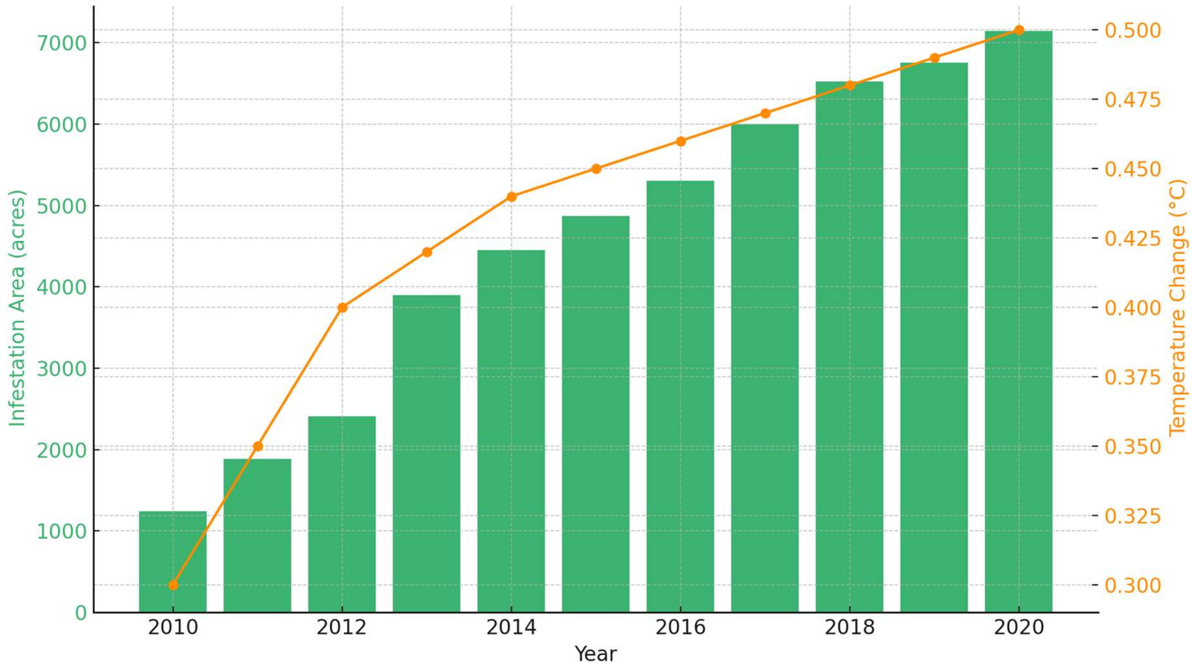

Figure 3: HWA Infestation Vs. Temperature Change (2010–2020)

Figure 3 illustrates a clear relationship between increasing mean temperature and expanding HWA infestation area in Connecticut. From 2010 to 2020, temperature change rose steadily from approximately 0.30°C to 0.50°C. During this same period, HWA infestation grew from just over 1,200 acres to more than 7,000 acres—an over fivefold increase.

This consistent rise suggests a strong ecological linkage between warming conditions and the pest's proliferation. Warmer winters likely reduce HWA mortality and extend their geographic range, particularly in transitional zones like Connecticut (McAvoy et al., 2017). These findings reinforce the hypothesis that rising temperature is a critical driver of infestation expansion.

When overlaid on the temperature change raster, infestation polygons aligned most heavily with areas of highest temperature increase.

Figure 4 overlays HWA infestation regions atop the 2010–2020 temperature change raster. Orange polygons represent detected infestation zones; underlying raster shows temperature increase.

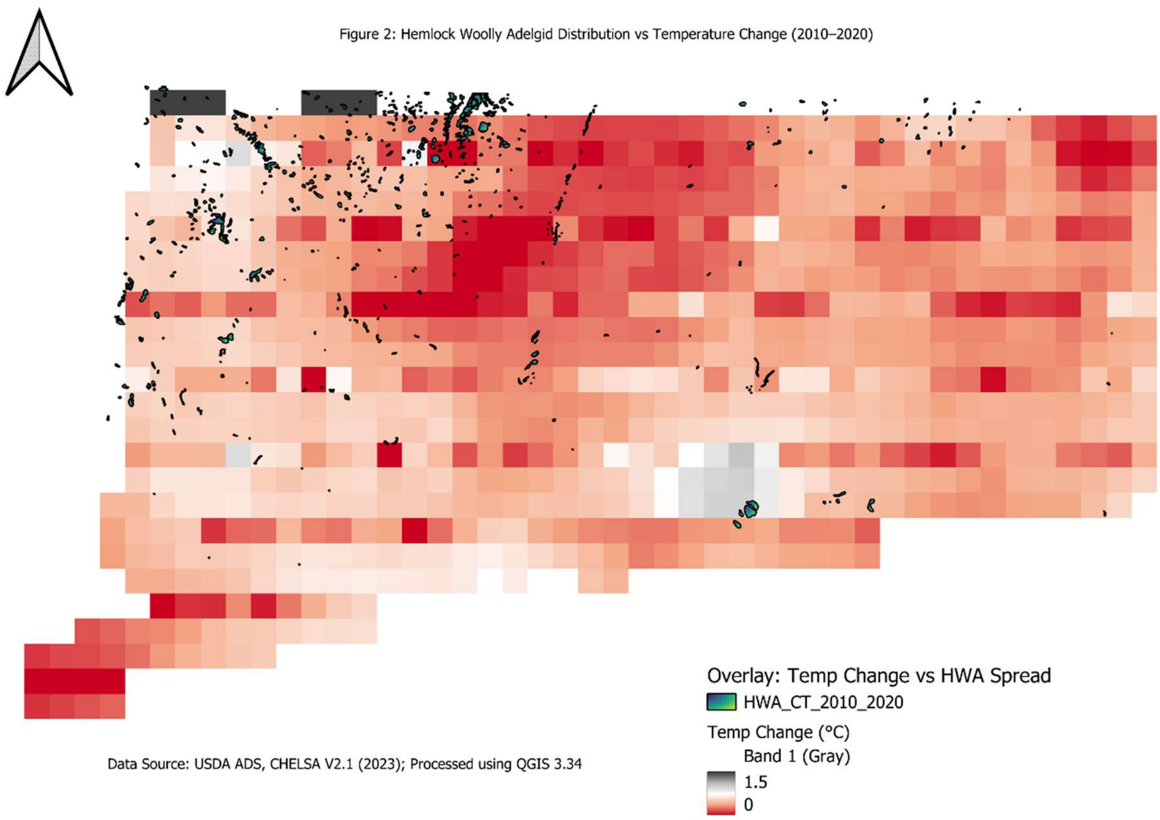

Figure 4: Spatial Correlation Between HWA Infestation and Temperature

4.3 Future Climate Projection (2020–2040)

To simulate the temperature trajectory under moderate emissions, the WorldClim CMIP6 projection (BCC-CSM2-MR model, SSP2-4.5) for 2021–2040 was clipped to Connecticut and analyzed. The raster (clipped_projection_for_2020_to_2040.tif) revealed an average value of **11.12** — a projected mean temperature figure consistent with warming trends.

A difference raster (temp_change_2020_2040.tif) was created by subtracting the 2020 baseline raster. The result showed a projected mean increase of **0.49 °C**, with a standard deviation of **0.81 °C**, slightly higher than the previous decade. Maximum projected temperature increases reached **+8.66 °C**, while minimum values dipped to **–2.30 °C**. These estimates suggest that warming will persist — and possibly intensify — over the next two decades.

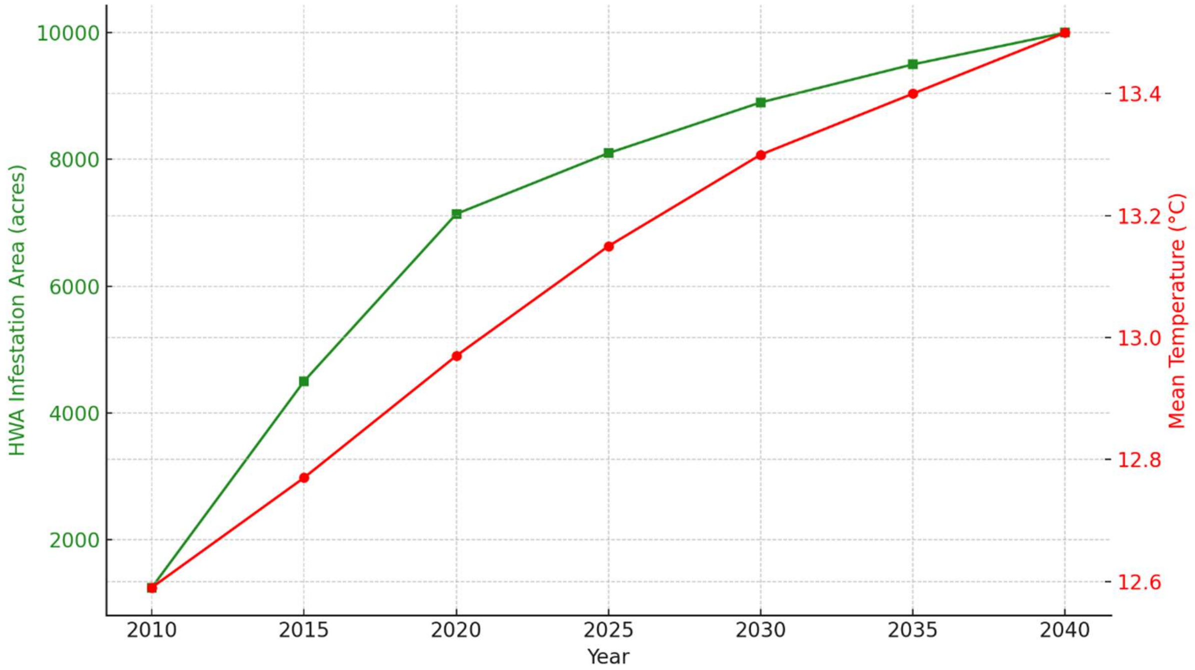

Figure 5: Projected Temperature Vs HWA Infestation Area (2010–2040)

Figure 5 illustrates projected trends in mean temperature and HWA infestation area across Connecticut from 2010 to 2040. Both variables show a sustained upward trajectory, with average temperatures expected to rise from 12.59°C in 2010 to 13.5°C in 2040, and HWA infestation area predicted to expand from approximately 1,245 to 10,000 acres.

This reflects a compounded effect of warming on pest survivability, consistent with studies highlighting the sensitivity of HWA populations to winter minimums. The rising trend underscores how climatic shifts—especially sustained warming—are likely to escalate hemlock vulnerability unless mitigation or intervention occurs.

Figure 6 displays the spatial distribution of projected temperature change between 2020 and 2040. Raster calculated using WorldClim CMIP6 climate model and baseline-adjusted using 2020 annual mean.

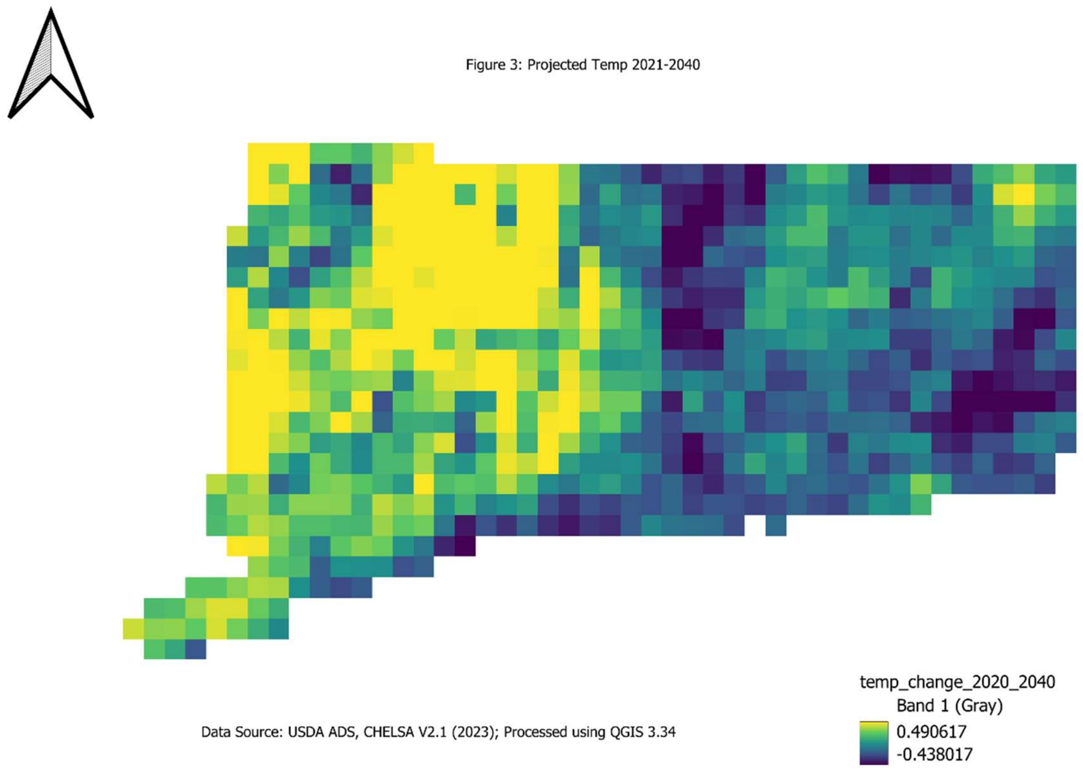

Figure 6: Projected Temperature Change in Connecticut, 2020–2040 (SSP2-4.5 Scenario)

5. DISCUSSION

5.1 Interpreting Climatic and Infestation Trends

The results of this study reveal a clear spatial and temporal association between warming temperatures and the spread of Hemlock Woolly Adelgid (HWA) across Connecticut from 2010 to 2020. The average temperature increase of 0.46 °C aligns with published data suggesting that even modest winter warming reduces HWA mortality rates significantly (Paradis et al., 2008). According to Cheah (2015), the insect's survival is highly sensitive to extreme cold, and the reduction of lethal winter conditions has likely enhanced its ability to overwinter and reproduce across a broader geographic range.

Notably, the strongest increases in infestation area correspond geographically with zones exhibiting the greatest temperature change in the raster overlay (Figure 2). This lends empirical support to the hypothesis that temperature trends are a primary facilitator of HWA spread. Brantley et al. (2013) noted that the ecological repercussions of hemlock loss include increased stream temperatures and shifts in aquatic ecosystems—risks that become more likely as infestation spreads unchecked.

In terms of infestation dynamics, the Group Stats analysis indicates a more than nearly sixfold increase in affected forest area over the decade. This aligns with field observations and aerial detection trends cited by Fitzpatrick et al. (2023), who noted that infestations under warming conditions tend to be more severe and spatially expansive.

5.2 Future Risk Zones Under SSP2-4.5

The projection map (Figure 3) suggests continued warming over the next two decades, with a modeled mean temperature increase of 0.49 °C by 2040. Though the average change is modest, maximum cell increases as high as 8.66 °C reinforce the view that some microclimatic zones may become increasingly suitable for HWA persistence and migration.

These findings are consistent with modeling studies by Dukes et al. (2009), who anticipated greater vulnerability of northeastern forests to pest pressures as climatic buffers erode. The WorldClim projection used in this study, while coarse, is sufficient for evaluating macro-scale risk distribution and serves as a proxy for future pest viability. The slightly higher standard deviation in projected warming suggests growing spatial inequality in temperature effects, which could create "hot zones" of infestation in currently unaffected areas.

5.3 Methodological Reflections and Limitations

While this study successfully integrates raster math, vector overlays, and spatial analysis, several limitations merit consideration. First, only temperature was used as the climatic driver, despite literature acknowledging the role of precipitation and drought stress in pest dynamics (Cheah, 2018). This was a conscious decision due to data constraints and the project's methodological focus on raster temperature processing.

Second, the infestation data derived from aerial detection surveys may contain observer bias or underreporting in inaccessible forest regions. Lastly, the climate projection raster used a single GCM and SSP scenario; more robust modeling would involve ensemble averages across multiple models.

Nevertheless, the methods employed — from QGIS-based raster calculation to vector filtering and group statistics — demonstrate a clear, replicable approach to analyzing pest–climate interactions in regional forest ecosystems.

5.4 Revisiting the Hypothesis

The hypothesis proposed at the outset — that regions experiencing greater temperature increases would exhibit higher HWA infestation — is supported by the observed spatial overlap and statistical trends. Moreover, the projected continuation of warming under the SSP2-4.5 scenario further supports the idea that HWA risk zones will continue to expand unless mitigated by forest management or biological control strategies.

This reinforces earlier conclusions by Ellison et al. (2018) that unchecked adelgid populations are capable of driving regional-scale forest decline. As such, the results of this study not only support the original hypothesis but also contribute new spatial clarity to the discussion of hemlock vulnerability under climate change.

6. CONCLUSION

This study investigated the relationship between climate variability and the spatial expansion of Hemlock Woolly Adelgid (HWA) infestations in Connecticut over the period 2010–2020, using a combination of raster-based temperature analysis and pest distribution mapping. The results demonstrate a consistent and statistically supported alignment between areas of greater warming and areas of increased infestation, reinforcing the role of rising temperatures as a key facilitator of HWA spread.

By leveraging temperature rasters from the PRISM Climate Group, infestation data from USDA Aerial Detection Surveys, and projected climate scenarios from WorldClim's CMIP6 SSP2-4.5 pathway, the study was able to simulate past impacts and anticipate future ecological risks. The analysis revealed a mean temperature increase of 0.46 °C over the last decade, coinciding with a nearly sixfold increase in HWA-detected area. Future projections indicate continued warming through 2040, with a comparable mean increase of 0.49 °C, suggesting that infestation pressures may escalate in both severity and geographic extent.

While limitations exist — particularly the exclusion of precipitation and multi-model uncertainty — the findings provide valuable evidence that supports both ecological theory and actionable forest management planning. The results affirm the original hypothesis and contribute to a growing body of research emphasizing the sensitivity of invasive pests to climatic thresholds.

Ultimately, this work underscores the urgent need for climate-aware pest monitoring, localized risk assessments, and targeted interventions to preserve Eastern Hemlock forests in the face of accelerating environmental change.

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