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Evaluating war-induced damage to agricultural land in the Gaza Strip since October 2023 using PlanetScope and SkySat imagery

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ABSTRACT

The ongoing 2023 Israel-Hamas War has severe and far-reaching consequences for the people, economy, food security, and environment. The immediate impacts of damage and destruction to cities and farms are apparent in widespread reporting and first-hand accounts from within the Gaza Strip. However, there is a lack of comprehensive assessment of the war's impacts on key Gazan agricultural land that are vital for immediate humanitarian concerns during the ongoing war and for long-term recovery. In the Gaza Strip, agriculture is arguably one of the most important land use systems. However, remote detection of damage to Gazan agriculture is challenged by the diverse agronomic landscapes and small farm sizes. This study uses multi-resolution satellite imagery to monitor damage to tree crops and greenhouses, the most important agricultural land in the Gaza Strip. Our methodology involved several key steps: First, we generated a pre-war cropland map, distinguishing between tree crop fields (e.g., olives, orchards) and greenhouses, using a random forest and the Segment Anything Model (SAM) on 3-m PlanetScope and 50-cm Planet SkySat imagery, obtained from 2022 to 2023. Second, we assessed damage to tree crop fields due to the war, employing a harmonic-model-based time series analysis using PlanetScope imagery. Third, we assessed the damage to greenhouses by classifying PlanetScope imagery using a random forest model. We performed accuracy assessments on generated tree crop fields damage map using 1,200 randomly sampled 3 × 3-m areas, and generated error-adjusted area estimates with a 95% confidence interval. To validate the generated greenhouse damage map, we used a random sampling-based analysis. We found that 64–70% tree crop fields and 58% greenhouses had been damaged by 27 September 2024 after almost one year of the war in the Gaza Strip. Agricultural land in Gaza City and North Gaza were the most heavily damaged with 90% and 73% of tree crop fields damaged in each governorate, respectively. By the end of 2023, all greenhouses in North Gaza and Gaza City had been damaged. Our damage estimate overall agrees with that from UNOSAT but provides more detailed and accurate information such as the timing of the damage as well as fine-scale changes. Our results attest to the severe impacts of the Israel-Hamas War on Gaza's agricultural sector with direct relevance for food security and economic recovery needs. Due to the rapid progression of the war, we have made the latest damage maps and area estimates available on GitHub (https://github.com/hyinhe/Gaza).

1. Introduction

In October 2023, Palestinian armed groups and Hamas fighters broke through the border and attacked Israeli communities along the eastern Gaza Strip border, leading to a massive Israeli military response. The resulting war has caused a severe humanitarian crisis, including extensive damage to buildings, infrastructure, and agriculture across the Gaza Strip, which, together with the Israeli-imposed blockade, poses serious threats to both immediate and long-term food security (FAO UNOSAT, 2024; UNEP, 2024). Agricultural production has

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been impacted by the war in multiple ways, including the destruction of agricultural lands through razing, heavy vehicle activity, bombing and shelling, destruction of water and irrigation infrastructure, and contamination of soils from the explosion of munitions (Insight Insecurity, 2024). Forced displacement, the risk of unexploded ordnance, or direct casualties can also cause farmland to become abandoned in the war zone (Eklund et al., 2024; Yin et al., 2019). Assessing the damage to crops and greenhouses in this densely populated, small geographic area during an ongoing conflict without direct ground access presents significant challenges.

Remote sensing has been widely used for monitoring agricultural land use changes caused by natural hazards and societal disasters such as armed conflicts (Sticher et al., 2023; Witmer, 2015). Among all available information sources, remote sensing offers the most comprehensive view of terrestrial dynamics, enabling a comprehensive investigation of the direct environmental consequences of war. This is particularly important for monitoring conflict-affected areas where physical access is limited for security reasons. In the past, remote sensing techniques have been effectively applied to study the impacts of war on agricultural land cover in e.g. the Caucasus (Buchner et al., 2022; Yin et al., 2018), South Sudan (Anderson et al., 2021; Olsen et al., 2021), Iraq (Eklund et al., 2021; Jaafar et al., 2022), Syria (Eklund et al., 2017; Li et al., 2022), Ethiopia (Kerner et al., 2024; Weldegebriel et al., 2024), and Ukraine (Chen et al., 2024; Qadir et al., 2024). However, challenges remain in using remote sensing techniques to monitor the damage to agriculture caused by armed conflicts. Firstly, existing studies often take a retrospective, bi-temporal approach by comparing land cover conditions before and after a conflict to assess the conflict impact, rather than taking a multi-temporal approach to monitoring changes throughout the course of the conflict. The devastating impacts and rapid progression of war necessitate timely information from remote sensing to uncover the extent, timing, and type of damage and inform decision-making for humanitarian aid efforts. Secondly, there are challenges in monitoring heterogeneous, small-scale, and dynamic croplands, particularly in the Global South (Rufin et al., 2019). Different crops and management practices create diverse spectral reflectance signatures captured by sensors, leading to potential confusion with other land covers. For example, tree crops have similar spectral reflectance to natural forests, and greenhouses often resemble built-up structures in visual bands. Additionally, publicly available imagery from medium-resolution sensors like Landsat or Sentinel-2 often fails to capture agricultural land at the plot level. Fragmented landscapes, such as those in the Gaza Strip, require higher spatial and temporal resolution imagery to accurately monitor agricultural land.

Existing efforts to monitor the impacts of the 2023 Israel-Hamas War on agricultural land use, such as the Gaza Strip Agricultural Damage Assessment from the United Nations Satellite Centre (UNOSAT), provide nearly monthly estimates of agricultural land damage since the conflict began (UNOSAT, 2023). While these efforts have supported an overall understanding of changes during the war, limitations exist regarding imagery selection and methodology. First, the 10-m Sentinel-2 imagery used by UNOSAT may not be suitable for monitoring small-scale farms with agricultural holdings of less than 1 ha, much less detecting damage within such plots (PCBS, 2023a). Secondly, area estimates based on remote sensing-derived maps can be biased due to mapping errors. It is crucial to examine errors and uncertainties through a rigorous accuracy assessment to guide appropriate interpretation and use of remote sensing-derived maps (Olofsson et al., 2014). To the best of our knowledge, UNOSAT's Gaza Strip Agricultural Damage Assessments do not report the accuracy of generated maps and account for the errors in the maps when reporting area estimates. Third, while the Sentinel-2 imagery used to produce the UNOSAT maps is open-access, there is little information on the methodology used to produce the maps. This fundamentally challenges the replication of the analysis but also obscures the assumptions, limitations, and strengths of the approach.

Very high-resolution datasets from commercial companies, such as the daily 3-m PlanetScope and 50-cm SkySat imagery from Planet Labs, present a great opportunity to enhance near real-time monitoring of small-scale farms, such as those in Gaza. In addition, deep learning algorithms facilitate the detection of small objects from VHR imagery, such as greenhouses (Chen et al., 2021; Ma et al., 2021). Our goal is to leverage the high temporal and spatial resolution PlanetScope and SkySat imagery to provide near real-time monitoring of damage to agricultural land in the Gaza Strip since the start of the war in 2023. The focus of our study is on two key types of agricultural land in Gaza: tree crop fields and greenhouses. Given their distinct spectral characteristics and temporal dynamics, we apply different methodologies to monitor damage to each. To ensure the accuracy of our damage estimates, we generate error-adjusted area estimates using a sampling-based approach. This study aims to capture the spatial and temporal dynamics of agricultural damage across the Gaza Strip throughout the war by addressing three specific research objectives:

1. Map the damage to tree crop fields using 3-m PlanetScope imagery and a harmonic time series model.
2. Identify individual greenhouses using 50-cm Planet SkySat imagery using a Deep Learning model and assess their damage using PlanetScope imagery.
3. Generate error-adjusted area estimates of tree crop fields and greenhouse damage using a sampling-based approach.

2. Methods

2.1. Study area

The Gaza Strip, part of the Occupied Palestinian Territories, spans a small geographic area of 365 km^2, measuring approximately 41 km in length with a width varying between 6 and 12 km along the Mediterranean coast. It has one of the highest population densities globally, with 2.3 million people, the majority of whom are registered Palestinian refugees (PCBS, 2023b). The Gaza Strip forms part of the Fertile Crescent where plant and animal domestication occurred around 12,000 years ago. This transition from hunter-gatherer to sedentary communities led to some of the earliest agricultural settlements in the world and the establishment of ancient civilizations (Fuller and Stevens, 2019; Nigro, 2023). Today, local agricultural production remains an important part of Palestinian society, contributing to food security in addition to maintaining cultural bonds to the land (King, 2013; Qumsiyeh, 2024). Agriculture contributed 11% to the GDP and helped alleviate the high unemployment rate of 45.1% before the war started in 2023 (International Labour Organization, 2024). The agricultural sector has also long been the main source of exports for the Gaza Strip, contributing more than 45% of the total export flow (PCBS, 2023a). In 2022, the total value of agricultural production in the Gaza Strip amounted to about USD 575 million, 54% of it from plant production (PCBS, 2023a). At the same time, 56% of the food consumed in the Gaza Strip in 2022 was imported.

Crops are cultivated across roughly 33% of the total land area across the five governorates (PCBS, 2023a). Similar to the broader Palestinian Territories, small-scale family farming dominates with about 74.2% of agricultural holdings covering less than 1 ha and the average size of each holding being 3.8 dunums (1 dunum equals 1,000 m^2). Agricultural production includes fruit trees, vegetables, and field crops. During the 2020/2021 agricultural year, 35,969 dunums were planted with tree crops (PCBS, 2023a). Of these, 80% were evergreen species, primarily olive and citrus trees, followed by grapes, guava, date palm, figs, and other species. Beyond their economic importance, tree crops, particularly olive trees, hold significant cultural heritage value in Palestinian culture (De Cesari, 2019; King, 2013). Additionally, 16,778 dunums were used for cultivating various vegetables under some form of protection such as surface tunnels, French tunnels, and protected cover (PCBS, 2023a). Greenhouses or protected cover structures that we focus on in this study are mainly made of plastic, mainly growing tomatoes, cucumbers, peppers, and strawberries (Ministry of Agriculture in Palestine, 2024; personal communication).

Years of conflict with Israel and the blockade imposed on the Gaza Strip since 2007 have resulted in severe food insecurity for residents of the Gaza Strip (FAO, 2020), undermining efforts to meet the second Sustainable Development Goals (SDGs) to end hunger (Hassoun et al., 2024). An Integrated Food Security Phase Classification (IPC) report estimated that 96% of Gaza's population was facing high levels of acute food insecurity in September 2024 (IPC, 2024). Additionally, climate studies have identified the Eastern Mediterranean, including the Gaza Strip, as a climate change hotspot, characterized by extreme and worsening weather conditions such as intensified heatwaves, droughts, dust storms, and torrential rain events. These phenomena are expected to have detrimental impacts on Gazan agriculture and food production (Zittis et al., 2022). Key Mediterranean crops like olives, vines, legumes, wheat, barley, and maize are particularly vulnerable to the combined effects of prolonged droughts and increased heat stress (Aurelle et al., 2022; Fraga et al., 2020).

2.2. Data

We used 3-m PlanetScope imagery as the main source for mapping damage to tree crop fields and greenhouses. We also used 50-cm Planet SkySat imagery to generate a pre-war greenhouse map as a baseline for damage assessment. We used all available PlanetScope imagery that had a cloud cover of $<10\%$ across the entire Gaza Strip from September 2022 to September 2024. These images were collected by the PlanetScope satellite constellation of Dove satellites based on the newest PSB. SD instrument and include eight spectral bands: coastal blue (central wavelength = 443 nm), blue (490 nm), green I (531 nm), green (565 nm), yellow (610 nm), red (665 nm), red edge (705 nm), and near-infrared (865 nm). The passing time of Dove satellites over the Gaza Strip varied from 7:30 to 8:30 a.m. local UTC + 3 time. To ensure consistency across atmospheric conditions and minimize uncertainty in spectral response across time and location, we used the surface reflectance dataset derived from the PlanetScope Ortho Analytic Scene product that is radiometrically, sensor, and geometrically corrected. To obtain clear observations, we used the useable data mask (UDM2) band and removed pixels labeled as snow, shadow, haze, or cloud for each spectral band.

We also obtained 50-cm SkySat Pan-sharpened Multispectral Ortho Scene and Visual Ortho Scene products from Planet Labs from May 2023 to August 2024. These images were used to 1) map pre-war greenhouses and 2) facilitate visual interpretation for sample labeling. Given the very limited physical access due to security constraints, very-high-resolution (VHR) imagery offers an alternative way of generating labels. Both SkySat products are orthorectified, pan-sharpened, and color-corrected with the former product having a 4-band (blue, green, red, near-infrared) composite while the latter includes 3-band RGB Imagery. In total, we obtained 390 image stripes, including 14 pre-war imagery stripes. Additionally, we visually inspected these images and excluded the images that have geomatic errors larger than 2 m (i.e., 4 pixels).

We compared our results with UNOSAT's monthly maps and estimates of agricultural and greenhouse damage through September 2024 (FAO UNOSAT, 2024). The UNOSAT analysis relied on Sentinel-2 satellite imagery collected between July 2017 and 2024. The analysis included a Normalized Difference Vegetation Index (NDVI) evaluation and a multitemporal classification to identify changes in orchards and other trees, field crops, and vegetables since October 2023.

2.3. Analysis

We first generated a pre-war tree crop fields map using 3-m PlanetScope imagery obtained between October 2022 and September 2023. We then detected damage to tree crop fields based on a harmonic model. Because of the small size of greenhouses, we used 50-cm SkySat imagery as well as PlanetScope imagery to detect pre-war individual greenhouses. Then we applied a supervised classification to label the damage to each individual greenhouse from PlanetScope imagery. Lastly, we validated all maps generated and constructed error-adjusted area estimates using a sampling-based approach (Fig. 1).

2.3.1. Mapping damage to tree crops

We used spectral-temporal metrics from the PlanetScope images, widely used for land use mapping to map pre-war land cover (Yin et al., 2017, 2020). These metrics include median, standard deviation, and percentiles at an interval of 20% (i.e., 20, 40, 60, and 80%) for each of the eight spectral bands and five derived indices: NDVI, Difference Water Index (NDWI), Modified Soil-adjusted Vegetation Index (MSAVI2), Modified Triangular Vegetation Index (MTVI2), and Triangular Greenness Index (TGI); this yielded a total of 78 metrics for classification. We visually interpreted pre-war VHR images and generated training samples for six land cover and land use classes: tree crops (161 samples), developed areas (150), barren land (30), shrubs and vegetation (121), greenhouses (78), and water bodies (31) (Table 1).

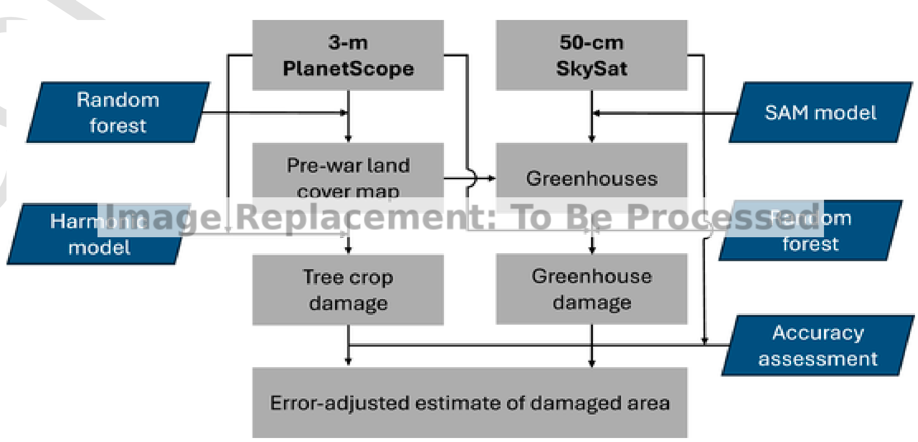

Fig. 1. Flowchart of data analysis.

Table 1
Land cover classes used in the pre-war land cover map.

Class	Definition
Tree crops	Orchards that include olive trees, nuts, and fruit trees
Developed area	Built-up areas such as urban areas, roads, settlements, etc.
Barren land	Unused land covered with little vegetation
Greenhouses	Agricultural land covered structures enclosing house a plot of land typically used to grow vegetables and small fruit crops
Shrubs and vegetation	Shrublands and vegetation-covered land such as grassland, shrubs, and other annual crops (e.g., wheat)
Water bodies	Lakes, ponds, and reservoirs

We generated a pre-war land cover and land use map using a random forest classifier (Breiman, 2001). We set the number of variables that were randomly sampled as candidates at each split (mtry) to 9, which is the square root of the number of input variables (i.e. the 78 metrics), and the minimum size of the terminal nodes to 10. To reduce the salt and pepper effects in the classified land cover map, we used a minimum mapping unit of 10 PlanetScope pixels (90 m^2).

We employed a harmonic model for each PlanetScope pixel identified as tree crops in the pre-war period to assess damage during the war (Fig. 2). This model was fitted to the NDVI time series from September 2022 to 2023, representing a typical growing season in the Mediterranean region, where the growing season typically begins in late autumn (around October) with the arrival of winter rains and concludes in early summer (around June) (Ortiz-Miranda et al., 2013). Using this model, we predicted NDVI values for the period following the onset of the war on October 7, 2023, assuming that the 2023–2024 growing season would have similar conditions to 2022–2023. We then compared the predicted NDVI values with the observed data and calculated residuals. A pixel was classified as damaged if the NDVI dropped by more than 30%, based on our sensitivity testing, as a balance of omission and commission errors (Supplementary file, Table S1). To rule out the noise in the time series, such as undetected clouds of smoke, we required that the 30% decline be sustained over three consecutive dates. The timing of the damage was recorded, and we aggregated the occurrences monthly for validation purposes. For instance, a pixel would be mapped as damaged in July 2024 if it exhibited damage on July 31, 2024.

2.3.2. *Mapping damage to greenhouses*

We used both SkySat and PlanetScope imagery to identify pre-war greenhouses, leveraging the advantages of the very high spatial resolution of SkySat and the temporal information from PlanetScope images. To identify the footprint of individual greenhouses present before the war, we used the median RGB composite from SkySat imagery obtained before October 7, 2023. We used the Segment Anything Model (SAM), an image segmentation model by Meta AI (Kirillov et al., 2023), to generate objectives from the SkySat imagery epoch. The SAM is trained on the Segment Anything 1-Billion mask dataset (SA-1B) which includes 11 million images. This makes the model highly robust in identifying object boundaries and differentiating between various objects. Although SAM can struggle with objects having unclear boundaries, such as natural vegetation (Li et al., 2024), it performs well for objects with defined shapes, like greenhouses. We also selected SAM due to its zero-shot learning capabilities, which require no additional training for unfamiliar objects (Osco et al., 2023).

Since SAM segments the entire image and includes all object types, we labeled the generated segments using PlanetScope-derived land cover maps (Fig. 3). To minimize errors due to mixed pixels and geometric inaccuracies in SkySat imagery, we reduced the segment size by one PlanetScope pixel (3 m) and used a minimum segment size of 100 m^2. We then calculated the percentage of land cover types within each segment and classified a segment as a greenhouse if the majority of its land cover was mapped as a greenhouse according to our PlanetScope-derived land cover map. While alternative fine-tuned SAM models exist, such as one-shot learning models PerSAM and PerSAM-F (Zhang et al., 2023), our approach requires minimal inputs and leverages existing PlanetScope maps, which offer greater spectral and temporal information.

Since SkySat imagery strips do not cover the entire Gaza Strip at frequent time intervals such as PlanetScope, we therefore used PlanetScope images to map monthly damage to greenhouses. A single greenhouse is considered damaged if more than 10% of the greenhouse-classified pixels within the segment representing the greenhouse footprint or rooftop were lost since the war started. We assume that since the war started, the changes in greenhouses due to farmers' activities such as constructing new greenhouses or modifying existing greenhouses are minimal. Our analysis was done at the object level with each segment including the statistical summaries calculated from all pixels within the segment, including the standard deviation and percentiles at an interval of 10% of each spectral band, and indices NDVI, NDWI, MSAVI2, MTVI2, and TGI. We reduced the size of each segment by 3 m from the boundary, considering the shadows and mixed pixels at the edges of greenhouses observed in the PlanetScope imagery (Supple-

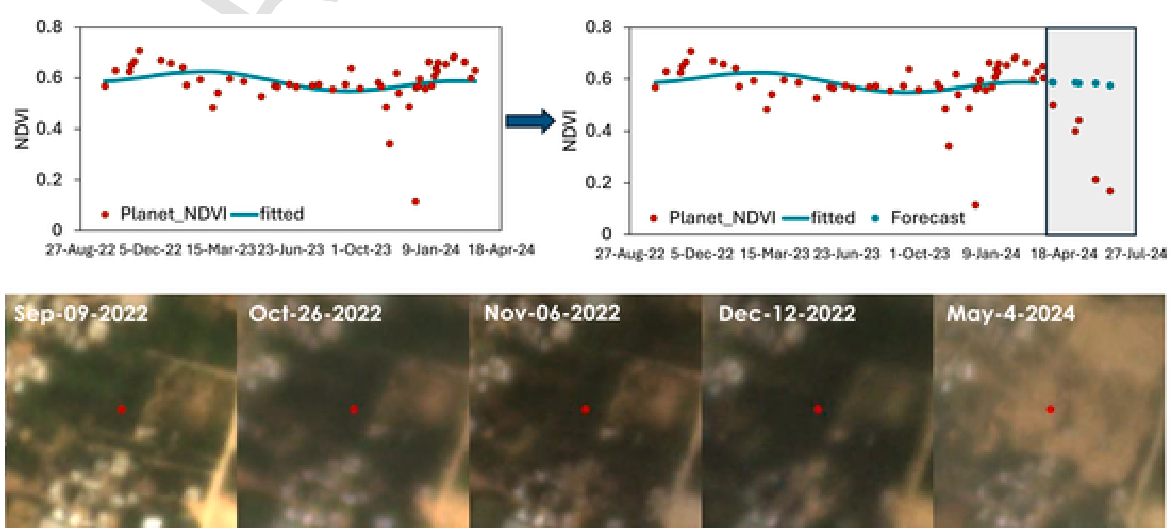

Fig. 2. Illustration of a harmonic model fitting for one pixel (noted as a red dot) classified as tree crops in the pre-war period but showing signs of damage by May 4, 2024. The PlanetScope imagery obtained at different dates is shown here as RGB true color composites.

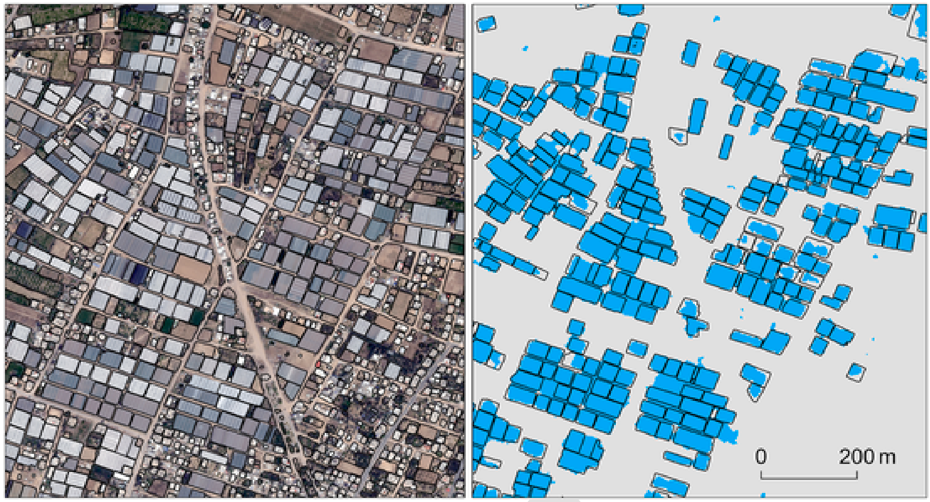

Fig. 3. Segment output from the SAM model (left) and identified greenhouses based on the pre-war PlanetScope-derived land cover map (right). Pixels representing greenhouses in the pre-war land cover map are shown in blue.

mentary file, Figure S1). We then stacked these statistical summaries and calculated a pair of PlanetScope images obtained before and during the war to classify damaged and undamaged greenhouses. The training samples were manually collected based on the visual interpretation of the SkySat imagery.

2.3.3. *Accuracy assessment and area estimate*

To validate our pre-war tree crop fields map generated from PlanetScope imagery, we randomly selected 1,200 samples across Gaza, each with a size of 3 × 3 m to match the PlanetScope pixel resolution. Each sample was labeled using Planet SkySat imagery (Fig. 4), and where SkySat imagery was unavailable, we utilized the PlanetScope time series. Since our primary focus is tree crops, we aggregated all other land cover classes (e.g., developed areas, and water bodies) into a single category. Accuracy metrics, including overall accuracy and F1 scores for tree crops, were reported based on the labeled samples.

We also used the same 1200 samples to validate the map of tree crop field damage. We labeled these samples as one of four categories: 1) non-tree crops, 2) stable tree crops, 3) damaged tree crops, or 4) no data (i.e., no imagery coverage or uncertain class). If a sample was labeled as damaged, we recorded the estimated month of the damage. For instance, if a sample appeared undamaged in imagery from October 27 but showed damage in the next available imagery on November 5, we assigned the damage to November. Using the approach from Olofsson et al. (2014), we generated mapping accuracy as well as error-adjusted area estimates at a confidence interval of 95% for the damage of tree crops.

To validate the prediction accuracy of the identified greenhouses, we used metrics like Intersection over Union (IoU), Pixel Accuracy, and Dice Coefficient, following Osco et al. (2023). These metrics are widely used to evaluate the performance of image segmentation models (Minaee et al., 2022). Intersection over Union (IoU) is calculated as the area of overlap between the predicted segmentation and the reference geometry, divided by the area of their union, providing a measure of how well the predicted segmentation matches the reference geometry (Rahman and Wang, 2016). Pixel Accuracy, defined as the ratio of correctly classified pixels to the total number of pixels, indicates the percentage of pixels that were accurately labeled. The Dice Coefficient, calculated as twice the area of overlap between the predicted and reference segmentations divided by the total number of pixels in both, is often used to assess the similarity between two segmentations. Because greenhouses represent a small fraction of the landscape, we adopted a stratified sampling approach to generate validation samples for calculating these metrics. Using the land cover map derived from PlanetScope imagery, we randomly selected 500 segments each from areas identified as greenhouses and non-greenhouses. SkySat imagery was then used to visually interpret and label these 1,000 segments, capturing both pre-war conditions and monthly damage since the onset of the war. Each segment was labeled either as a greenhouse or non-greenhouse. If a segment contained both greenhouses and other land cover types, it was labeled as non-greenhouse. To validate the generated greenhouse damage map, we randomly selected 10% of the identified greenhouses and labeled each as either damaged or undamaged. For damaged greenhouses, we recorded the month when the damage first occurred based on visual interpretation of the SkySat and PlanetScope imagery, following the same criteria used in the greenhouse damage mapping process (Fig. 4).

We compared both our map and area estimates with those from UNOSAT's analysis (FAO UNOSAT, 2024). Since UNOSAT's map includes all cropland types at a 10-m resolution, we resampled it to 3-m resolution using nearest-neighbor sampling to align with our PlanetScope-derived tree crop damage map. We then focused on pixels representing either damaged or undamaged tree crops based on our PlanetScope-derived map. We used our set of 1,200 accuracy assessment samples for tree crop damage to evaluate the accuracy of UNOSAT's map. Additionally, we compared greenhouse damage estimates, but since the raw data from UNOSAT's greenhouse analysis is publicly unavailable, our comparison was limited to percentages of reported damage.

3. Results

3.1. *Tree crops and their damage during the war*

Before the war began in October 2023, tree crops covered 23% (8,242 ± 323 ha) of the entire Gaza Strip. Among the five governorates, Khan Yunis had the largest share of tree crop fields (2102 ± 167 ha) and Rafah had the smallest area of tree crops, covering only 10% (619 ± 185 ha) of its territory (Fig. 5). Tree crops classification across all governorates achieved a Producer's Accuracy (PA) and User's Accuracy (UA) above 90%, except in Rafah, where PA and UA were 79% and 78%, respectively. This lower accuracy is largely due to Rafah's drier environment and the sparse distribution of individual trees within fields, which led to confusion between tree crops and barren land.

Fig. 4. SkySat imagery © 2025 Planet Labs PBC illustrating damage to tree crops (top panel) and greenhouses (bottom panel) in the Gaza Strip.

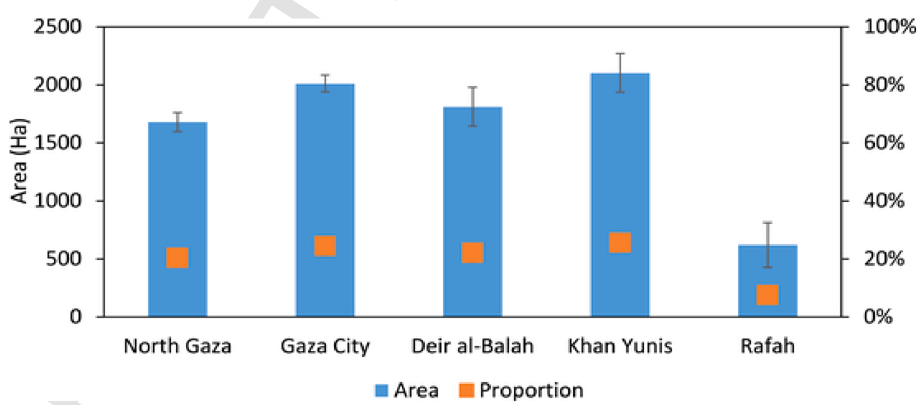

Fig. 5. Area (ha) and proportion of tree crops (%) relative to the total territory in each governorate of the Gaza Strip before October 2023. The error bars indicate the estimate at a 95% confidence interval.

We found that 64–70% (5,305–5,795 ha) of tree crop fields in Gaza were damaged at a 95% confidence interval between October 2023 and September 2024, with significant spatial variations (Fig. 6). Among the governorates, Gaza City experienced the highest degree of damage, with over 90% of tree crop fields lost, followed by North Gaza (73%), Khan Yunis (52%), Deir al-Balah (50%), and Rafah (42%). In addition to the spatial differences, the damage also displayed clear temporal dynamics. Most of the damage occurred between November 2023 and January 2024 (Fig. 7). In February, the damage significantly declined, followed by a steady increase until June 2024. In recent months, from July to September 2024, less damage was observed. North Gaza and Gaza City saw rapid increases in damage, with nearly 50% of tree crops damaged before the end of 2023 (Fig. 7). Since November 2023, Deir al-Balah and Khan Yunis have experienced steady tree crop loss, though at a slower rate. After May 2024, most governorates, except for Rafah, experienced a slower rate of damage. In Rafah, however, the damage to tree crops started later, i.e. April 2024, but has been increasing ever since.

The overall mapping accuracy of the tree crop damage maps is 88% ± 1%, with varying PA and UA across different damage classes (Fig. 8). The lowest accuracy was observed for the damage in February 2024, when both UA and PA were below 20%, followed by the damage classes in May and June 2024. Mapping accuracy improved when all monthly damage classes were aggregated into a single class, resulting in a new map with three categories: non-tree crops, undamaged tree crops, and damaged tree crops. The overall accuracy of this aggregated

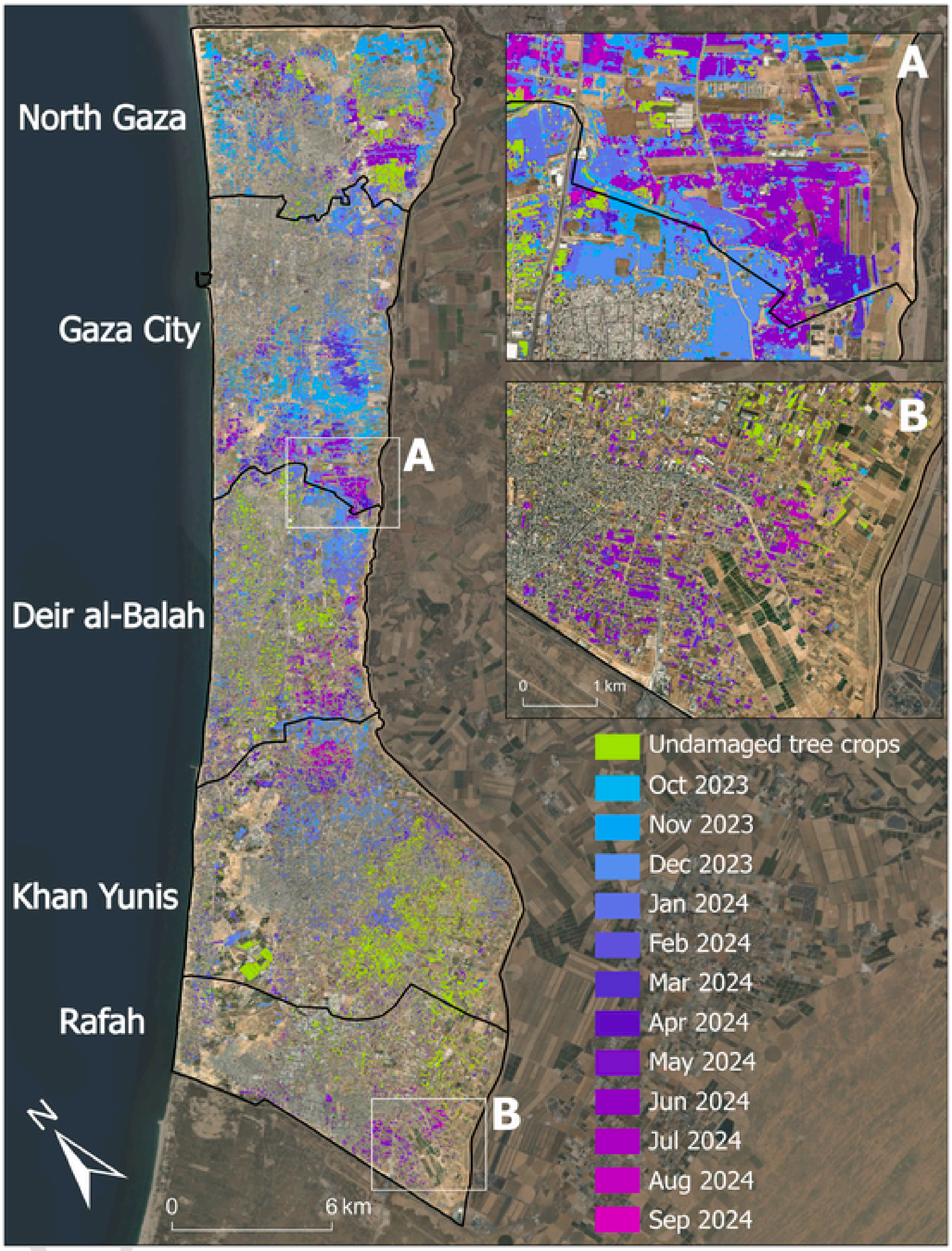

Fig. 6. Spatial pattern of tree crops damage at monthly intervals from October 2023 to September 2024. The months in which damage first occurred are in blue and purple colors, while undamaged tree crops are shown in green.

map is 96% ± 1%, with a PA of 97% and a UA of 82% for the damaged tree crops.

3.2. Greenhouses and their damage during the war

We identified 7,219 greenhouses larger than 81 m^2 (equivalent to 3 × 3 PlanetScope pixels) present before the onset of war in October 2023. The average greenhouse size was 1,386 m^2, with a median size of 1,104 m^2. Most greenhouses were located in southern and central Gaza, with Khan Yunis having the highest number (2,708), followed by Rafah (2,603), and Deir al-Balah (1,257). Accuracy metrics indicate reliable identification of greenhouses, with an IoU of 0.91, Pixel Accuracy of 0.99, and a Dice Coefficient of 0.94.

We found that 58% of all greenhouses in the Gaza Strip had been damaged by September 2024. Similar to the damage to tree crops, there are significant spatial and temporal variations in the extent of greenhouse damage (Figs. 9 and 10)(). Overall, the most severe damage to greenhouses occurred during November and December 2023. In the early stages of the war, e.g., October–November 2023, greenhouses in North Gaza and Gaza City were primarily affected, while damage in the

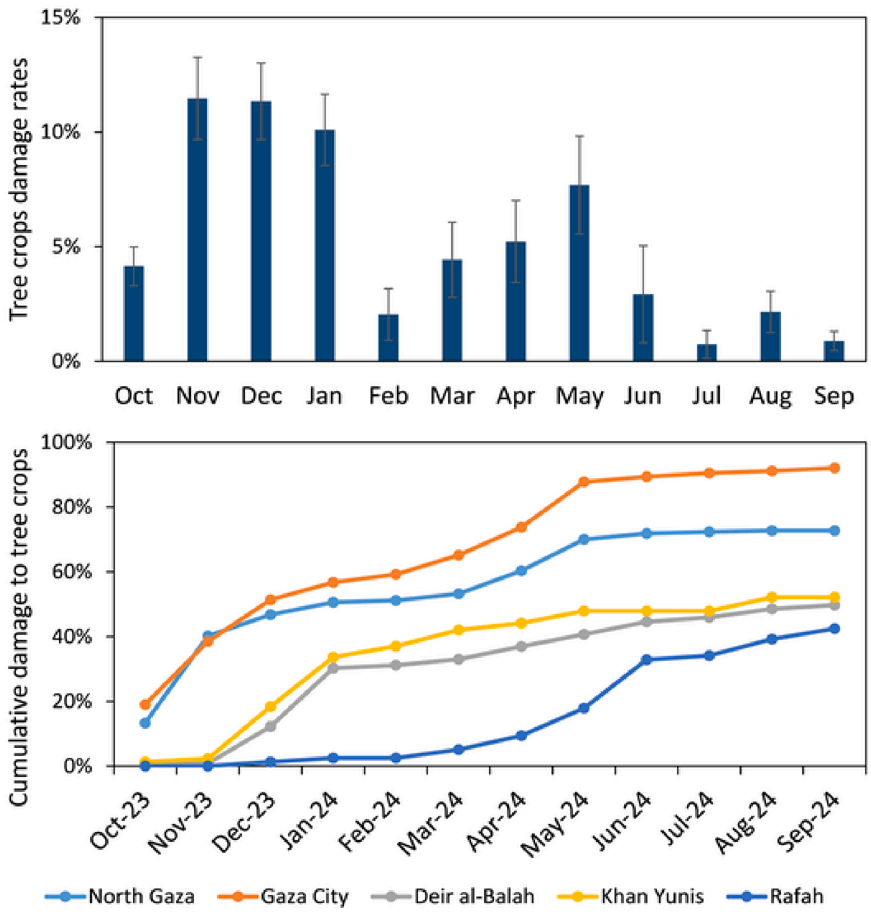

Fig. 7. Monthly rates of tree crop damage in the Gaza Strip (top) and cumulative damage per governorate (bottom) between October 2023 and September 2024.

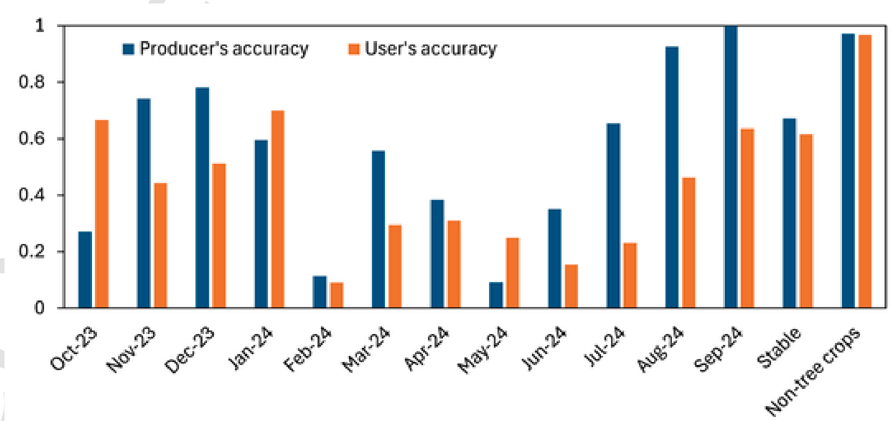

Fig. 8. Producer's accuracy (PA) and user's accuracy (UA) of the tree crop fields damage map.

three southern governorates began later. By the end of 2023, all greenhouses in North Gaza and Gaza City had been damaged. Since November 2023, greenhouse damage in the southern governorates has steadily increased. Unlike the damage to tree crops, the damage to greenhouses has continued to rise in recent months, especially in Rafah, which saw a significant increase in damage in September 2024 (Fig. 10).

The overall mapping accuracy of the greenhouse damage maps is 73%, with varying PA and UA across different damage classes (Fig. 11). The median PA and UA for the damage classes are 76% and 72%, respectively. Mapping accuracy improved when the monthly damage classes were aggregated into a single class, leading to an overall accuracy of 86% for the aggregated map.

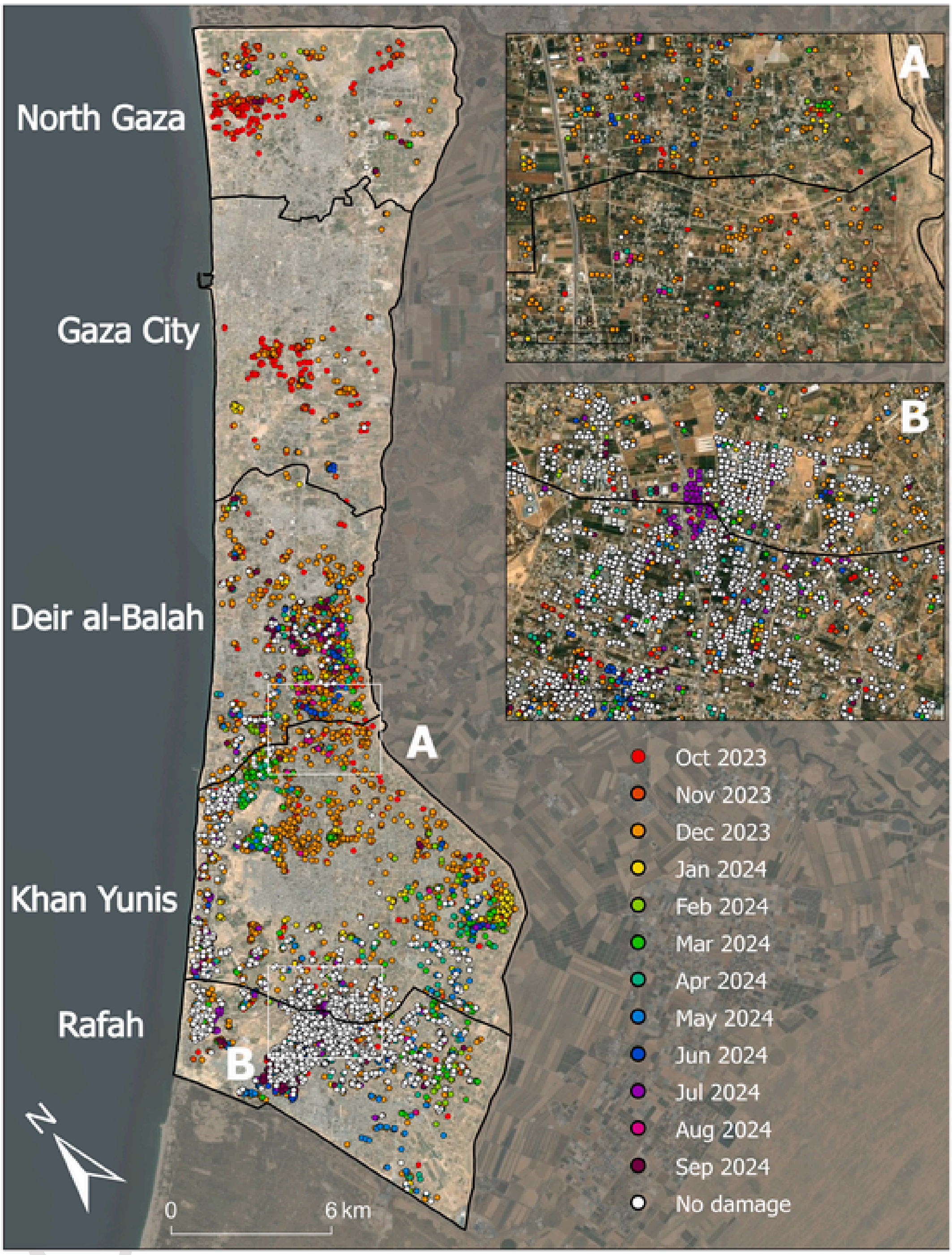

Fig. 9. Greenhouses and the date of initial damage in the Gaza Strip between October 2023 and September 2024.

3.3. Comparison with UNOSAT's maps and estimate

Our tree crop damage estimate (64–70%, 5,305–5,795 ha) is slightly lower than that from the UNOSAT, which estimated that 71% of orchards and other trees were damaged until September 1st, 2024. However, considerable disagreement exists in terms of the spatial distributions of the tree crops (Fig. 12). Of all damaged pixels both mapped in this study and from UNOSAT, only 39% of pixels shared the same month when damage first occurred. Using our 1,200 accuracy assessment samples (section 2.3.3), we examined the areas that had a disagreement and found that the UNOSAT map had a lower mapping accuracy (overall accuracy = 50%), with much lower mapping accuracy for specific months of damage (median PA and UA of 0.2).

In terms of greenhouse damage, UNOSAT's product detected a lower amount of damage (44%) compared to our estimate (58%). However, it is important to note that the definition of greenhouse damage used in UNOSAT's product is unclear. When examining the damage at the governorate level, both UNOSAT's product and our study found that nearly all greenhouses in Gaza City were damaged.

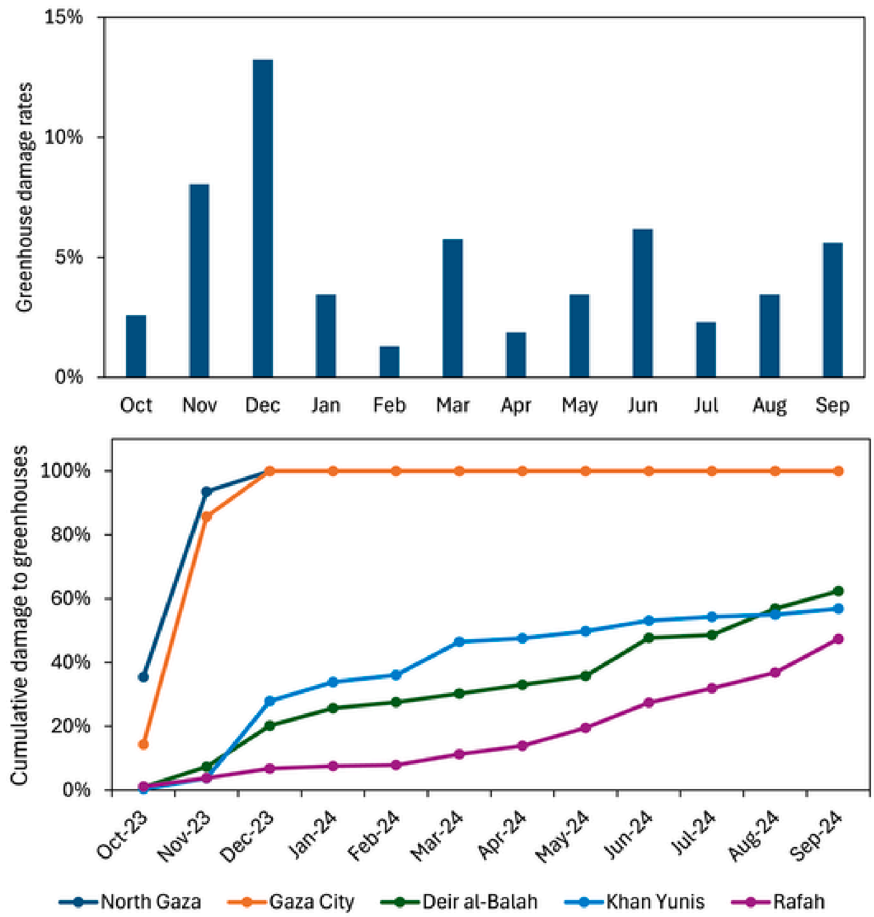

Fig. 10. The rates of greenhouse crop damage in the Gaza Strip (top) and cumulative damage per governorate (bottom) between October 2023 and September 2024.

4. Discussion

4.1. Mapping damages to tree crops and greenhouses

In this study, we utilized VHR imagery from PlanetScope and SkySat to map pre-war distributions of tree crop fields and greenhouses in the Gaza Strip, as well as assess the damage sustained during the conflict. The choice of these data sources was well-suited to the Gaza Strip's fragmented and diverse landscape. Given the ongoing conflict, producing near real-time estimates of damage is crucial for raising awareness of the war's impacts. PlanetScope's daily observations demonstrated their potential for near real-time monitoring, consistent with other applications, particularly in forest monitoring (Francini et al., 2020; Keay et al., 2023).

Our damage assessment of tree crops achieved an overall accuracy of 88%, though errors persisted in detecting the timing of the damage. This was primarily due to several factors. First, the diversity of tree crops and their varying management practices pose challenges to their mapping. In the drier areas, such as Rafah, more sparse and shorter trees resulted in spectral reflectance dominated by bare soil, making detection difficult. Similarly, young or newly planted orchards are difficult to map. Incorporating texture information from PlanetScope imagery with deep learning models, may improve the accuracy of tree crop mapping (Lin et al., 2021). Second, the rainy season and ongoing conflict limited clear-sky satellite observations. Although PlanetScope provides daily imagery, frequent clouds during the Mediterranean winter created data gaps even for weeks. Additionally, frequent black smoke from war-related fires further obstructed imagery. Despite our efforts to remove contaminated pixels, it remains difficult to mask out all types of smoke, leading to false positives, especially when observation opportunities are limited. Using SAR imagery, such as commercial VHR X-band data, could help overcome these challenges.

For greenhouse mapping, we achieved reliable results by leveraging both SkySat and PlanetScope imagery, with an IoU of 0.91, Pixel Accuracy of 0.99, and a Dice Coefficient of 0.94. While other deep learning algorithms exist, we chose the SAM model due to its minimal input requirements. Alternative encoder-decoder structure models, such as U-Net (Chen et al., 2021), ResNet (Li et al., 2022), and EGENet (Chen et al., 2023) may also support reliable monitoring of greenhouses. Further improvement of the SAM model for greenhouse detection could involve using a few examples as prompts, though we did not collect additional prompts as our land cover maps already reliably labeled the segments, with accuracy assessments validating the robustness of our approach. Our map showed more commission than omission errors, largely due to the wide variety of materials used for greenhouse coverings, ranging from dark to light colors, which caused confusion with other objects with similar colors and shapes. While we applied a minimum spatial filter to remove small objects, this also excluded small and narrow greenhouses.

Our damage assessment for greenhouses was also reliable, with median PA and UA for damage classes at 76% and 72%, respectively. However, unique challenges existed for greenhouse damage mapping. For example, variations in management practices occasionally led to misidentifications, such as greenhouses that had temporary rooftop lift-

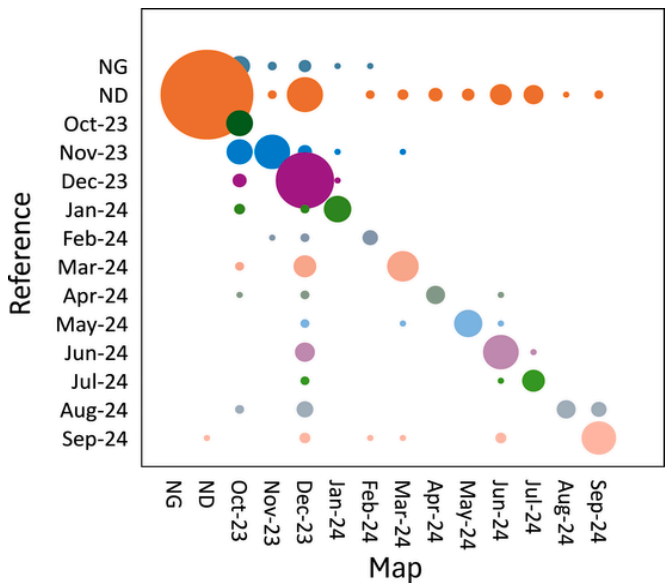

Fig. 11. Error matrix for greenhouse damage mapping. Categories include NG (non-greenhouses), ND (undamaged greenhouses), and specific months indicating the timing of the damage. For example, Oct-23 refers to greenhouses that were first damaged in October 2023. Larger dot sizes represent larger sample sizes.

ing, which was falsely classified as damage. Although it is not common, such false positives occur. Shadows cast by surrounding buildings or trees also caused false positives, and PlanetScope's 3-m resolution presented additional challenges due to its coarseness and potential geometric errors. While SkySat could provide better resolution for damage mapping, it is not feasible to obtain SkySat imagery covering the entire Gaza Strip at a daily interval. Leveraging other commercial data, such as WorldView imagery from Maxar may improve damage mapping, yet the cost of such commercial imagery limits its applications.

Our estimate of tree crop damage (64–70%) closely aligns with UNOSAT's estimate (71%), regarding the overall rate of damage. However, we observed significant differences in the spatial and temporal distribution of damages, with only 39% of pixels matching the exact month when the damage first occurred. The reasons for these discrepancies are difficult to pinpoint, especially given the lack of detailed documentation on UNOSAT's methodology, but the coarser resolution of Sentinel-2 imagery may be a contributing factor. Additionally, UNOSAT's product grouped tree crops with other trees or shrubs, while our analysis focused on tree crops only. In addition, the area estimates from UNOSAT were - to the best of our knowledge - based on pixel-counting, whereas we employed a sampling-based approach to rectify errors in the map. We therefore advise caution against using unvalidated maps for area estimates, as recommended by established guidelines (Olofsson et al., 2014; Stehman and Foody, 2019). Similarly, we observed more greenhouse damage (58%) than UNOSAT (44%). This discrepancy could be due to differences in the definition of “damage" and the time period covered (UNOSAT's estimate extends until September 1st, while ours extends until September 27th). Despite these differences, both UNOSAT's estimate and ours highlight the severe damage to agricultural land in the Gaza Strip.

Although this study focuses on the Gaza Strip, it also provides a framework for assessing war-induced damages to agricultural lands in other conflict-affected regions, particularly in the Global South, where agricultural plots are often fragmented (Lesiv et al., 2019). Additionally, the use of daily PlanetScope imagery may facilitate the monitoring of agricultural land with short growing seasons, particularly in regions such as Africa, where the growing season may last only a few months (Vrieling et al., 2013).

4.2. Implications

Our study estimates that 64–70% of tree crop fields have been damaged, significantly impacting food production in the region. The highest rates of damage in the North Gaza and Gaza City governorates occurred between October 2023 and January 2024, followed by similar trends in the Deir al-Balah and Khan Yunis governorates beginning in November 2023. Damage to tree crops in Rafah was observed at a slower pace, starting in February 2024 and accelerating from April through September 2024. The chronology is in line with the timeline of Israeli land incursions that proceeded north to south (Asi et al., 2024; Holail et al., 2024). The damage to tree crops has serious implications for food security and sustainable food production as olives and citruses are evergreen trees that can take 5–7 years to start becoming productive and up to 15 years to reach maturity (Sharkawi, 2020). This longer time for recovery of these tree species has a larger impact on ensuring the delivery of sustainable food systems when compared to the recovery of other damaged crops such as seasonal vegetables or grain crops. Furthermore, the majority of trees grown in the Gaza Strip are olive trees (PCBS, 2023a) and olive oil are traditionally and historically used as a high-value stored food for subsequent years and periods of poor harvest or economic and political instability (Meneley, 2011).

Regarding crops in the greenhouses, data from the 2022 Palestinian census (PCBS, 2023b) documents that a wide range of vegetables and soft fruits were cultivated in greenhouses and fields across the Gaza Strip, covering an area of 61,491.17 dunums (6149.12 ha or 61.49 km^2). Our study estimates that 58% of all structures supporting vegetables grown under plastic greenhouses in the Gaza Strip have been damaged, with total destruction reported in North Gaza and Gaza City. This has immediate and severe implications for food production, as this category represents an estimated 56.3% of the protected covers used for vegetable cultivation and 15.4% of the total area (including all forms of protected cover and open fields) utilized for growing vegetables (PCBS, 2023a).

Previous conflicts in the Gaza Strip have presented significant challenges to restoring agriculture. The UN estimated USD 449 million in damages to the agricultural sector during the 2014 conflict (UNDP, 2014), while the 2021 war resulted in substantial destruction of agricultural land as well. Yet, the level of destruction in the Gaza Strip since October 2023 is unprecedented, with overall estimated damages of USD 629 million until March 2024 (World BankUNEU, 2024). Targeted destruction of water wells and irrigation networks has had lasting effects on crop yields, and soil degradation and contamination have further impeded recovery. Additionally, the ongoing risk of unexploded ordnance threatens farmers' access to their land, delaying the resumption of agricultural activities.

Our study not only provides timely information to the international community about the ongoing war in the Gaza Strip but also enhances understanding of how armed conflict disrupts local food systems. The findings can directly inform recovery policies by identifying priority areas for rehabilitation, including severely damaged farmland and agricultural infrastructure. Notably, infrastructure near damaged farms is likely to have sustained collateral damage (Fig. 4; Supplementary file, Figure S2), further compounding the challenges faced by the agricultural sector (Hoeffler, 1998). The results also highlight the need for targeted investments in rebuilding water management systems, restoring soil health, and providing technical support to farmers for reconstruction. Additionally, our analysis can guide efforts to safely clear unexploded ordnance, enabling farmers to regain access to their land and resume agricultural activities (Duncan et al., 2023). By providing accurate and timely data, our study supports evidence-based decision-making and helps international organizations, governments, and hu-

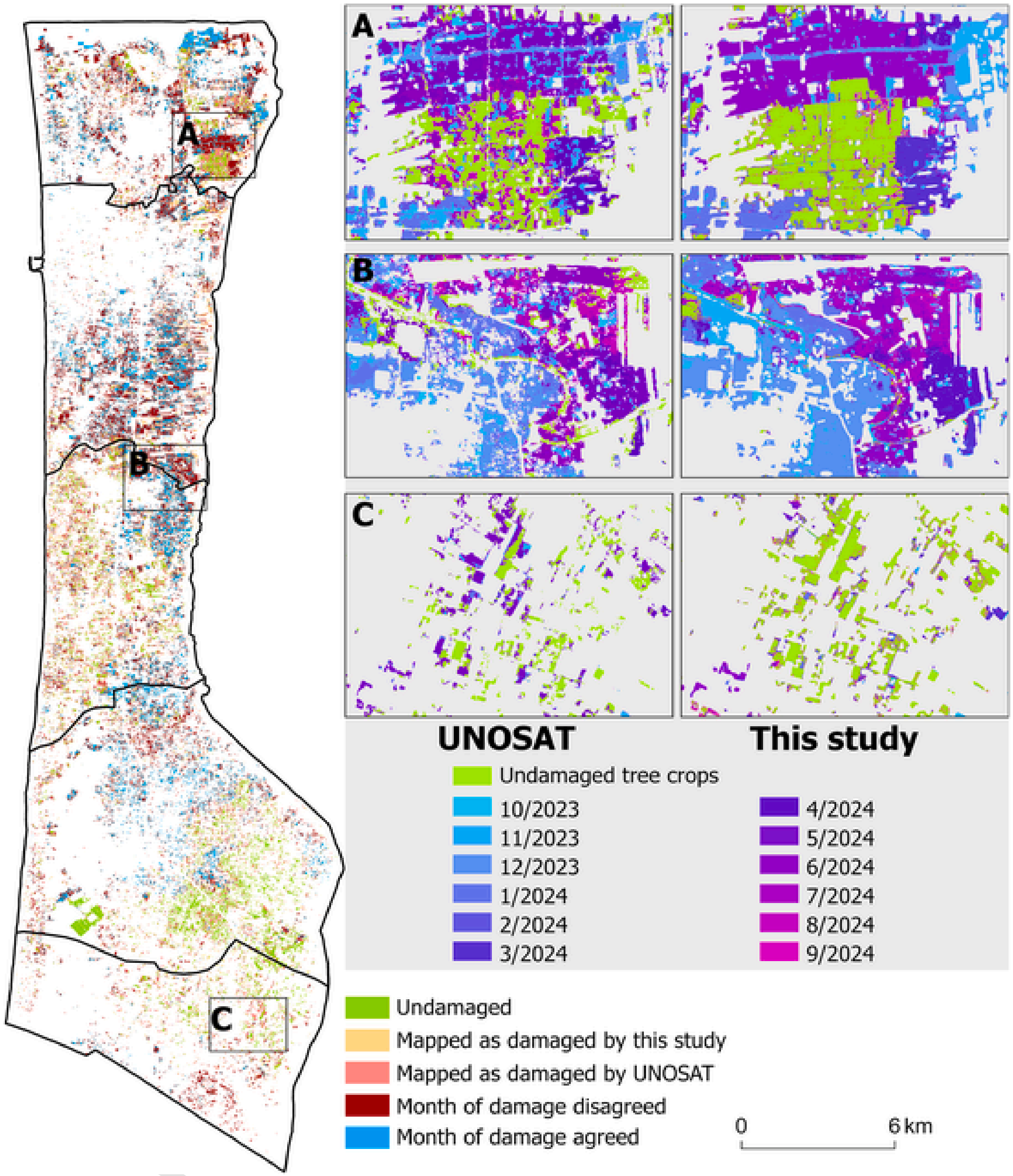

Fig. 12. Comparison of tree crop damage mapped in this study and the damage mapped by UNOSAT.

manitarian agencies prioritize interventions that support rebuilding Gaza's agricultural sector.

CRediT authorship contribution statement

He Yin: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Lina Eklund:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Dimah Habash:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Mazin B. Qumsiyeh:** Writing – review & editing, Writing – original draft, Resources, Investigation. **Jamon Van Den Hoek:** Writing – review & editing, Writing – original draft, Resources, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: He Yin reports financial support was provided by Kent State University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.srs.2025.100199.

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