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INVASION NOTE

Extensive gypsy moth defoliation in Southern New England characterized using Landsat satellite observations

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Abstract Southern New England is currently experiencing the first major gypsy moth (*Lymantria dispar*) defoliation event in nearly 30 years. Using a novel approach based on time series of Landsat satellite observations, we generated consistent maps of gypsy moth defoliation for 2015 (first year of the outbreak), 2016 (second year of outbreak), and 2017 (third year of outbreak). Our mapped results demonstrate that the defoliation event continued through the 2017 growing season. Moreover, the affected area more than doubled in extent each year and expanded radially to encompass 4386 km^2 of forested area in Rhode Island, eastern Connecticut, and central Massachusetts. The current gypsy moth outbreak is believed to be the result of a series of unusually dry springs in 2014, 2015, and 2016, which suppressed *Entomophaga maimaiga*, a fungal mortality agent that has historically reduced gypsy moth impacts in this region. The continuation and marked expansion of the outbreak in 2017 despite average spring rainfall suggests that caterpillars were active early in the growing season, and mortality from the fungus likely peaked after significant defoliation had already occurred. Our Landsat time series approach represents an important new source of data on spatial and temporal patterns in gypsy moth defoliation, and continued satellite-based monitoring will be essential for tracking the progress of this and other gypsy moth outbreaks.

Keywords Gypsy moth · *Lymantria dispar* · Defoliation · *Entomophaga maimaiga* · New England · Remote sensing

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Introduction

Widespread defoliation events associated with outbreaks of gypsy moth (*Lymantria dispar*), an invasive pest introduced to the U.S. in the 1860s, were once a regular occurrence in Southern New England (Elkinton and Liebhold 1990; Liebhold et al. 2000). Outbreak cycles were significantly reduced in both their occurrence and magnitude following the emergence of a fungal mortality agent (*Entomophaga maimaiga*) in the late 1980s. This fungus acted in combination with other mortality agents to keep gypsy moth defoliation at relatively low levels for many years (Hajek and Roberts 1991; Hajek et al. 1995; Ostfeld and Jones 2010). However, in 2015, areas of defoliation were noted in southeastern Massachusetts, and in 2016, a large-scale gypsy moth defoliation event was observed for the first time in over 30 years (Pasquarella et al. 2017). The initiation of this outbreak may have resulted from drought conditions in late spring (May and June) for three consecutive years (2014, 2015, and 2016) that decreased the effectiveness of *E. maimaiga*. Multiple years of defoliation in combination with drought stress can result in decreased growth and eventual mortality of host tree species, particularly oaks (Fajvan and Wood 1996; Davidson et al. 1999; Morin and Liebhold 2004; Barron and Patterson 2008; Morin and Liebhold 2016). Therefore, continued regional monitoring is needed to assess outbreak dynamics and subsequent impacts on forest health. In this note, we build on our previous efforts to map gypsy moth defoliation in Southern New England (Pasquarella et al. 2017) and estimate the extent and severity of the recent gypsy moth outbreak in terms of changes in forest condition based on time-series analysis of Landsat satellite imagery.

Methods

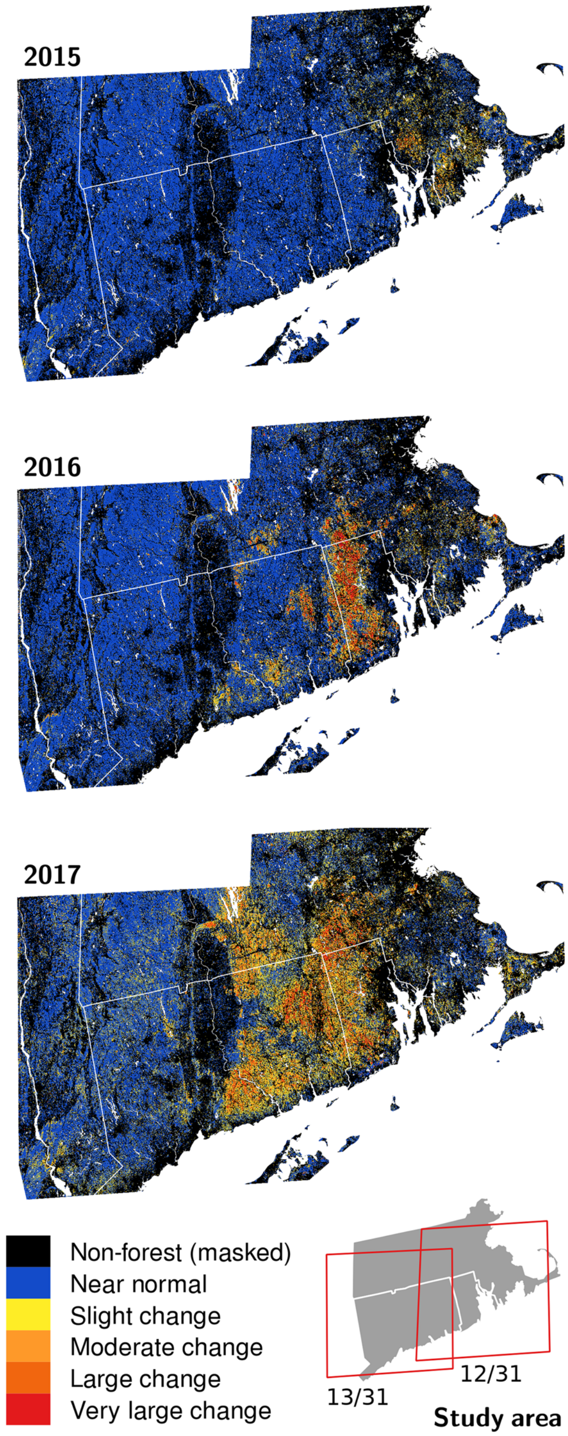
We used the Landsat-time series condition assessment methods introduced and more fully described in Pasquarella et al. (2017) to generate both near-real-time assessments and annual products for two Landsat scenes (WRS-2 Path/Row 12/31 and 13/31) covering Southern New England (southern MA, CT, RI). The dataset includes the complete archive of Landsat Level 1 precision- and terrain-corrected (L1T) surface reflectance products with less than 80% cloud cover, which is available from the USGS EROS Science Processing Architecture (ESPA; https://espa.cr.usgs.gov/). The Landsat data used in this study were orthorectified, atmospherically corrected, and included a cloud mask, facilitating their use for time series analysis. We apply the Tasseled Cap transform to observed surface reflectance values in order to produce an index of forest canopy "Greenness". We then fit a harmonic regression model to historic time series of all Greenness observations for each pixel for a (relatively) stable monitoring interval (in this case, 2005–2015), producing a base-line estimate of expected forest Greenness for any day of year. We use this model to predict Greenness values for scheduled acquisition dates (every 8 days with Landsat 7 and Landsat 8 in operation). New images for each scene were downloaded as they became available, and predicted values were compared to observed Greenness values calculated for these newly acquired images to measure 'change in condition' as a metric of defoliation. Thus, we can potentially produce condition assessments for each cloud-free pixel every 8 days during the May through September monitoring period, capturing the gypsy moth defoliation event (late May through June).

Changes in condition scores were calculated as the raw difference between observed and predicted Greenness, normalized by the root mean squared error (RMSE) of the regression model. These scores were computed as new imagery became available, resulting in a series of single-date near-real-time assessment products. At the end of the growing season, all near-real-time assessments were averaged to produce a final map of potential defoliation for that year. Larger differences between observed and predicted Greenness values are assumed to indicate more severe defoliation. Our condition assessments provide a continuous measure of change; however, to aid in interpretation, we use four severity categories to visualize condition scores: *slight change* (deviations 1–2 times the model RMSE), *moderate change* (deviations 2–3 times the model RMSE), *large change* (deviations 3–4 times the model RMSE), and *very large change* (deviations greater than 4 times the model RMSE) (following Pasquarella et al. 2017).

Results

Annual maps of defoliation for 2015 (first year of the outbreak), 2016 (second year of outbreak), and 2017 (third year of outbreak) are shown in Fig. 1. The total extent of defoliation doubled between 2015 and 2016 and doubled again between 2016 and 2017 (Fig. 2; Table 1), with an estimated 4386 km^2 of forest canopy affected in 2017. However, changes in defoliated area varied by severity class (Table 1), with slight and moderate defoliation accounting for the majority of range expansion in 2017.

In 2015, the first year of the outbreak, gypsy moth populations caused significant defoliation for the first time since the 1980s, although defoliation extent and severity were both relatively low. Areas of defoliation were concentrated in southeastern Massachusetts (Fig. 1), and total defoliated area was 808 km^2 (Fig. 2). As would be expected at the onset of an outbreak, changes in condition were relatively low in



◀**Fig. 1** Landsat-based gypsy moth defoliation maps for 2015, 2016 and 2017. Mapped results represent average 'change in condition' scores calculated using all available observations from May through September of the corresponding year. Though low-magnitude changes in condition were observed in 2015, the extent and severity of defoliation increased dramatically in 2016. Defoliation in 2016 was concentrated in and around Rhode Island, but expanded radially into eastern Connecticut and central Massachusetts in 2017

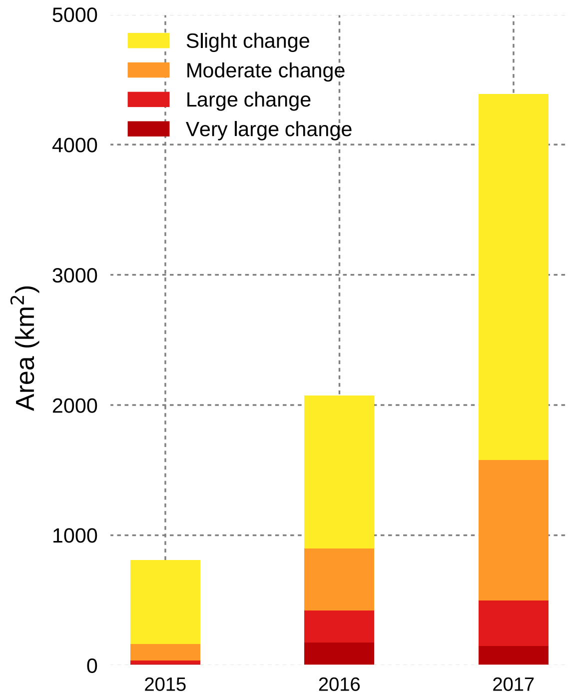


Fig. 2 Total defoliated area by year and severity class. Defoliated forest area in Southern New England more than doubled in extent each year, with the greatest increase in areas exhibiting slight and moderate changes in condition

magnitude, with 96% of defoliated areas falling in the *slight change* (80%) or *moderate change* (16%) categories (Table 1).

In 2016, defoliation was more widespread (Fig. 1). The majority of damage occurred in Rhode Island, with smaller hotspots present in eastern Connecticut and south-central Massachusetts. The total defoliated area for 2016 was 2071 km^2, over 2.5 times the area of damage in 2015 (Fig. 2). The 2016 changes in condition also tended to be of a higher magnitude, with 20% of defoliated areas falling in the *large change* (12%) or *very large change* (8%) categories (Table 1).

In 2017, isolated patches of defoliation observed in 2016 in Rhode Island, eastern Connecticut, and south-central Massachusetts increased dramatically in extent

Table 1 Defoliated area by severity class and year

Change in condition	2015 Area km^2 (%)	2016 Area km^2 (%)	2017 Area km^2 (%)
Slight change	644 (80%)	1176 (57%)	2808 (64%)
Moderate change	129 (16%)	474 (23%)	1078 (25%)
Large change	27 (3%)	246 (12%)	353 (8%)
Very large change	8 (1%)	175 (8%)	147 (3%)
Total	808 km^2	2071 km^2	4386 km^2

Percentages are calculated as the proportion of total defoliated area in a given year. A larger proportion of defoliated land area falls in moderate to very large change categories during the outbreaks in 2016 and 2017

(Fig. 1). The total defoliated area for 2017 was 4386 km^2, or 2.1 times the area of damage in 2016 (Fig. 2). Interestingly, while the 2017 defoliation is greater in terms of overall extent, this damage was largely driven by *slight* (64%) and *moderate* (25%) changes in condition, with only 11% of condition change in *large* or *very large* change categories (Table 1). These lower damage values are consistent with field observations of high gypsy moth mortality on individual trees in 2017 caused by two gypsy moth mortality agents: *E. maimaiga* and a viral disease LdNPV (Elkinton et al. 2018).

Discussion

While gypsy moth outbreaks still occur periodically in more southern regions of the U.S. (e.g. Foster et al. 2013; Asaro and Chamberlin 2015), gypsy moth populations have been well-controlled in New England for over 30 years (Barron and Patterson 2008; Ostfeld and Jones 2010). The 2015–2017 gypsy moth defoliation event characterized here suggests that despite the presence of a number of mortality agents, including the highly effective fungal pathogen *E. maimaiga*, a viral disease that impacts high-density populations (LdNPV; *Lymantria dispar* NucleoPolyhedrosis Virus) and several egg parasitoids, occasional outbreaks of this major insect pest may recur in the Northeastern US. The total area of defoliated forest in Southern New England in 2016 was more than twice the total area of defoliated forest in 2015 and included a greater proportion of high-magnitude change. Total defoliated forest area doubled again as the outbreak progressed from 2016 to 2017, indicating the potential for rapid expansion of gypsy moth impacts across large areas. Given the unexpected onset, multi-year duration, and the extent and severity of impacts, the 2015–2017 gypsy moth defoliation event represents an important change in the status of the gypsy moth invasion in Southern New England.

We estimated the extent and severity of gypsy moth defoliation over all of Southern New England using observations from the Landsat series of satellites. Our time series-based method (Pasquarella et al. 2017) facilitates repeat monitoring of outbreak dynamics in near-real-time and can be used to generate annual estimates of potential defoliation as reported in this note. We mapped the 2017 outbreak as new imagery became available, and widespread defoliation was evident as early as the second week of June. Because the severity categories are based on comparison with modeled long-term average reflectance patterns (2005–2015), these metrics are comparable between years and enable landscape-scale mapping of multi-year outbreak dynamics. Though low levels of defoliation may be present in any given year, using a decade-long time series of Landsat observations and a robust harmonic modelling approach provides a high confidence estimate of the long-term Greenness signal. Defoliation events during the initial model fitting period (2005–2015) could increase the overall error estimate for a given pixel and bias the results toward a less severe impact. However, previous tests using different base intervals showed little change in the overall condition assessments (unpublished data), therefore we assume the fitting period used here is representative of relatively stable forest conditions in our study area.

Understanding how satellite-based condition assessment metrics relate to other measurements of defoliation remains an ongoing challenge due to the ephemeral nature of defoliator outbreaks. Future work on validation approaches involving field-based measurements of defoliation and recovery in combination with more widely available tree ring and aerial survey datasets, which also quantify changes in tree/stand health, will be necessary to relate Landsat-based condition scores to more biophysically meaningful metrics of defoliation severity, e.g. percent canopy loss. Future work could also attribute defoliation events to specific defoliators. We assume that given the scale and severity of impacts, the vast majority of condition changes observed in our products were due to gypsy moth defoliation. However, damage from other agents such as winter moth (*Operophtera brumata*), forest tent caterpillar (*Malacosoma disstria*) and drought, may also be included in the results presented here. Improved attribution could potentially be achieved through integration with aerial survey data, as well as identification of distinct phenological patterns in the spectral signatures of different change agents. For example, damage from winter moth would be expected to occur earlier than gypsy moth, during timing of initial bud-burst, while land cover changes such as development will result in more dramatic, persistent changes in reflectance.

Despite current limitations on validation and attribution, our methodology has several important advantages over more conventional defoliation mapping approaches. More conventional survey methods such as aerial detection and field surveys are typically only conducted once per season and the timing of surveys is inconsistent over large areas. While these surveys provide important expert-interpreted information on the nature of defoliation, they are challenging to implement consistently over large areas. Remote sensing approaches for monitoring defoliation have often relied on sensors with a high temporal repeat time, such as MODIS (e.g. de Beurs and Townsend 2008; Spruce et al. 2011). However, the coarse resolution of MODIS imagery poses a challenge for fine-scale mapping of ephemeral canopy changes like defoliation. There has been a long history of using a limited subset of carefully selected Landsat images to map gypsy moth impacts at finer spatial resolutions (e.g. Nelson 1983; Rock et al. 1986; Townsend et al. 2012), but the availability and temporal resolution of Landsat imagery has remained an ongoing concern (Rullan-Silva et al. 2013).

Following the opening of the Landsat archive for free public use in 2008 (Woodcock et al. 2008) and increasing availability of other moderate resolution optical datasets (e.g. the Sentinel-2 series), there are new opportunities to use time series of Landsat and Landsat-like images for improved forest health monitoring both within and across years (Senf et al. 2015). By fully utilizing the 8-day repeated acquisitions of Landsat 7 and Landsat 8 and a novel model-based approach, we are able to provide relatively stable estimates of changes in forest condition that can be generated consistently over large spatial extents. Our Landsat-based defoliation maps can be used to estimate the extent of outbreak extent and severity with a greater degree of precision than aerial detection surveys or other satellite-based assessments using fewer dates (Pasquarella et al. 2017). This improved precision is essential for spatial modeling of invasion dynamics and ecological impacts, particularly in the highly heterogeneous forested landscapes of the Northeastern US.

Widespread gypsy moth defoliation events like the one shown here can have both short-term and long-term impacts on forest composition and structure. Significant defoliation has been shown to suppress the growth of defoliated trees (Barron and Patterson 2008), and repeated defoliation has been linked to increased oak mortality and regional declines in oak abundance across the Northeast (Morin and Liebhold 2016). Because oak mast provides an important food source for many species of birds and mammals, increased frequency of gypsy moth outbreaks could have profound effects on wildlife communities (McShea et al. 2007; Ostfeld and Jones 2010). Changes in litter fall and light availability may also alter nutrient cycling at watershed scales, leading to changes in the productivity of both terrestrial and aquatic ecosystems (Gandhi and Herms 2010). Therefore, even if 2018 marks an end to the current outbreak, we expect the gypsy moth defoliation event reported here will have lasting impacts on the forest ecosystems of Massachusetts, Connecticut and Rhode Island.

Understanding the ecological impacts of the 2015–2017 gypsy moth outbreak in Southern New England will require continued monitoring of defoliated areas. The results presented here provide a starting point for tracking outbreak dynamics, and we expect the methods used to be extendable to other defoliators and further refined based on site-specific knowledge, including long-term monitoring plots and other forest health monitoring programs. Defoliation products could potentially be used to guide management actions, such as additional monitoring, the introduction of mortality agents, and large-area spraying (where permitted). Spatial and temporal patterns of defoliation may also aid in efforts to model future invasion and outbreak risk. The calculation and interpretation of condition scores can be easily modified for other applications, and our methods may also be suitable for detecting other lower-magnitude changes in forest condition, such as drought stress. Thus, this note provides both a benchmark summary of the current gypsy moth outbreak status in New England, as well as the introduction of a new Landsat-based approach for forest canopy condition monitoring that can provide insights on broad-scale forest health dynamics at a relatively fine spatial and temporal resolution.

Data availability

Annual gypsy moth defoliation assessment products for 2015, 2016, and 2017 are available as georeferenced GeoTIFF datasets at http://doi.org/10.5281/zenodo.1163679.

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