forests

MDPI

Article

Ability of Remote Sensing Systems to Detect Bark Beetle Spots in the Southeastern US

Demian F. Gomez [1,*], Haley M.W. Ritger [2], Christopher Pearce [3], Jeffrey Eickwort [3] and Jiri Hulcr [1,4]

1 Institute of Food and Agricultural Sciences, School of Forest Resources and Conservation, University of Florida, 136 Newins-Ziegler Hall, Gainesville, FL 32611, USA; hulcr@ufl.edu
2 D.B. Warnell School of Forestry and Natural Resources, University of Georgia, 180 E Green Street, Athens, GA 30602, USA; hmwritger@gmail.com
3 Florida Forest Service, Florida Department of Agricultural and Consumer Services, Forest Health Section, 1911 SW 34th St., Gainesville, FL 32608, USA; Christopher.Pearce@fdacs.gov (C.P.); Jeffrey.Eickwort@fdacs.gov (J.E.)
4 Entomology and Nematology Department, Institute of Food and Agricultural Sciences, University of Florida, 1881 Natural Area Drive, Gainesville, FL 32611, USA
* Correspondence: demiangz@gmail.com

Received: 24 September 2020; Accepted: 30 October 2020; Published: 31 October 2020

check for updates

Abstract: Research Highlights: Sentinel-2 Normalized Difference Vegetation Index (NDVI) products show greater potential to detect indications of disturbance by bark beetles in the southeastern US than Moderate Resolution Imaging Spectroradiometer (MODIS), as the high spatiotemporal heterogeneity of the southeastern forest land prevents its deployment at the current resolution. Background and Objectives: Remote sensing technologies have been an essential tool to detect forest disturbances caused by insect pests through spectral trait variation. In the US, coordinated efforts such as ForWarn, led by the US Forest Service and based on MODIS satellite data, are used to monitor biotic and abiotic disturbances. Because of the particular characteristics of the southeastern US landscape, including forest fragmentation and rapid forest turnover due to management, detection and visualization of small bark beetle spots using remote sensing technology developed for more homogeneous landscapes has been challenging. Here, we assess the ability of MODIS and Sentinel-2 time-series vegetation index data products to detect bark beetle spots in the Florida Panhandle. Materials and Methods: We compared ForWarn's detection ability (lower resolution images) with that of Sentinel-2 (higher resolution images) using bark beetle spots confirmed by aerial surveys and ground checks by the Florida Forest Service. Results: MODIS and Sentinel-2 can detect damage produced by bark beetles in the southeastern US, but MODIS detection via NDVI change exhibits a high degree of false negatives (30%). Sentinel-2 NDVI products show greater potential for identifying indications of disturbance by bark beetles than MODIS change maps, with Sentinel-2 capturing negative changes in NDVI for all spots. Conclusions: Our research shows that for practical bark beetle detection via remote sensing, higher spatial and temporal resolution will be needed.

Keywords: forest health; NDVI; MODIS; Sentinel-2; insect monitoring

1. Introduction

Tree mortality has significant effects on the ecology and value of both natural and commercial forests. In the southeastern region of the United States (US), including northern Florida, large-scale tree mortality can severely affect the forestry industry, with both economic and social impacts [1,2]. Monitoring programs that measure disturbances in forest ecosystems have gained importance due to the increasing prevalence of biotic threats and stress factors. Insects and pathogens are one of the main threats to forest resources in North America [3]. In the Southeast, bark beetles such as southern pine beetle (*Dendroctonus frontalis*) and *Ips* engraver beetles (*Ips avulsus*, *I. grandicollis*, and *I. calligraphus*) cause extensive damage to pine forests, shaping the forest structure and composition [4–6]. Because of their potential to grow rapidly, spots of infestation require effective and economically efficient interventions. The earliest stage of attack, the green-attack, occurs when the beetle first interacts with the host tree and the infested tree is still physiologically functional and green. During early stages of the attack, the next generation of adult beetles has not yet emerged. Later stages of beetle colonization include discoloration of the foliage, with crowns turning red-brown as the attack continues (red-stages). During the latter stage, mature beetles often have already emerged and moved to neighboring trees. For effective control strategies, bark beetle outbreaks need to be detected accurately, in early stages, and with cost-effective information [7]. Annual aerial surveys are currently used to monitor tree mortality caused by forest pests, though this method can exclude some early affected areas. For large areas, satellite-based remote sensing can assist forest managers in their need to detect and monitor these disturbances.

Remote sensing technologies have been an essential tool to detect spectral trait variation in forest disturbances caused by insect pests, providing large-scale coverage and a perspective on vegetation that is not possible with field data [8]. In the US, coordinated efforts have been made to develop monitoring and assessment technologies [9]. ForWarn is a vegetation change recognition system developed by the US Forest Service that shows the impacts of forest disturbances, such as wildfires, windstorms, and pests. It relies on daily Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data to track changes in the Normalized Difference Vegetation Index (NDVI), providing change maps for the continental US that are updated every eight days [10]. The NDVI compares the visible red and near infrared spectral bands, available on most multispectral satellite systems, to estimate photosynthetic activity and thus measure the impact of environmental and biotic factors on vegetation [11,12]. Stress affects tree biophysical and biochemical properties, producing a change in the spectral trait. Hence, spectral signal change associated with bark beetle damage can be inferred from tree defoliation, chlorophyll fluorescence change, and water content decrease in needles due to water stress [8].

Terrestrial observations are not efficient enough for identifying susceptible or infested trees [13]. Remote sensing technologies offer the ability to collect large quantities of data over wide geographic areas and aid in general forest monitoring efforts [14]. Previous studies have shown that moderate resolution satellite data from MODIS is valid for detection of disturbances. Despite the low resolution, ForWarn can successfully detect moderate-sized biotic and abiotic disturbances. For example, in eastern North America, MODIS NDVI time series can successfully detect forest defoliation by gypsy moth outbreaks [15,16]. In western pine forests, MODIS NDVI data products have been used for mapping tree mortality in forests subjected to mountain pine beetle bark beetle outbreaks and severe drought [17].

The MODIS-based ForWarn is currently one of the main tools for remote monitoring of forest health disturbances across most of the US. However, the southeastern US landscape poses some unique challenges for early detection using satellites. Southeastern pine forests are highly fragmented and incur frequent disturbances. Damaged forest tracts may be obscured by rapid greening of plantations. Commercial forest harvests, prescribed burns, and salvage logging operations occur year-round and interfere with interpretation of remotely-sensed data. The low resolution of MODIS (250 m spatial resolution) compounds these issues because once enough tree crowns turn red for detection at the resolution of ForWarn maps, widespread mortality may have already occurred.

To monitor the small and scattered bark beetle outbreaks in the southeastern US, improving detection and visualization of bark beetle spots is required due to the aforementioned characteristics of the southeastern US landscape. Recently launched satellites equipped with finer-scale sensing technologies provide opportunities to refine bark beetle detection. Imagery based on Sentinel-2 satellites, with higher spatial resolution (10 m), effectively detected infected *Ips* engraver beetle spots in

Europe [18]. Here, we comparatively assess the ability of MODIS and Sentinel-2 time-series vegetation index data products to detect bark beetle spots in the Florida Panhandle. Our goal was to compare multiple contemporary approaches for the detection of existing, ground-truthed bark beetle spots to equip managers with information about which method(s) may provide the most feasible avenue for improving bark beetle monitoring tools in the Southeast. We compare ForWarn (MODIS) and Sentinel-2 resolutions and detections in forest stands containing bark beetle spots confirmed by aerial surveys and ground checks from Florida Forest Service. Our objectives are to (a) evaluate the ability to detect spots in MODIS and Sentinel-2 images, and (b) quantify the agreement in NDVI departure between MODIS and Sentinel-2 images.

2. Materials and Methods

2.1. Experimental Design and Study Area

The impact of Hurricane Michael in October 2018 triggered numerous incipient bark beetle infestations in loblolly (*Pinus taeda* L.), slash (*P. elliottii* Engelm.), and sand pine (*P. clausa* (Chapm ex Engel.) Vasey ex Sarg.) stands in northern Florida. These new outbreaks in previously uninfested forest stands provided us with an opportunity to evaluate the effectiveness of two remote sensing technologies for detection of emerging bark beetle spots in the challenging southeastern landscape: (1) MODIS NDVI change (analogous to the system currently used by US Forest Service's ForWarn disturbance detection tool) and (2) Sentinel-2 NDVI change [10,19]. In order to focus our comparison on these two technologies' abilities to detect bark beetle spots, we used ground-checked spots from the Florida Forest Service's summer 2019 aerial surveys as our study area.

Aerial surveys throughout Northeastern Florida were conducted by the Florida Forest Service from July to August 2019. Potential bark beetle spots in the red-stages, detected through the aerial survey, were georeferenced and ground checked for confirmation during Fall 2019. Only confirmed spots were included to avoid false positives and focus our analysis on the incidence of false negatives, evaluating whether utilizing remotely sensed data from MODIS or Sentinel-2 would lead to omission of active bark beetle spots. When active bark beetle spots were confirmed, we delimited the entire forest stand as a georeferenced polygon. We used true color composites from Sentinel-2 in the July 2019 imagery to estimate the impacted area within each forest stand by delimiting the extent of red tree canopies as georeferenced polygons in ArcGIS. The bark beetle spots occupied a variable area of our forest stand polygons, ranging from ~31% to ~89%. Therefore, our NDVI measurements for July 2019 were calibrated by the presence of infested and non-infested trees in the studied stands.

Only stands with active spots and active bark beetle galleries that started in 2019 and indicated detectable change in the satellite imagery were selected for the analysis. This time frame was selected based on a bark beetle trapping survey conducted by one of the authors during June 2019. The survey suggested high activity of *Ips* beetles during June, with observed signs of infestation and spots during August 2019, two months after the high *Ips* beetle population activity. Active spots without available or cloud-free satellite images matching the dates of the aerial observations were discarded. Stands with tree damage unrelated to beetles, designated as such by the ground survey, were discarded. The confirmed active bark beetle locations included in our study are shown in Figure 1, with county, stand area, estimated infested area within each stand, and survey flight date noted in Table 1.

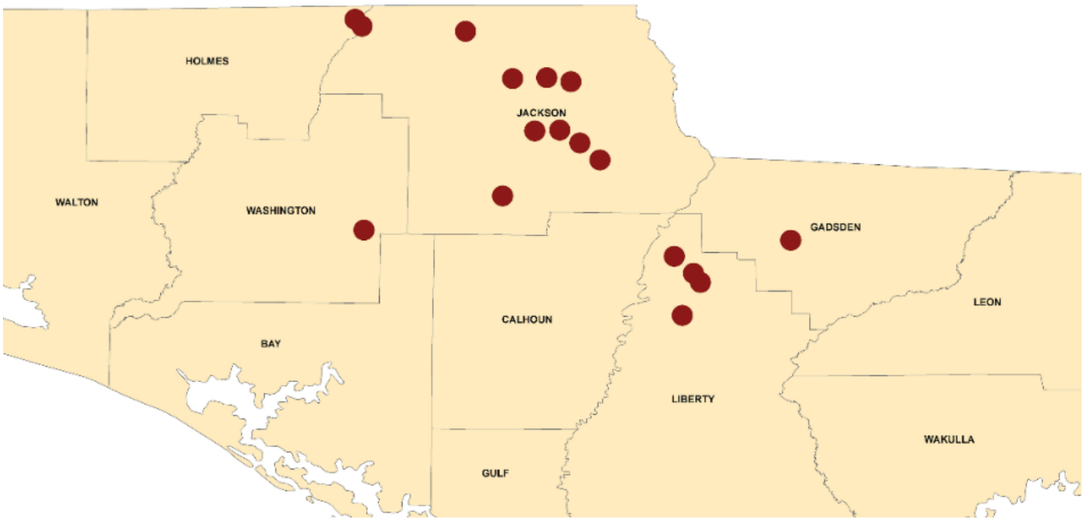

Figure 1. Active locations of *Ips* bark beetle infestations occurring in 2019 used for analysis as red dots (geolocation data provided by Florida Forest Service). Florida county names are listed.

Table 1. Counties and dates of aerial survey detection for active *Ips* bark beetle infestations occurring in 2019 in the Florida Panhandle (data form Florida Forest Service). Latitude, longitude, stand type, total stand area, average diameter at breast height (DBH), approximate area infested with bark beetles, and tree species information is provided. Spot detection in MODIS (Moderate Resolution Imaging Spectroradiometer) and Sentinel2 satellite images noted.

Spot	County	Date of Detection	Stand Type	Species	Average Height	Average _DBH	Stand Area (Ha)	Infested Area (Ha)	MODIS	Sentinel-2
1	Liberty	8 August 2019	Plantation	Sand	40	6	122.509	94.083	1	1
2	Liberty	8 August 2019	Plantation	Sand	40	6	114.465	72.851	1	1
3	Liberty	8 August 2019	Plantation	Sand	0	0	116.49	69.164	1	1
4	Gadsden	8 August 2019	Natural	Loblolly	30	5	7.927	4.452	0	1
5	Washington	15 August 2019	Plantation	Loblolly	45	10	27.827	16.141	1	1
6	Liberty	8 August 2019	Plantation	Sand	45	5	13.645	12.188	1	1
7	Jackson	26 July 2019	Plantation	Loblolly	70	12	0.404	0.326	1	1
8	Jackson	26 July 2019	Plantation	Loblolly	70	13	0.498	0.202	0	1
9	Jackson	26 July 2019	Plantation	Loblolly	30	4	12.689	8.047	1	1
10	Jackson	26 July 2019	Plantation	Loblolly	15	6	5.536	2.428	1	1
11	Jackson	26 July 2019	Plantation	Sand	25	4	4.61	2.428	1	1
12	Jackson	26 July 2019	Plantation	Loblolly	15	4	0.449	0.134	1	1
13	Jackson	26 July 2019	Plantation	Loblolly	25	3	20.811	7.012	0	1
14	Jackson	26 July 2019	Plantation	Loblolly	30	5	13.549	10.469	1	1
15	Jackson	26 July 2019	Plantation	Loblolly	25	3	16.06	9.856	0	1
16	Jackson	26 July 2019	Natural	Loblolly	15	3	1.311	0.405	0	1
17	Jackson	26 July 2019	Plantation	Loblolly	15	0	0.61	0.304	1	1

2.2. Image Sources and Baseline NDVI Determination

Sequences of true color images of bark beetle spot locations, obtained from the ESA-Copernicus Sentinel-2 database, were used to determine dates and area of red-brown discoloration of the tree crowns within the forest stands. Visual inspection of these images indicated detectable change in July 2019. Due to high cloudiness in the region, images were inspected to discard spots or time frames with cloud coverage. MODIS 8-day and Sentinel-2 NDVI data products were obtained from Climate Engine to calculate baseline NDVI and create change maps [20]. MODIS 8-day data is gathered twice a day for most areas in the US at a 250-m spatial resolution and processed to 8-day composites. Following a method analogous to that of ForWarn, we first determined a baseline condition of healthy forest for July 2019 by averaging maximum NDVI values for the month of July in the preceding years (2015–2018) [10]. Constructing a multi-year average as a baseline provides a reasonable estimate of the expected NDVI value in the current year in the absence of disturbance. Additionally, the stands selected did not show crown discoloration during the selected baseline period, nor were they directly affected by Hurricane Michael, allowing us to infer that our baseline calculation of NDVI was indicative of healthy forest conditions. Change maps were created by calculating the difference between the NDVI in the month of July 2019 and the baseline NDVI.

2.3. Image Processing and Evaluation Methods

Data visualization and analysis were conducted in ArcMap [21]. Images and raster data were clipped to the forest stand polygon shapes. MODIS images were converted to 10 m resolution to allow raster calculations for compatibility with Sentinel-2 data. Departures of NDVI from the "healthy forest" baseline were classified based on magnitude and direction to aid in visualization and interpretation and to allow more refined comparison in the disturbance sensing capabilities of MODIS and Sentinel-2. As even small negative changes in NDVI can indicate insect attack, we considered any negative change in NDVI from the baseline to signify detection of the known bark beetle activity [10,22]. To quantify the strength of correlation between MODIS and Sentinel-2 images, we calculated the Jaccard coefficient [23,24]. This coefficient is calculated as the intersection between the two rasters divided by the union between the two rasters and quantifies similarity. Accuracy of the different satellite images and the disagreement between them is quantified and discussed.

3. Results

A total of 917.4 ha (2267 ac) with bark beetle damage was observed and ground checked in the Florida Forest Service aerial surveys. Active bark beetle spots in the red-stages were confirmed to have active galleries of *Ips* species by ground checks. No southern pine beetle spots were found, and no black turpentine beetles (*Dendroctonus terebrans*) were recorded in the spots studied. After discarding spots with cloud coverage, seventeen stands with active bark beetle spots, corresponding to 479.39 hectares (1185 ac), were used to evaluate the NDVI products from MODIS and Sentinel-2. Within the studied stands, approximately 310.48 ha (767 ac) was infested by bark beetles while 168.90 ha was not infested. From the seventeen stands, Sentinel-2 NDVI image products were able to detect bark beetle spots in all stands. However, MODIS images failed to detect spots in 30% of the stands with known bark beetle infestations. The total number of px identified as harboring a confirmed attack was higher for Sentinel-2 than for MODIS, with 17 ha. (1694 px) undetected by MODIS. Within the studied stands, 343 ha. (847 ac) actively attacked by bark beetles was detected by Sentinel-2, whereas 327 ha. (808 ac) attacked by bark beetles was detected by MODIS. In addition, 152.35 ha of non-infested area was detected by Sentinel-2 and 135.44 ha by MODIS, with a respective difference of 16.55 ha and 33.46 ha from the true color images.

Difference in image resolution between MODIS and Sentinel-2 can be observed in Figure 2. Sentinel-2 NDVI products were able to detect smaller bark beetle spots. Five categories of NDVI departure, based on magnitude and direction, were selected for visualization (Figure 2, Table 2). Classes 2–4 of NDVI departure were detected by both Sentinel-2 and MODIS. Sentinel-2 captured 71.75% of the negatively departed areas (classes 2–4), while MODIS captured 68.21% (Table 2). However, class 5 of departure, which indicates the largest negative changes detected, was only detected by Sentinel-2. For the five classes analyzed, 49% of px (23,327 px) disagree between Sentinel-2 and MODIS images (Table 2).

We calculated the strength of agreement between the MODIS and Sentinel-2 NDVI products at the pixel level using the Jaccard coefficient. Sentinel-2 and MODIS images show 75% similarity in detecting any negative change in NDVI (Table 3). However, the agreement of detection of each class differs between satellites, with only 37% similarity for category 2, 12% similarity for category 3, and 0% similarity for categories 4 and 5.

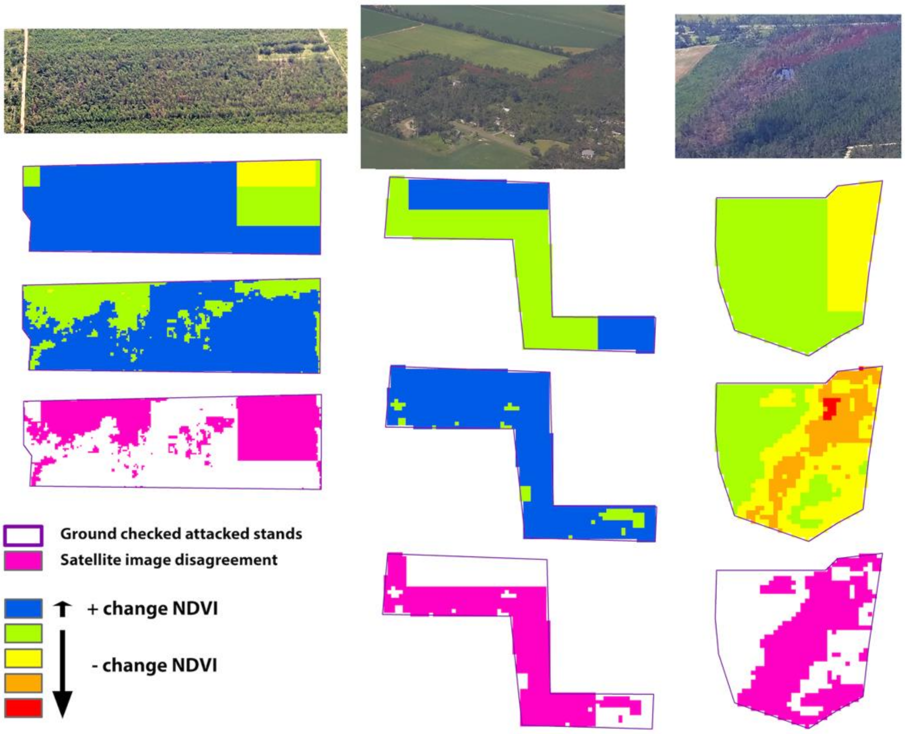

Figure 2. Comparison of bark beetle detection data in three forest stands with active *Ips* bark beetle spots in 2019. Each column of images shows the same stand, from top to bottom, aerial survey photograph, Moderate Resolution Imaging Spectroradiometer Normalized Difference Vegetation Index (MODIS NDVI) change product, Sentinel-2 NDVI change product, and px of disagreement between MODIS and Sentinel-2 products. Colors correspond to classification of NDVI departure and disagreement. Blue corresponds to positive changes in NDVI values. Colors green, yellow, orange, and red, correspond to negative NDVI departure values. Pink corresponds to disagreement between MODIS and Sentinel-2 images.

Table 2. Assessment of the NDVI change products from MODIS and Sentinel-2 in stands with confirmed *Ips* spots. Class colors correspond to classification of NDVI departure and disagreement. Blue corresponds to positive changes in NDVI values. Colors green, yellow, orange, and red correspond to negative NDVI departure values.

	Class	NDVI Departure	Pixels	Hectares	Percentage
MODIS	1	0–0.1	15,238	152.38	31.79
	2	−0.1–0	21,661	216.61	45.18
	3	−0.2–−0.1	10,671	106.71	22.26
	4	−0.3–−0.2	369	3.69	0.77
	5	−0.4–−0.3	0	0	0.00
Sentinel-2	1	0–0.1	13,544	135.44	28.25
	2	−0.1–0	25,504	255.04	53.20
	3	−0.2–−0.1	8580	85.8	17.90
	4	−0.3–−0.2	296	2.96	0.62
	5	−0.4–−0.3	15	0.15	0.03
Agreement	1–5	−0.4–0.1	24,612	246.12	51.34
Disagreement	1–5	−0.4 – 0.1	23327	233.27	48.66

Table 3. Similarity between NDVI products from MODIS and Sentinel-2 with negative departure. Class colors correspond to classification of NDVI departure. Colors green, yellow, orange, and red correspond to negative NDVI departure values.

Class	Jaccard Coefficient
negative departure (2–5)	0.75
2	0.37
3	0.12
4	0
5	0

4. Discussion

Our results show that higher resolution imagery from Sentinel-2 shows greater potential in detecting Southeastern bark beetle spots than MODIS. Sentinel-2 detected negative departures in NDVI for all of our study stands with known bark beetle infestations, while MODIS failed to detect negative changes in NDVI for 30% of the stands. Our study showed a difference between the infested/non-infested area delimited in true color images and the Sentinel-2 and MODIS products, with more infested area detected by NDVI change. Moreover, the extent of detection of each class of NDVI departure differs between satellites. High resolution remote sensing data such as Sentinel-2, Landsat, and WorldView-2 have been used to record and estimate disturbances resulting from bark beetles in Europe and western North America [25–29]. In the eastern US, high-resolution imagery from Landsat 7 was used to develop hazard models for southern pine beetle [30]. In addition, preliminary results by Ritger et al. [19] studying *Ips* bark beetle outbreaks suggested that higher resolution imagery from Landsat 8 and Sentinel-2 improve precision in locating small bark beetle spots. We focused narrowly on comparing the utility of Sentinel-2 and MODIS products for confirmed active bark beetle infestations to show the potential for improving remote sensing of bark beetle spots. Although known stressed or attacked trees can be detected with hyperspectral remote sensing data, such data are not yet ready for operational use or as a replacement for in situ surveys in the fragmented southeastern US landscape. Similar results were found by Götz et al. (2020). Field verification is still an essential part of the process, adding value to remote sensing images used for forest health assessment [31].

Besides insufficient image resolution, there are also limitations resulting from the nature of bark beetle attacks and the ecological conditions in the Southeast. One of the main ones is that similar spectral trait variation observed for bark beetle attacks is produced by various other types of disturbances [8]. Refining methods for reliably distinguishing these various disturbances will be critical. The solution may lie in greater temporal resolution. Bark beetle spots develop with a certain speed that is greater than most abiotic stresses, while slower than management interventions such as harvest.

The issue of detection timing is particularly difficult in the southeast. Many studies, including ours, are limited to comparing annual index changes resulting from a single time point in a year. That has proven adequate for areas like Europe or northern North America, where pests are limited to one or a few generations per year [32]. However, southeastern bark beetles are active throughout much of the year, potentially having upwards of more than six generations annually, meaning outbreaks can grow quickly over shorter timescales especially in warmer environments [33]. Hurricane and storm events, common to Florida, may increase *Ips* activity throughout the year due to the increased abundance of breeding material such as fallen branches or boles caused by strong winds. Our area of study was impacted by Hurricane Michael in 2018, triggering numerous incipient bark beetle infestations.

The cloudiness of the region makes it difficult to get reliably clear imagery for the same geographic area over shorter intervals. Satellite imagery from MODIS offers twice-daily available data, providing time series on forest conditions that overcome cloud-free coverage. On the other hand, satellite imagery with lower temporal resolution such as 16-day Landsat and 5-day Sentinel-2, could increase cloud coverage by chance. Hirschmugl et al. [34] combined radar data from Sentinel-1 with optical data from Sentinel-2 and Landsat 8 to overcome cloud-cover challenges in tropical forests, and a similar approach may offer opportunities to detect southeastern disturbances more quickly.

The current limitations of remote sensing technologies mean that while we should strive to improve its utility, we should also continue to explore additional tools that can assist managers. Spatial modeling built on ecological understanding of bark beetles may successfully predict and detect early spots. Recent studies on the effect on climatic variables in the activity of bark beetles in the southeastern US, coupled with available information on historical pest occurrence, should be incorporated in monitoring strategies to improve early detection and prediction of spots [35–38].

5. Conclusions

Damage produced by bark beetles in the southeastern US can be detected by comparing NDVI products of high-resolution satellites but with a high degree of false negatives, and with spatial resolution exceeding the scope of individual beetle spots. Change detection of any type of remote sensing alone does not explain the cause of the change. Therefore, interpretation after change detection is required to avoid false positives or false negatives. Sentinel-2 NDVI products show greater potential for identifying indications of disturbance by bark beetles than MODIS change maps. Our research shows that using annual index changes with higher spatial as well as temporal resolution may provide a useful tool for forest managers for early bark beetle detection. Continued evaluation of these methods and integration with predictive modeling and improved risk assessment methodology are needed to improve early detection systems such as ForWarn.

Author Contributions: Conceptualization, D.F.G., C.P., H.M.W.R., J.E., and J.H.; methodology, H.M.W.R. and C.P.; software, D.F.G., H.M.W.R., and C.P; formal analysis, D.F.G. and H.M.W.R.; investigation, D.F.G., C.P., and H.M.W.R.; writing—original draft preparation, D.F.G.; writing—review and editing, D.F.G., C.P., H.M.W.R., J.E., and J.H.; supervision, J.H.; funding acquisition, J.H. and J.E. All authors have read and agreed to the published version of the manuscript.

Funding: D.G. and J.H. were partially funded by a cooperative agreement with the Florida Forest Service.

Acknowledgments: We thank Bill Christie, Steve Norman, Jason Vogel, and Eben Broadbent for their help with conceptualization.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Boby, L.; Henderson, J.; Hubbard, W. *The Economic Importance of Forests in the South*; SREF-FE-00; Southern Regional Extension Forestry: Athens, GA, USA, 2014.
2. Hanson, C.; Yonavjak, L.; Clarke, C.; Minnemeyer, S.; Boisrobert, L.; Leach, A.; Schleewis, K. *Southern Forests for the Future*; World Resources Institute: Washington, DC, USA, 2010; ISBN 9781569737378.
3. Food andAgriculture Organization (FAO); United Nations Environment Programme (UNEP). Forests, Biodiversity and People. In *The State of the World's Forests 2020*; FAO: Rome, Italy; UNEP: Nairobi, Kenya, 2020; ISBN 978-92-5-132419-6.
4. Coyle, D.R.; Klepzig, K.D.; Koch, F.H.; Morris, L.A.; Nowak, J.T.; Oak, S.W.; Otrosina, W.J.; Smith, W.D.; Gandhi, K.J.K. A review of southern pine decline in North America. *For. Ecol. Manag.* **2015**, *349*, 134–148. [CrossRef]
5. Clarke, S.R.; Evans, R.E.; Billings, R.F. Influence of pine bark beetles on the West Gulf Coastal Plain. *Tex. J. Sci.* **2000**, *52*, 105–126.
6. Bryant, C.M.; Kulhavy, D.L.; Billings, R.F.; Clarke, S.R. Characteristics of bark beetle infestations in east Texas during a period of low southern pine beetle activity. *Southwest. Entomol.* **2006**, *31*, 187–199.
7. Wulder, M.A.; Ortlepp, S.M.; White, J.C.; Coops, N.C.; Coggins, S.B. Monitoring the impacts of mountain pine beetle mitigation. *For. Ecol. Manag.* **2009**, *258*, 1181–1187. [CrossRef]
8. Lausch, A.; Erasmi, S.; King, D.J.; Magdon, P.; Heurich, M. Understanding forest health with remote sensing—Part I—A review of spectral traits, processes and remote-sensing characteristics. *Remote Sens.* **2016**, *8*, 1029. [CrossRef]

9. Hargrove, W.; Spruce, J.P.; Gasser, G.E.; Hoffman, F.M. Toward a National Early Warning Using Remotely Sensed Canopy. *Photogramm. Eng. Remote Sens.* **2009**, *75*, 1150–1156.
10. Norman, S.; Hargrove, W.; Spruce, J.; Christie, W.; Schroeder, S. *Highlights of Satellite-Based Forest Change Recognition and Tracking Using the ForWarn System*; SRS-GTR-18; USDA Forest Service: Asheville, NC, USA, 2013; p. 30.
11. Tucker, C.J. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sens. Environ.* **1979**, *8*, 127–150. [CrossRef]
12. Rouse, J.W.; Hass, R.H.; Schell, J.; Deering, D.W. Monitoring vegetation systems in the great plains with ERTS. In Proceedings of the Third Earth Resources Technology Satellite Symposium (ERTS), Washington, DC, USA, 10–14 December 1973; Volume 1, pp. 309–317, ISBN 0027-8424.
13. Götz, L.; Psomas, A.; Bugmann, H. Early detection of bark beetle infestations by remote sensing: What is feasible today? *Schweiz. Z. Forstwes.* **2020**, *171*, 36–43. [CrossRef]
14. Masek, J.G.; Hayes, D.J.; Hughes, J.M.; Healey, S.P.; Turner, D.P. The role of remote sensing in process-scaling studies of managed forest ecosystems. *For. Ecol. Manag.* **2015**, *355*, 109–123. [CrossRef]
15. Spruce, J.P.; Sader, S.; Ryan, R.E.; Smoot, J.; Kuper, P.; Ross, K.; Prados, D.; Russell, J.; Gasser, G.; McKellip, R.; et al. Assessment of MODIS NDVI time series data products for detecting forest defoliation by gypsy moth outbreaks. *Remote Sens. Environ.* **2011**, *115*, 427–437. [CrossRef]
16. de Beurs, K.M.; Townsend, P.A. Estimating the effect of gypsy moth defoliation using MODIS. *Remote Sens. Environ.* **2008**, *112*, 3983–3990. [CrossRef]
17. Spruce, J.P.; Hicke, J.A.; Hargrove, W.W.; Grulke, N.E.; Meddens, A.J.H. Use of MODIS NDVI products to map tree mortality levels in forests affected by mountain pine beetle outbreaks. *Forests* **2019**, *10*, 811. [CrossRef]
18. Abdullah, H.; Skidmore, A.K.; Darvishzadeh, R.; Heurich, M. Sentinel-2 accurately maps green-attack stage of European spruce bark beetle (*Ips typographus*, L.) compared with Landsat-8. *Remote Sens. Ecol. Conserv.* **2019**, *5*, 87–106. [CrossRef]
19. Ritger, H.; Blanks, D.; Robinov, L.; Armistead, J.; Murphy, M.; Quick, D.; Spruce, J.; Hargrove, W.; Christie, W.; Norman, S. Improving Forest Management Through Early Detection of Bark Beetle Outbreaks in the Southeastern United States Using Earth Observations. In Proceedings of the American Geophysical Union Fall Meeting 2018, Washington, DC, USA, 10–14 December 2018.
20. Huntington, J.; Hegewisch, K.; Daudert, B.; Morton, C.; Abatzoglou, J.; McEvoy, D.; Erickson, T. Climate Engine: Cloud Computing of Climate and Remote Sensing Data for Advanced Natural Resource Monitoring and Process Understanding. *Bull. Am. Meteorol. Soc.* **2017**, *98*, 2397–2409. [CrossRef]
21. *ArcGIS*; Release 10.7; Environmental Systems Research Institute (ESRI): Redlands, CA, USA, 2019.
22. Foster, A.C.; Walter, J.A.; Shugart, H.H.; Sibold, J.; Negron, J. Spectral evidence of early-stage spruce beetle infestation in Engelmann spruce. *For. Ecol. Manag.* **2017**, *384*, 347–357. [CrossRef]
23. Jaccard, P. Nouvelles recherches sur la distribution florale. *Bull. Soc. Vaud. Sci. Nat.* **1908**, *44*, 223–270.
24. De Baets, B.; De Meyer, H.; Naessens, H. A class of rational cardinality-based similarity measures. *J. Comput. Appl. Math.* **2001**, *132*, 51–69. [CrossRef]
25. Wulder, M.A.; White, J.C.; Bentz, B.; Alvarez, M.F.; Coops, N.C. Estimating the probability of mountain pine beetle red-attack damage. *Remote Sens. Environ.* **2006**, *101*, 150–166. [CrossRef]
26. Coops, N.C.; Waring, R.H.; Wulder, M.A.; White, J.C. Prediction and assessment of bark beetle-induced mortality of lodgepole pine using estimates of stand vigor derived from remotely sensed data. *Remote Sens. Environ.* **2009**, *113*, 1058–1066. [CrossRef]
27. Immitzer, M.; Atzberger, C. Early detection of bark beetle infestation in Norway Spruce (*Picea abies*, L.) using worldview-2 data. *Photogramm. Fernerkund. Geoinf.* **2014**, *2014*, 351–367. [CrossRef]
28. Grabska, E.; Hawrylo, P.; Socha, J. Continuous detection of small-scale changes in scots pine dominated stands using dense sentinel-2 time series. *Remote Sens.* **2020**, *12*, 1298. [CrossRef]
29. Meddens, A.J.H.; Hicke, J.A.; Vierling, L.A.; Hudak, A.T. Evaluating methods to detect bark beetle-caused tree mortality using single-date and multi-date Landsat imagery. *Remote Sens. Environ.* **2013**, *132*, 49–58. [CrossRef]
30. Cook, S.; Cherry, S.; Humes, K.; Guldin, J.; Williams, C. Development of a Satellite-Based Hazard Rating System for *Dendroctonus frontallis* (Coleoptera: Scolytidae) in the Ouachita Mountains of Arkansas. *J. Econ. Entomol.* **2007**, *100*, 381–388. [CrossRef]

31. Pause, M.; Schweitzer, C.; Rosenthal, M.; Keuck, V.; Bumberger, J.; Dietrich, P.; Heurich, M.; Jung, A.; Lausch, A. In situ/remote sensing integration to assess forest health-a review. *Remote Sens.* **2016**, *8*, 471. [CrossRef]
32. Hollaus, M.; Vreugdenhil, M. Radar Satellite Imagery for Detecting Bark Beetle Outbreaks in Forests. *Curr. For. Rep.* **2019**, *5*, 240–250. [CrossRef]
33. Nebeker, T.E. Southern Pine Bark Beetle Guild. In *Southern Pine Beetle II*; Coulson, R.N., Klepzig, K.D., Eds.; USDA Forest Service, Southern Research Station: Asheville, NC, USA, 2011; Volume 140, pp. 199–210.
34. Hirschmugl, M.; Deutscher, J.; Gutjahr, K.H.; Sobe, C.; Schardt, M. Combined use of SAR and optical time series data for near real-time forest disturbance mapping. In Proceedings of the 2017 9th International Workshop on the Analysis of Multitemporal Remote Sensing Images (MultiTemp) 2017, Bruges, Belgium, 27–29 June 2017.
35. *Southern Pine Beetle Outbreak Model (SPBOM)*; Version 1.0; Forecasting Short- and Long-Term Southern Pine Beetle Risk in the Southeastern US; USDA Southeast Climate Hub: Durham, NC, USA, 2019.
36. Gan, J. Risk and damage of southern pine beetle outbreaks under global climate change. *For. Ecol. Manag.* **2004**, *191*, 61–71. [CrossRef]
37. McNulty, S.; Cobb, J.; Treasure, E.; Nowak, J.; Sun, G.; Kumar, A. Improved Forest Insect Outbreak Modeling Under Increased Climate Variability. In Proceedings of the IUFRO World Congress, Curitiba, Brazil, 29 September–5 October 2019.
38. Munro, H.L.; Montes, C.R.; Gandhi, K.J.K. Spatio-temporal effects of climate change on southern pine beetle. In Proceedings of the IUFRO World Congress, Curitiba, Brazil, 29 September–5 October 2019.