Ukraine's Crop Storage Infrastructure: Post-Invasion Impact Assessment

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Yale SCHOOL OF PUBLIC HEALTH
Humanitarian Research Lab

OAK RIDGE National Laboratory

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EXECUTIVE SUMMARY

The Yale School of Public Health's (YSPH) Humanitarian Research Lab (HRL), working in collaboration with the Department of Energy's Oak Ridge National Laboratory (ORNL), concludes with high confidence that approximately 14.57% of Ukraine's estimated 58 million tonnes[1] of crop storage capacity has been impacted by conflict since Russia's full-scale invasion of Ukraine in February 2022. One in six (15.73%) crop storage facilities has been impacted by the war since 24 February 2022. Intentional and indiscriminate targeting of crop storage infrastructure can constitute a war crime and a crime against humanity under international law.

This assessment determines that Russia and its aligned forces controlled approximately 6.24 million tonnes of Ukraine's crop storage capacity as of July 2022 regardless of damage.[2] Furthermore, 2.25 million damaged tonnes pertained to 48 damaged facilities within territory under Ukrainian control as of July 2022 and 0.82 million damaged tonnes pertain to 27 damaged facilities under Russian control as of the same date. Therefore, in both Ukraine-controlled and Russia-controlled territories, at least 3.07 million metric tonnes of storage capacity have been destroyed or visibly damaged since 24 February 2022. These damaged facilities constitute at least 5.36% of Ukraine's pre-war crop storage capacity nationwide. This assessment determines a minimum extent of impact to Ukraine's crop storage capacity.

The assessment also concludes that at least 60 of the 75 facilities (80%) identified as damage-affected are found at port facilities or within less than one kilometer of a railroad. In some cases, certain facilities are located next to railroad tracks at port facilities. Further analysis is required to draw any definitive conclusions about why the overwhelming majority of damage-affected facilities identified by this assessment are co-located with critical transportation infrastructure. Regardless, the finding is significant. Proximity to transportation infrastructure should be considered relevant to any future analysis of visibly damaged crop storage facilities attempting to a) differentiate between damage from indiscriminate or intentional targeting of these facilities; and b) attempting to determine whether strikes on these facilities are occurring as part of a larger command-directed campaign of attacks on crop storage facilities by Russia and its proxies.

This assessment represents the first study to remotely evaluate a substantial sample of crop storage facilities through the analysis of recently collected very high resolution (VHR) commercial satellite imagery. The primary methodology for this assessment is change detection analysis of crop storage facilities determined to likely have been in range of bombardment from Russia-aligned ground forces since February 2022. The change detection analysis was supported by the collection and review of open source

[1] N.B. This report uses metric tonnes. One metric tonne equals 1,000 kilograms, or 2,240 pounds. This is distinct from the American ton, which is 907.1847 kilograms, or 2,000 pounds.
[2] This assessment was largely conducted in July and August 2022. The line of control used was provided by Janes and reflects their analysis as of July 26, 2022. Territorial gains made by Ukraine since September 1, 2022 are not reflected in this assessment.

data relevant to alleged attacks on these facilities. A custom-built object detection machine learning model was built and deployed by Oak Ridge National Laboratory as part of this study to support the identification of facilities.

The findings presented by this assessment are deemed high confidence due to the following five factors: 1) access to a 2019 dataset identifying all certified crop storage facilities nationwide; 2) application of a conservative damage scale to account for pre-existing dilapidation present at many crop storage facilities, as well as the presence of other confounding factors, such as conflict-related damage preceding the February 2022 invasion; 3) ability to collect recent VHR imagery of targets within the most areas affected by the conflict since 24 February 2022; 4) deployment of a target-tailored object detection machine learning model to capture facilities not included in the 2019 dataset; and 5) robust cross-corroboration of apparently damaged facilities with a diverse area of open source data where available.

I. ASSESSMENT CONTEXT, TARGETS, AND DESIGN

a) Assessment context

Millions of people around the world rely on Ukrainian agricultural products and are directly impacted by price spikes in global commodities markets caused by shortages linked to Russia's invasion of Ukraine. Ukraine was the world's fifth largest exporter of wheat in the world prior to the full-scale invasion by Russia on 24 February 2022.[3] The UN Food and Agriculture Organization (FAO) estimates that Ukraine accounted for 16% of the world's corn exports and 40% of the world's sunflower oil.[4]

The World Food Program (WFP) relies on Ukraine for as much as 40% of the wheat it uses to provide emergency nutrition to the world's most vulnerable people.[5] Since Russia's 24 February invasion of Ukraine, the price of wheat in Africa has risen by 45%, according to the African Development Bank.[6] The FAO's Food Price Index has been at record high levels for most of 2022, exacerbated by prior effects from COVID-19-affected supply chain challenges and climate change-driven crop losses.[7]

Much attention has been paid to the limited exports of agricultural and other commodities from Ukrainian ports due to wartime activities including blockades and mining – one trigger for the price inflation referenced above. A recent UN-brokered deal has helped move some shipments.[8] However, Russia and Russia-aligned forces' damage and seizure of Ukrainian crop storage capacity threatens to turn Ukraine's current agricultural crisis into catastrophe. Farmers are now running out of room to store crops due to attacks on storage facilities, as well as the continuing backlog in exports due to blockages at port.[9] Insufficient storage could interrupt or severely limit

[3] The Observatory of Economic Complexity. "Wheat in Ukraine." https://archive.ph/FznRF.Accessed September 7, 2022. https://oec.world/en/profile/bilateral-product/wheat/reporter/ukr.
[4] The Food and Agriculture Organization of the United Nations. "The Importance of Ukraine and the Russian Federation for Global Agricultural Markets and the Risks Associated with the War in Ukraine," 2022. https://archive.ph/9Fz5l. https://www.fao.org/3/cb9013en/cb9013en.pdf
[5] Harter, Fred. "'Marching towards Starvation': UN Warns of Hell on Earth If Ukraine War Goes On." *The Guardian*, June 17, 2022, sec. Global development. https://archive.ph/yLfwQ. https://www.theguardian.com/global-development/2022/jun/17/united-nations-wfp-hell-on-earth-ukraine-war-russia.
[6] African Development Bank. "African Development Bank Board Approves $1.5 Billion Facility to Avert Food Crisis," May 20, 2022. https://archive.ph/3bROj. https://www.afdb.org/en/news-and-events/press-releases/african-development-bank-board-approves-15-billion-facility-avert-food-crisis-51716.
[7] The Food and Agriculture Organization of the United Nations. "FAO Food Price Index Drops for the Fifth Consecutive Month in August." https://archive.ph/avvDm. Accessed September 7, 2022. https://www.fao.org/worldfoodsituation/foodpricesindex/en/.
[8] Reuters. "Grain Exports from Ukraine Helping to Push Prices down -U.N. Spokesperson," September 7, 2022, sec. European Markets. https://archive.ph/wip/pLPWR Accessed 9 September, 2022. https://www.reuters.com/markets/europe/grain-exports-ukraine-helping-push-prices-down-un-spokesperson-2022-09-07/.
[9] Balmforth, Tom, and Pavel Polityuk. "Ukraine Grain Storage Crisis Hits Home as Farmers Harvest New Crops." *Reuters*, July 19, 2022, sec. Commodities. https://archive.ph/IcvkF. https://www.reuters.com/markets/commodities/ukraine-grain-storage-crisis-hits-home-farmers-harvest-new-crops-2022-07-19/.

the next planting cycle, including winter wheat, which is the majority of Ukraine's wheat crop.[10]

The destruction of these facilities may constitute a war crime and a crime against humanity.[11] Intentional destruction of agricultural infrastructure may constitute a violation of Article 54(2) of the 1977 Additional Protocol I to the Geneva Conventions of 1949. The article states:

It is prohibited to attack, destroy, remove, or render useless objects indispensable to the survival of the civilian population, such as foodstuffs, agricultural areas for the production of foodstuffs, crops, livestock, drinking water installations and supplies and irrigation works, for the specific purpose of denying them for their sustenance value to the civilian population or to the adverse Party, whatever the motive, whether in order to starve out civilians, to cause them to move away, or for any other motive.[12]

b) Assessment targets

Russia-aligned forces have allegedly been damaging and destroying Ukraine's crop storage facilities since the full-scale war began on 24 February. Silos, crop elevators, grain bins, and other critical crop storage infrastructure have been visibly damaged from multiple weapons systems, including artillery, long-range missiles, aerially-dropped ordnance, and other munitions.[13]

These crop storage facilities range from large industrial complexes with footprints of several acres to smallholder family farms with only a silo and a few outbuildings visible. Crop storage in Ukraine includes both cylindrical storage, which can range from a single silo-shaped grain bin to massive elevator facilities, to rectangular warehouse-shaped facilities in both industrial warehouses and in barn buildings. Depending on the scale and functionality of the operation, silo installations may contain a range of silos between one and approximately 30 structures. Similarly, elevator morphology ranged from modest single-story warehouses to large multi-story and multi-building complexes.

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[10] United States Department of Agriculture. "Commodity Intelligence Report" https://archive.ph/MhQX9 Accessed September 7, 2022. https://ipad.fas.usda.gov/highlights/2020/01/ukraine/index.pdf. McCullough, Chris. "Vital Ukrainian Harvest in Jeopardy." AgUpdate. https://archive.ph/X3Q98. Accessed September 7, 2022. https://www.agupdate.com/agriview/news/business/vital-ukrainian-harvest-in-jeopardy/article_f1264f05-b7dd-51ed-ab8c-441dc38a61b2.html.

[11] UN General Assembly, Rome Statute of the International Criminal Court (last amended 2010), 17 July 1998, ISBN No. 92-9227-227-6, available at: https://www.refworld.org/docid/3ae6b3a84.html https://archive.ph/wip/sA5UA [accessed 7 September 2022]

[12] International Committee of the Red Cross (ICRC), Geneva Convention Relative to the Protection of Civilian Persons in Time of War (Fourth Geneva Convention), 12 August 1949, 75 UNTS 287, https://archive.ph/IjDbe available at: https://www.refworld.org/docid/3ae6b36d2.html [accessed 7 September 2022]

[13] Holland, Steve, and Michelle Nichols. "EXCLUSIVE-Photos Show Russian Attacks on Ukraine Grain Storage - U.S. Official." *Reuters*, April 1, 2022, sec. World. https://archive.ph/PTWaq. https://www.reuters.com/world/exclusive-photos-show-russian-attacks-ukraine-grain-storage-us-official-2022-04-01/.

1.A. 241k tonne capacity shipping facility ©2022 Maxar Technologies 1.B. 9.5k tonne capacity rural crop facility ©2020 Maxar Technologies

1.C. 50k tonne capacity shipping facility ©2021 Maxar Technologies 1.D.150k tonne capacity rural crop facility ©2022 Maxar Technologies

Figure 1. *Examples of crop facility morphology.*

Fig.1.A 241 tonne capacity shipping facility Brooklyn-Kyiv-ZPK[14] in Odesa oblast.
Fig.1.B 9.5 tonne capacity rural operation Safety SFH in Donetsk oblast.
Fig.1.C Prometeus Artsyz Elevators, a 50k tonne capacity facility in Odesa oblast.
Fig.1.D. Zhelev SS and the Kamysh-Zaryansky Elevator Company, a 150k tonne facility in Zaporizhzhya oblast.

Crop storage facilities can hold one crop, such as wheat, or contain multiple crops at one time in separate sub-containers. The crops stored at a facility will often change depending on the season. Additional structures may also be present at some of these facilities, including barns and coops for livestock. Some of these installations have fermenting, milling, and drying apparatuses for creating derived products, such as oils and flours. Some of these structures are highly susceptible to damage from

[14] Note: Names come from a 2019 dataset of certified crop storage locations scraped from Elevatorist.com. Grain facilities and the Elevatorist dataset entries often abbreviate sections of facility names.

bombardment. Silos, for example, are made from aluminum and can be easily perforated by shrapnel and other debris.

It is critical to note that any damage to these facilities, even if the buildings are still utilizable, can result in crop loss. Crops must be cleaned and stored under a specific range of temperature and moisture parameters.[15] Crop storage must be able to keep crops dry, maintain uniform temperature, and prevent insects and other pests such as birds and rodents from accessing the crop.[16] Therefore, crop storage facilities must maintain sufficient ventilation, insulation, moisture and temperature controls, space, and cleanliness to store crops safely.[17] An increase in temperature or moisture content beyond the optimal levels will reduce safe storage time and increase the rate of crop spoilage.[18] Specific grains, seeds, and certain processed oils need to be stored at specific moisture percentages ranging from 8% (oil sunflowers) to 13.5% (wheat and corn).[19] Thus even minor damage to the exterior walls, power connectivity, and drying apparatuses can render an entire storehouse of crops unsellable at market despite primary structures appearing largely intact.

Yale HRL, working with its partners at the Conflict Observatory and ORNL, saw an urgent need in late June 2022 for a comprehensive damage assessment to Ukraine's crop storage infrastructure located in the areas most affected by Russia's invasion. The Yale HRL research team established a list of targets comprising all elevators in Ukraine prior to the February 24 invasion. A 2019 dataset of certified crop storage locations scraped from the Elevatorist website by the US Department of Agriculture, now no longer publicly available, provided the locations of at least 1,377 crop storage facilities. The object detection machine learning model ORNL custom built and tested in collaboration with HRL enabled the assessment team to rapidly detect potential facilities not included in the Elevatorist dataset. This machine learning model detected 19 additional crop storage facilities, increasing the total to 1,396 facilities. The additional facilities identified by ORNL are included in the overall estimation of storage capacity and damages.[20] The machine learning model methodology is described in Section III. Finally, three (3) sites were identified through verified open source reporting that were not included in either the Elevatorist or ORNL datasets and cross-corroborated with geospatial imagery. Therefore, the grand total of crop storage facilities in Ukraine targeted for this assessment is 1399.

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[15] Food and Agriculture Organization of the United Nations, "Grain Crop Drying, Handling and Storage." In *Rural Structures in the Tropics*, 363, 2011.https://archive.ph/YWiDV https://www.fao.org/3/i2433e/i2433e10.pdf.
[16] *Ibid* 375
[17] *Ibid*. 380
[18] North Dakota State University Agriculture. "Approximate" Allowable Storage Time for Cereal Grains," n.d. https://archive.ph/OADoq https://www.ag.ndsu.edu/graindrying/documents/Allowable%20Storage%20Time%20Cereals.pdf.
[19] North Dakota State University Agriculture. "Keep Stored Grain Cool, Dry During Summer," June 28, 2021. https://archive.ph/0NQso. https://www.ag.ndsu.edu:8000/agriculture/ag-hub/ag-topics/crop-production/drying-storage/keep-stored-grain-cool-dry-during-summer.
[20] To estimate storage capacity for all 19 crop facilities identified by ORNL, HRL analysts performed a median imputation on these facilities with the median value of Elevatorist capacity. This imputed value was 29.2 thousand metric tonnes. Median imputation was chosen due to skewness in the data.

c) Assessment design

This assessment's intended purpose is to provide policymakers, international agencies, donor governments, and, most importantly, the Ukrainian agriculture industry as detailed an accounting as possible of the damage done to Ukraine's crop storage capacity. This assessment is also intended to support future efforts to hold alleged perpetrators accountable for attacks on these facilities that may have occurred in violation of international and Ukrainian domestic law.

Over an approximately ten-week period, Yale HRL and its partners worked to observe as many of Ukraine's crop storage complexes as possible in the areas most affected by the war. The goal of the observation was to assess whether the storage complexes sustained visible damage since 24 February 2022. Given the size of Ukraine, Europe's second largest country, an Area of Interest (AOI) was designated to narrow the number of facilities and geographic area that required the collection of recent imagery. The AOI was limited to only include the regions within Ukraine most likely affected by bombardment from Russia-aligned ground forces since the invasion. The AOI was then used to determine which facilities in Ukraine would be initially targeted for this assessment.

The AOI has three components. The first component of the AOI consists of Ukraine-controlled territory within 120 km of the line of contact with Russia-controlled territory as of July 2022. Because Russia and Russia-aligned forces had previously controlled territory in the north, a second component to the AOI was included in the north. This second component consists of Ukraine-controlled territory within 120 km of the line of control with Russia-controlled territory as of March 2022, at the height of Russia's territorial control in the north as of this report's publication. The AOI's third and final component consists of that northern territory which had been under Russia's control as of March 2022 but has since been reclaimed by Ukraine . With these three components combined, all of the territory in the AOI was controlled by Ukraine as of July 2022. Every facility within this AOI was reviewed for imagery availability and damage. Approximately half of all facilities identified within the AOI (344/694) had satellite imagery of sufficient visibility available for review.

Creation of the AOI allows each facility in the entirety of Ukraine to be classified as one of three categories: 1) within AOI; 2) within Russia's control as of July 2022; 3) not within AOI or Russia's control as of July 2022.

Open source information of any alleged attack on a crop storage facility was collected and translated. The open source information served two purposes: 1) support site prioritization for satellite imagery collection and 2) enable more accurate analysis of potential damage indicators. Open source information was also used to identify potential damage to facilities in Russia-controlled territory as of July 2022, as not every site in Russia-controlled territory was reviewed by geospatial analysts.

Commercial imagery was tasked for as many sites as possible within the AOI in the past six months. As new imagery was collected, the assessment team employed a two-part process for damage identification and ascertaining whether identified visible damage was related to the past six months of conflict (*See Section III for detailed methodology, including flowchart of two part process*). If the site passed the two part process, it was added to the tally of damage-affected facilities.

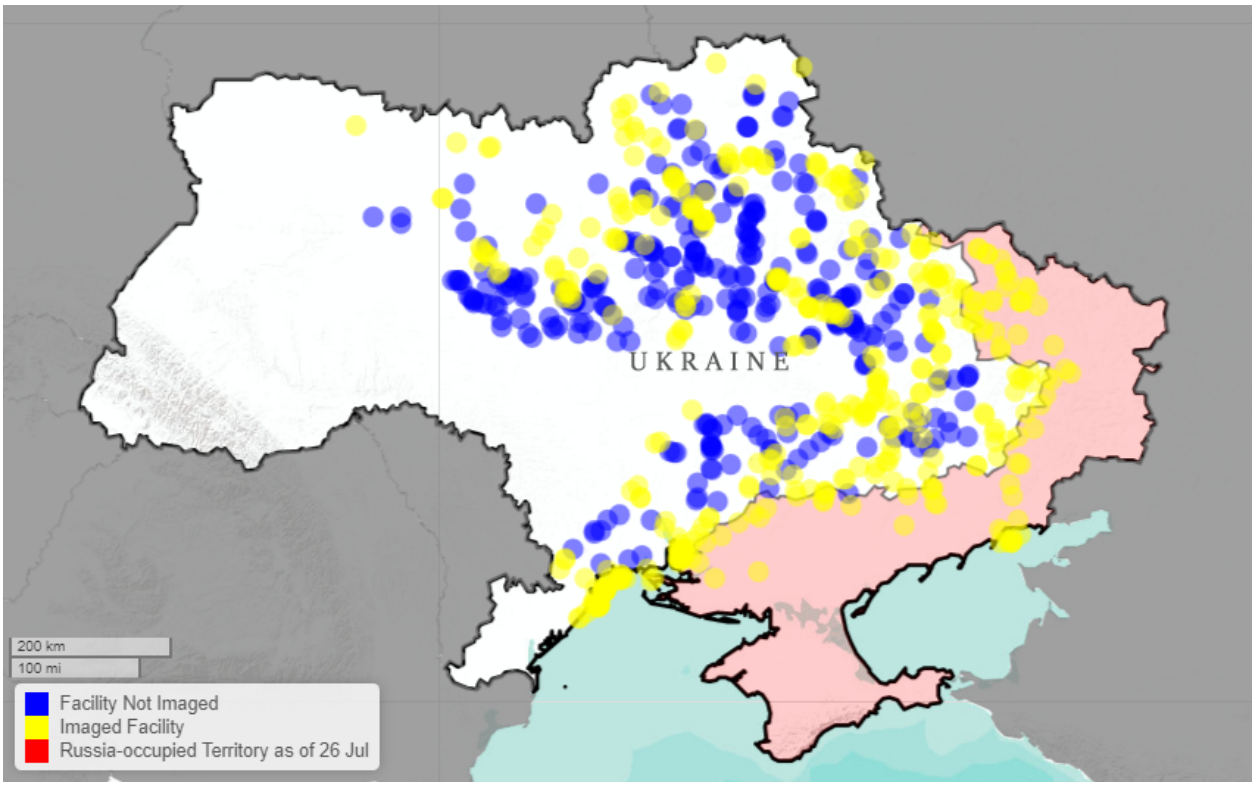

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Figure 2: *Post-Invasion Imagery Availability of Facilities.*

This illustration has been adjusted to obscure the precise geo coordinates of the facilities using a randomization tool. All facilities are located within Ukraine's territorial borders, including contested territory currently under occupation by Russia and its aligned forces.

II. SUMMARY OF KEY FINDINGS

a) 8.49 million tonnes of storage capacity impacted by conflict

At least 8,488,650 tonnes of Ukraine's total national storage capacity have been impacted by Russia's invasion of Ukraine in February 2022. Prior to Russia's invasion, Ukraine had an estimated 58 million tonnes of storage capacity, according to the Elevatorist dataset and ORNL's algorithmically identified additional facilities. That number is now 49.8 million tonnes or less, according to this assessment.

This reduction in capacity (8.49 million tonnes impacted) is the combination of the amount of storage capacity damaged in areas under Ukrainian control within the AOI and the storage capacity lost to Russia's control of Ukrainian territory as of July 2022. This figure represents approximately 14.57% of Ukraine's pre-invasion storage capacity. The volume of storage capacity pertaining to damaged facilities within the AOI is 2.25 million tonnes, and the volume of storage under Russia's control as of July 2022 is 6.24 million tonnes. Therefore, of the crop storage in tonnage impacted by conflict, three-quarters of that tonnage has been by Russia-aligned forces while just over one quarter has sustained damage.

Table 1: *Impacted storage capacity in million metric tonnes (rounded)*

Location category as of July 2022	Pre-war storage capacity	Impacted storage capacity	Remaining storage capacity	Percent of pre-war storage capacity impacted
Under Russia's control	6.24	6.24 (in RU control)	0.00	100.00%
In AOI	30.84	2.25 (damaged)	28.59	7.35%
*Elsewhere in Ukraine *(not assessed for damage)*	*21.18*	*0.00**	*19.30**	*0.00%*
Total	58.26	8.49	49.80	14.57%

It is important to note that around only 50,000 tonnes of storage capacity were likely under control of Russia-aligned forces after 2014 and before February 2022 (i.e., in Russia-backed so-called Donetsk People's Republic or Luhansk People's Republic). Thus, nearly 6.24 million tonnes of storage capacity have been captured by Russia as of July 26, which is approximately 10.7% of Ukraine's pre-war national storage capacity as calculated with Elevatorist and ORNL data. Territorial control of facilities determines export control and market access – when crop storage facilities are under the control of Russia and its proxies, the processing and storage capacity as well as any commodities stored within are lost to Ukrainian national production and exports.

b) 75 damage-affected facilities identified by assessment

The assessment identified 75 facilities within the borders of Ukraine as of February 24 as affected by damage caused by bombardment or other modes of combat occurring after 24 February 2022.[21] The 75 damage-affected facilities identified by this assessment account for at least 3.07 million tonnes of storage capacity, 0.82 million tonnes of which are in areas controlled by Russia and its proxies as of July 2022. The 3.07 million tonnes of storage capacity within these 75 damaged facilities alone represents over 5% of Ukraine's total national storage capacity prior to the full-scale invasion. Damaged facilities, whether they are in areas controlled by Ukraine or Russia and its proxies, are significant because they represent storage capacity which would need to be reconstructed to return to full pre-invasion capacity.

The assessment can generally attribute the overwhelming majority of the damage to Russia and its proxy forces due to when and where the imagery broadly indicates the attacks most probably occurred. The time and location windows represented in the available post-February 24 imagery generally align with Janes, Geographic Information Service ALCIS (section III.d) [22] and other non-imagery data sources showing that these locations were contemporaneously under attack by Russia's offensive.

This assessment does not attempt to identify what types of ordnance or weapons systems may have damaged each facility. Further analysis will be required to make determinations on platforms and material, though the visible damage at these facilities is broadly consistent with artillery, missile, and aerial bombardment in most cases. Also, this assessment was not able to rule out whether any incidents of "friendly fire" may have occurred at any of the damaged facilities.

[21] One facility in the original Elevatorist dataset was determined to be outside of Ukrainian control (in the Donbas region) prior to February 24, 2022 and was removed.
[22] Alcis. "Alcis." Accessed September 14, 2022. https://archive.ph/wip/4z7bx, https://www.alcis.org. For more information, please see Part III, Assessment Methodology, Challenges and Limitations, d) Identifying an Area of Interest.

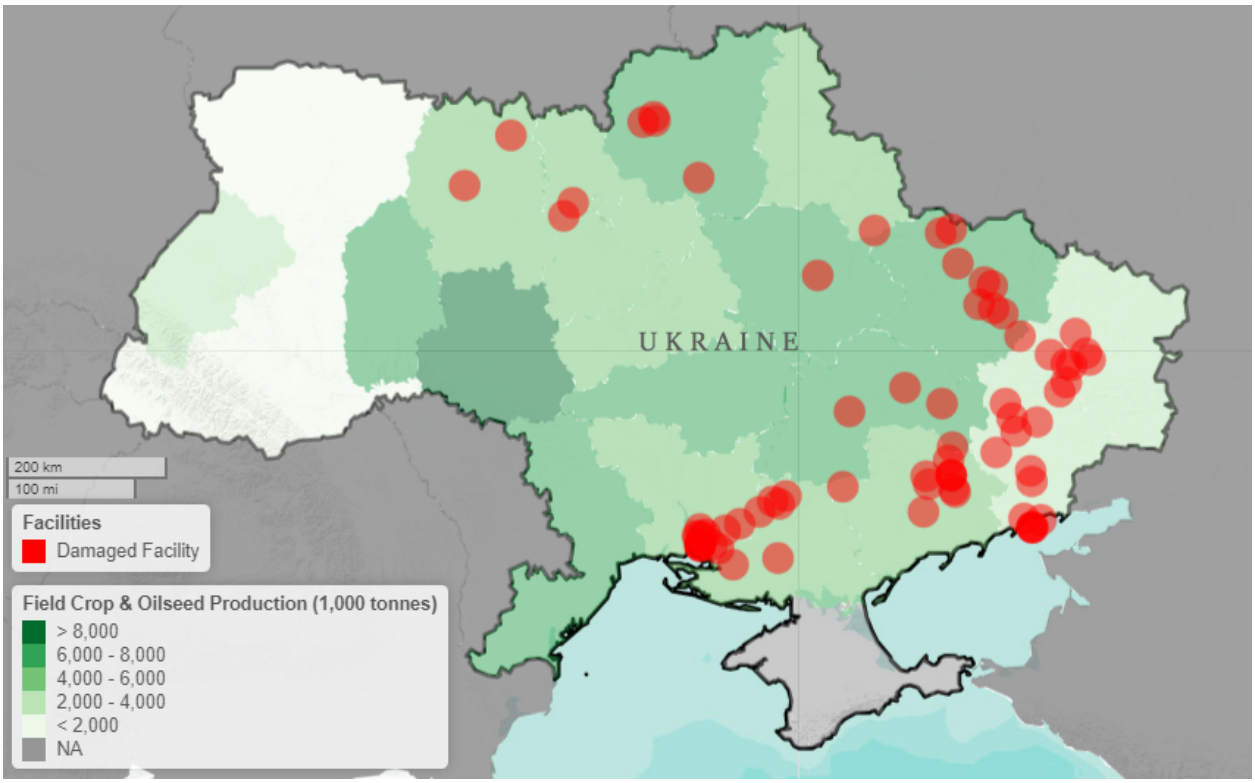

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Figure 3: *Damaged Facilities and Ukrainian Agricultural Production by Oblast.*[23] *This illustration has been adjusted to obscure the precise geo coordinates of the facilities using a randomization tool. All facilities are located within Ukraine's territorial borders, including contested territory currently under occupation by Russia and its aligned forces.*

c) Mykolayiv, Zaporizhzhya, and Donetsk oblasts have sustained the most damage to crop storage facilities

The three oblasts with the greatest amount of damage, both in terms of number of facilities and tonnage damaged, are Mykolayiv, Zaporizhzhya, and Donetsk, respectively. 40 of the 75 facilities that appear damage-affected are within these oblasts. The other 35 facilities assessed to be damaged are present across nine other oblasts. These other oblasts each had fewer than ten damaged facilities and fewer than 300,000 tonnes of affected storage capacity. It is important to note, however, that disparities in imagery collection across oblasts may have affected these totals. Not every facility in the Elevatorist dataset has adequate pre-invasion imagery, and until those that do are imaged post-invasion (as well as additional facilities identified by the ORNL machine learning model), these numbers should be considered preliminary results.

[23] The volume of production, yield and the area of agricultural crops collected by their species as of 01 December, 2021." State Statistics Service of Ukraine, 17 December 2021.

Table 2: Damaged Facilities by Oblast[24]

Oblast	Number of Facilities	Number of Facilities Assessed for Damage using Satellite Imagery	Number of Facilities Classified as Sustained Conflict-Affected Damage	Damaged Tonnage (million metric tonnes)
Total	1399	344	75	3.104
Donetsk	35	18	17	0.439
Mykolayiv	70	42	13	1.046
Zaporizhzhya	55	12	10	0.444
Kharkiv	87	32	9	0.300
Kherson	59	6	6	0.185
Chernihiv	74	41	4	0.135
Dnipropetrovsk	93	54	4	0.121
Luhansk	23	4	4	0.094
Kyiv	70	24	2	0.022
Poltava	109	27	2	0.159
Zhytomyr	54	14	2	0.111
Kirovohrad	98	0	1	0.030
Sumy	56	16	1	0.018
Cherkasy	62	8	0	0
Odesa	93	44	0	0
Vinnytsya	99	0	0	0
Rivne	28	1	0	0
Volyn	27	1	0	0
Other, no facility damage assessed	207	0	0	0

[24] N.B.: This report uses only the English name of place locations, as opposed to English and Ukrainian or English and Russian. English names are the variants provided by the 2021 Ukrainian census.

d) Majority of damaged facilities in close proximity to transportation infrastructure

The assessment team determined that 60 out of the 75 facilities (80%) identified as damaged through visual damage assessment were located along train routes, at shipping ports, or both. Of these facilities, two were algorithmically detected and 58 from the Elevatorist data. HRL found 49 visibly damaged facilities in close proximity to railways. Two smaller damaged facilities were found at small-sized shipping docks but did not connect to a railway. Nine other damaged facilities were located at major ports with rail access near the cities of Mykolayiv and Mariupol. Storage facilities near transportation infrastructure are especially critical parts of the production and export process, as they allow for preparation and movement of shipments.

The assessment team cannot conclude a potential reason for this correlation based on the available data analyzed to date. Hypotheses of future work could include that the high proportion of damage to crop storage facilities close to railroad and port infrastructure is the result of a) intentional targeting of transportation infrastructure by Russia-aligned forces that damaged crop storage infrastructure in the cross-fire; b) collateral damage due to indiscriminate shelling in areas where crop storage infrastructure and critical transportation infrastructure are co-located; c) intentional targeting of large scale crop storage infrastructure that tends to commonly be close to railways and ports; or d) a combination of these three hypotheses occurring at once.

Further study is required and, as previously mentioned in the executive summary, this finding should be seen as significant, regardless of the reason behind it being unknown. The potential pattern may have probative value in any investigation seeking to determine potential command responsibility for any targeting of crop storage facilities by Russia or as part of disambiguating between indiscriminate versus intentional targeting of facilities.

III. ASSESSMENT METHODOLOGY, CHALLENGES AND LIMITATIONS

a) Overview of methodology

This assessment was primarily conducted via analysis of remote sensing data. The primary methodology employed was multi-temporal change detection through analysis of very high resolution (VHR) satellite imagery. Multi-temporal change detection includes comparing and contrasting imagery across different points in time in order to capture changes and events and is a method for documenting features and changes in a landscape across time.[25] Yale HRL analysts compared imagery of crop storage facilities, including images captured both before and after Russia's full-scale invasion of Ukraine in February 2022 to determine if – and within which period – apparent damage had been sustained.

In some cases, pre-invasion baseline imagery was not available. OSINT reports of attacks allegedly occurring after Russia's invasion were used to inform analytic conclusions in these scenarios when possible. However, no crop storage facility was ever included in this assessment as damaged without at least one post-event image of that location being available to analysts.

Locations were primarily identified from one of two sources: the Elevatorist dataset or the use of an automated feature extraction classification machine learning model developed and custom built for this assessment by ORNL with Yale HRL. Section b below provides more details on both sources of data for ascertaining crop storage facility locations.

OSINT information about alleged attacks on crop storage facilities from social media, Ukrainian and Russian language media reports, and online videos proved essential in prioritizing which locations from either the Elevatorist or ORNL machine learning model datasets should be manually analyzed. The team utilized current best practice standards in open source geolocation consistent with training by the Human Rights Center at UC Berkeley School of Law, including the use of specific visual identifiers, building features, and other visually evident data (and available metadata) across multiple media sources to confirm the precise coordinates of a site and its function as a crop facility.[26]

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[25] Saira Khan, Isaac Baker, and Rob Baker, Nov. 2019. "Satellite Imagery Interpretation Guide of Landscape Features in Somaliland." Harvard Humanitarian Initiative, https://archive.ph/UGmbR https://hhi.harvard.edu/files/humanitarianinitiative/files/imagery_interpretation_guide.pdf?m=1612558570.

[26] UC Berkeley School of Law Human Rights Center. "Berkeley Protocol on Digital Open Source Investigations." https://perma.cc/3M8F-H98B. Accessed June 21, 2022. https://humanrights.berkeley.edu/resources/berkeley-protocol-digital-open-source-investigations; Aric Toler, 2020. "How to Verify and Authenticate User-generated Content," in Dubberley, Sam, Alexa Koenig, and Daragh Murray. *Digital Witness: Using Open Source Information for Human Rights Investigation, Documentation, and Accountability*. Oxford University Press, 2020, 185-227.

b) Identification of Crop Storage Facilities

Possible crop storage facilities were verified by HRL analysts from three data sources: the Elevatorist dataset, a machine learning model developed in partnership with ORNL, and compelling open-source information. Analysts located crop storage facilities in the Elevatorist dataset by confirming that the facilities identified at the Elevatorist's latitude and longitude coordinates matched visual indicators of crop storage facilities. The machine learning geolocation was conducted by visually inspecting geographic locations provided by ORNL for newly-identified crop storage facilities. For all methods, HRL analysts inspected the area for building structures typically associated with crop storage (i.e., vertical and cylindrical silos, and rectangular barn-like warehouse elevators) capable of various capacities. The morphology of warehouse elevators is somewhat homogenous with other storage facilities but was identifiable by the presence of temperature control units located on an end of a warehouse and sometimes between two warehouses. Conveyor systems across multiple buildings were also used to identify relevant facilities.

c) Imagery and non-imagery data sources

The VHR imagery used to support the damage assessments in this report was commercially available unclassified imagery captured by Maxar Technologies, Planet Labs PBC and BlackSky Global LLC. The imagery typically has a spatial resolution between 38 and 50 cm which allows analysts to identify changes to natural and manmade landscape features including individual buildings, vehicles, trees and more. In this case, the change being identified is potential damage to agricultural infrastructure, in particular grain silos, elevators, and other warehouses and storage facilities, primarily as a result of apparent bombardment.

The location of Ukrainian crop facilities was informed by two sources: the Elevatorist data set and through applying a machine learning model developed, tested, and run by ORNL (*See Subsection e "Machine learning model detection" for more)*. At the onset of the conflict, the Elevatorist's dataset of crop storage capacity including latitude and longitude was closed due to Ukrainian security concerns and removed from the internet. The now-publicly inaccessible data was shared with the Yale HRL team by the United States Department of Agriculture Foreign Agricultural Service (USDA FAS). A subsidiary of Latifundist Media, Elevatorist is a website that compiles information relevant to crops, agricultural production including a list of certified sites and subsequent storage capacity (approximately 76% of agricultural storage facilities in Ukraine,).[27] The Elevatorist data contains geographic coordinates, facility name, and storage capacity for 1378 crop and agricultural facilities across Ukraine capable of storing approximately 57.7 million tonnes. HRL analysts excluded one facility from the original dataset because it was located in the Donbas region in an area that had not been under Ukrainian government control prior to February 2022. The Elevatorist data was then filtered based on the area of interest, also referred to as an "AOI" by geospatial analysts, designated for this assessment (*See detailed description of AOI*

[27] Total capacity of simultaneous storage of cereals. leguminous and oil crops at enterprises engaged in their storage and processing and at enterprises directly growing them as of 1 January 2022." State Statistics Service of Ukraine, January 2022.

process below). The resulting subset of the original Elevatorist dataset contained 675 facilities with the capability of storing approximately 36.4 million tonnes.

OID_	latitude	longitude	id	OBJECTID	rank	url	name	capacity_t

Figure 4: *Description of Data in Elevatorist Dataset*

The types of data utilized in the Elevatorist data set include “latitude”, “longitude”, “url”, “name”, and “capacity_t”. Latitude and longitude were precise coordinate locations of respective storage facilities, url was a hyperlink to the storage facility’s Elevatorist webpage, name was the registered company name of the facility, and capacity_t was a record of the total storage capacity capability in 1,000 tonnes.

d) Additional detail on the Area of Interest (AOI) and line of control

Shapefiles of the respective Russia-controlled territory zones from July 2022 and March 2022 obtained from Janes were utilized in establishing the AOI.[28]

[28] Respective data layer dates: 26 July 2022 and 24 March 2022

Figure 5. *AOI Outside of Russia-controlled Territory.*

Facilities in the AOI, represented by blue points, are at most 120 km adjacent to territory under control of Russia-aligned forces as of July (east) or March (north) 2022. Mapped here are 674 crop facilities from the Elevatorist data with a total storage capacity of 30,284,000 tonnes.[29] Red area excluded from the AOI are areas currently believed to be the area of peak territorial control by Russia-aligned forces as of this report's publication. This illustration has been adjusted to obscure the precise geo coordinates of the facilities using a randomization tool. All facilities are located within Ukraine's territorial borders, including contested territory currently under occupation by Russia and its aligned forces.

HRL analysts estimated that the longest-range missile known to be deployed by Russia-aligned forces in this conflict to date can reliably reach targets 120 km from its point of origin. Therefore, the AOI for this analysis was set 120 km beyond the area of past and present control by Russia-aligned forces.[30] Additional sites beyond the defined 120 km radius were investigated when identified in available OSINT data, including news articles and open source text data harvested from social-media and messaging groups.

[29] As previously noted, ORNL's algorithm detected 17 additional facilities in the AOI with a combined capacity (from imputed median) of .50 million metric tonnes.

[30] Nair, Sunil. "Ukraine conflict: Russian forces employ guided rockets." Janes, 11 March 2022. https://archive.ph/iE9Fy https://www.janes.com/defence-news/news-detail/ukraine-conflict-russian-forces-employ-guided-rockets

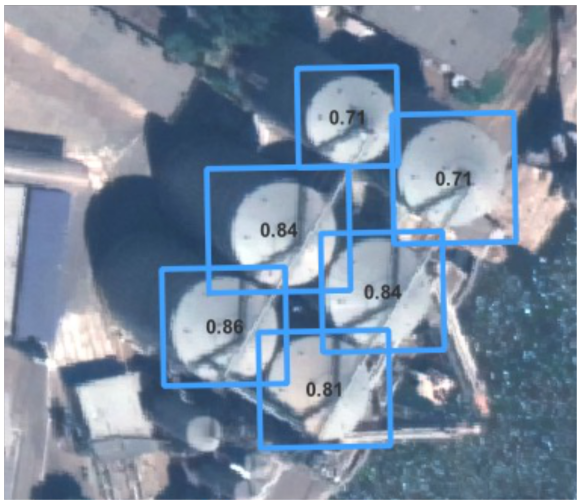
Additional sites outside the AOI, both within Russia-controlled areas in the east and in areas which have always remained under control of Ukraine, were identified through open source analysis. Satellite imagery for these sites was reviewed where it was available and damaged sites were tracked and added to the damage counts. Because there was not a comprehensive analysis of all facilities outside of the AOI, these additional sites are included in the secondary findings reported above (number of damaged facilities and damaged facilities by oblast). These numbers should be considered incomplete pending additional review.

This AOI of approximately 300,000 km^2 includes territory in 18 oblasts (Cherkasy, Chernihiv, Dnipropetrovsk, Donetsk, Kharkiv, Kyiv, Luhansk, Poltava, Rivne, Sumy, Vinnytsya, Volyn, Zhytomyr, Kherson, Kirovohrad, Mykolayiv, Odesa, and Zaporizhzhya) and includes 840 crop facilities, which were identified and analyzed for conflict related damage. Yale HRL analysts concluded that all storage capacity within conflict-affected areas were deemed lost due to evidence of Russia-installed authorities exporting stored crops out of the region.[31] Collectively, these Russia-controlled facilities account for 6.21 million tonnes in capacity of crop storage across 168 facilities, which is 10.66% of total Ukrainian crop storage.

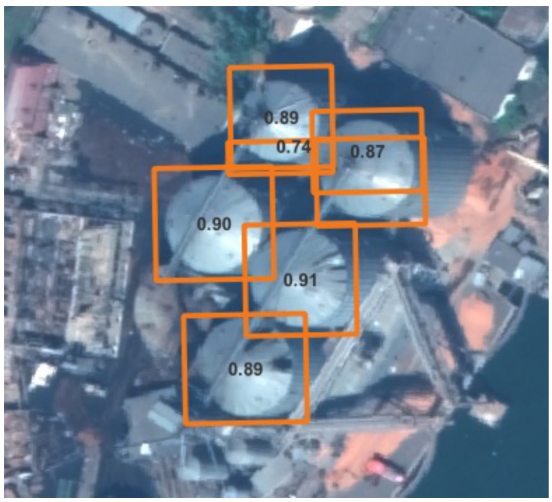
[31] Reuters. "Russia-Controlled Zaporizhzhia Says It's Exporting up to 7,000 T of Grain per Day," August 20, 2022, sec. Commodities. https://archive.ph/TaIP5. https://www.reuters.com/markets/commodities/russia-controlled-zaporizhzhia-says-its-exporting-up-7000-t-grain-per-day-2022-08-20/; Reuters. "Russian-Controlled Kherson Region in Ukraine Starts Grain Exports to Russia - TASS," May 30, 2022, sec. Commodities. https://archive.ph/8dNAt. https://www.reuters.com/markets/commodities/pro-moscow-kherson-region-starts-grain-exports-russia-tass-2022-05-30/.

e) Machine Learning Model Detection

A collaborative effort between Yale HRL and ORNL produced a fine-tuned model to detect additional facilities that were not included in the Elevatorist data set. To accomplish this task, ORNL researchers built a World View (WV) compatible model upon a baseline YOLOv5 model previously trained on Google Earth images by researchers at Yale HRL.



©2021 Maxar Technologies



©2022 Maxar Technologies

Figure 6a and 6b. *Examples of damaged structures at Elevatorist.*

Mariupol ICC Crop terminal identified through comparison of pre-event and post-event detection by Oak Ridge National Laboratory. The blue squares indicate detection of silos at the crop terminal pre-invasion; and the orange squares represent the detection post-invasion. The numeric value within each box reports the probability of a correct identification.

Following the transfer learning process, an optimal WV Crop Silo model was fine-tuned using 120 WorldView (RGB channels used only) labeled image tiles to generalize detection performance. Out of these 120 image tiles, 84 tiles were used for training, while 36 tiles were used for validation. Before processing, image contrast was enhanced where, for each band, a minimum and a maximum value are specified based on pre-observed imagery type statistics. The fine-tuned model was applied to images collected after 24 February 2022. In total, 1,787 post-invasion WV images covering approximately 220,000 km^2 were retrieved from the archive available at ORNL and used for the detection of silos. Due to recent coverage, these images cover mostly regions near Ukrainian borders, large cities, and regions reported as targeted during the ongoing conflict. A quantitative evaluation was performed utilizing 5-fold cross-validation where five different training and validation sets were generated randomly with a 70/30 % split and evaluated with precision and recall metrics.[32] The evaluation

[32] Buckland, M., & Gey, F. (1994). The relationship between recall and precision. Journal of the American society for information science, 45(1), 12-19.

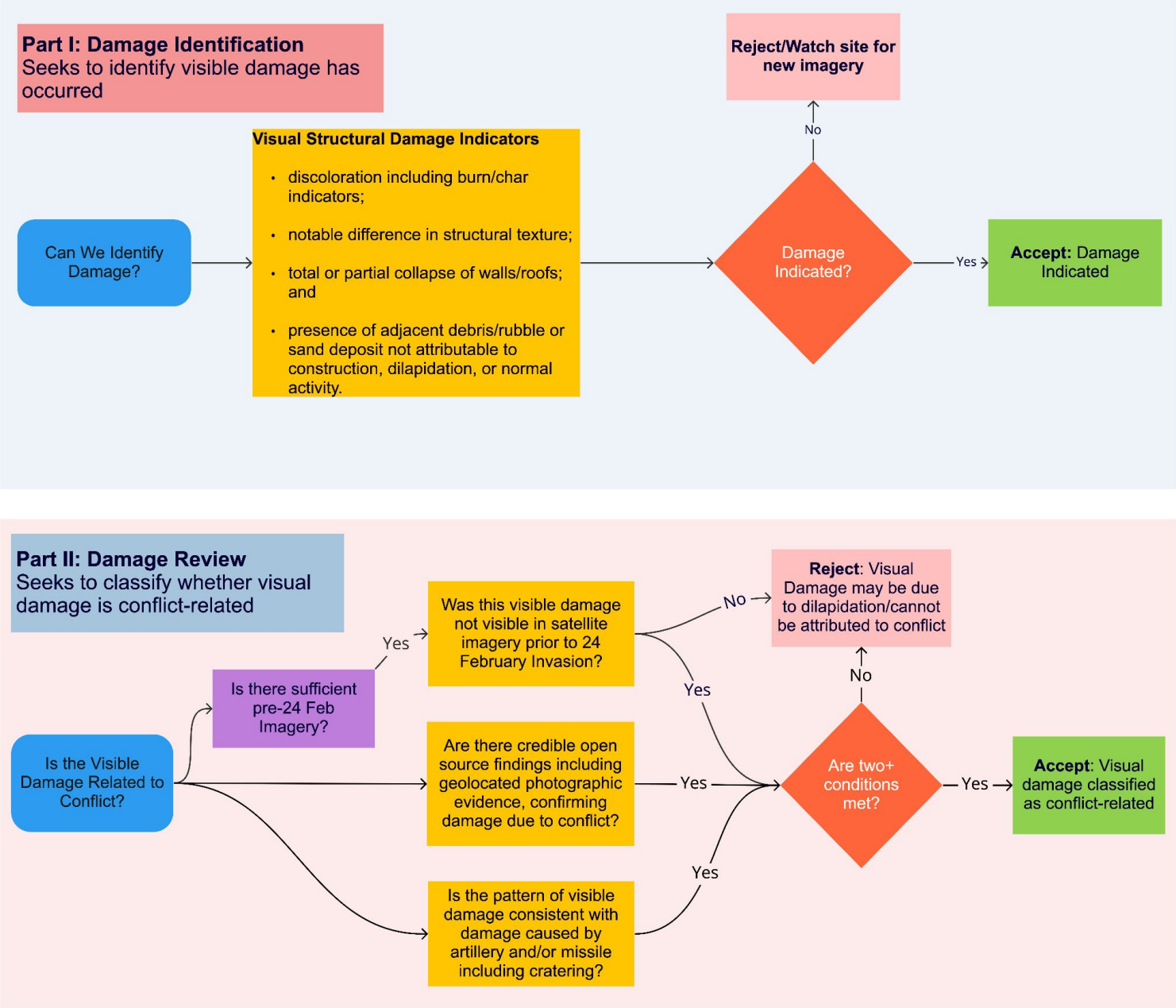
yielded a precision of 83.6 % and a recall of 73.9 %. The optimal model detected an additional 19 crop facilities.

f) Crop storage facility damage scale

Yale HRL classified the evidence of damage to crop facilities on a binary scale as either "visibly damaged" or "not visibly damaged". Indicators of damage included: discoloration to the analyzed structure, including indicators of possible burning or charring; notable difference in structural texture compared to pre-conflict dates; total or partial collapse or serious failure of the walls or roofs of the analyzed structure, to include black spots on the rooftop suggesting collapse of part of the roof, white spots on the rooftop suggesting tiles' lack or displacement, and collapse of chimneys; and presence of damage proxies like large debris/rubble or sand deposit around the building clearly not attributable to construction, dilapidation of an analyzed structure over time, or normal activity at the facility.[33]

[33] International Working Group on Satellite-based Emergency Mapping. "Emergency Mapping Guidelines," 2018. https://archive.ph/nz9qV. https://www.un-spider.org/sites/default/files/IWG_SEM_Guidelines_Building%20Damage%20Assessment_v1.0.pdf.

Figure 7: *Damage Identification Process*[34]



[34] Pattern of visible damage consistent with damage caused by artillery, aerially dropped munitions, and/or missiles: Visible locus of apparent direct impact (on a roof or on the ground) with indications of damage spreading beyond that single point – which may include, but is not limited to, gradually smaller markings and/or perforations in roofing, or a perimeter of rubble - is considered highly consistent with damage caused by artillery and/or missile fire. The visual profile of unforced structural dilapidation is not consistent with this pattern of damage. *See Appendix II for more information on damage indicators.*

g) Limitations and challenges

The Yale HRL and ORNL assessment teams faced multiple limitations and challenges while developing a methodology for conducting this assessment and conducting the assessment itself in an approximately 8-10 week period. These limitations and challenges include the following factors:

- Inconsistent availability of both pre-invasion and post-invasion imagery of specific crop storage locations including imagery with sufficiently minimal cloud cover. Specifically, HRL analysts were only able to inspect approximately 48.2% of the facilities within the AOI;
- The Elevatorist dataset was last updated in 2019 and is a list of certified crop storage facilities only. This means that it does not include non-certified storage, and facilities in the 2019 dataset may have gone out of use or new ones may have been created outside the context of the conflict since 2019. ORNL's algorithmic detection support was required to ensure that new facilities and/or those not certified by the Ukrainian Grain Council were routinely detected;
- Widespread dilapidation of many crop storage facilities creates a confounding effect complicating damage assessment, especially at facilities where buildings had been abandoned and/or allowed to fall down near buildings still in use (a phenomenon not limited to the Ukrainian agricultural sector);
- Specific attribution of attacks to a specific weapon system or conflict party, given the tempo and volume of damage in many areas, is not possible within the scope of this assessment, though it should be attempted at a later date. However, general attribution of damage to these facilities as being related to Russia's widespread use of indiscriminate bombardment is reasonable given the dispositive evidence of this tactic being used by Russia and its proxy forces in the oblasts included within this assessment's AOI;
- A lack of OSINT information about many of these attacks was noted in comparison with the numerous sources of OSINT reporting available about alleged attacks on hospitals and schools reviewed by HRL analysts for previous reports on Ukraine;
- Although the team identified 75 visibly damaged storage facilities and 3.06 million tonnes of affected capacity, HRL believes that the true damage rate is much higher. For example, HRL analysts identified 14 potential reported attacks on crop facilities in addition to the 75 cases cited above. However, these potential attacks were not included due to insufficient corroborating satellite imagery. To extrapolate further damage and affected capacity, a more complex statistical model would be required.

h) Identification of Transport Storage Facilities

Proximity to railroad tracks and ports was investigated at each facility identified as visibly damaged related to conflict. Facilities classified as proximate to train transport were located either immediately adjacent to train tracks, connected to a facility with direct access to a railway, connected by a spur to the main rail, or within less than 1 km of a railroad track. Facilities at major shipping hubs are located directly on a port but are connected to railways by networks of spurs. Facilities classified as "smaller ports"

are located within 1 km of a railway and do not have spurs leading to major railways and typically have a modest storage capacity.

APPENDIX I | SATELLITE IMAGERY OVERVIEW

Ukraine Crop Storage Infrastructure

Post-Invasion Impact Assement

PREPARED FOR THE CONFLICT OBSERVATORY BY

Yale SCHOOL OF PUBLIC HEALTH

Humanitarian Research Lab

CROP STORAGE: ORIKHIV VSP OPTIMUSAGRO TRADE ZAPORIZHZHYA OBLAST

Date: 2022.04.22
Source: WV01
Ground Sampling Distance: 50 cm
Off-Nadir: 19.7596°

There is no apparent damage to the facility or the surrounding area.

CROP STORAGE: ORIKHIV VSP OPTIMUSAGRO TRADE ZAPORIZHZHYA OBLAST

Date: 2022.05.11
Source: WV02
Ground Sampling Distance: 50 cm
Off-Nadir: 37.6843°

Damage appears consistent with effects of heavy artillery and/or missile fire: several facility roofs appear to have collapsed and there appears to be severe charring and substantial debris.

Substantial smoke visible emanating from the facility. The smoke obscures a significant portion of the site, including areas that appear to have sustained the greatest damage.

ELEVATOR: GLOBAL GRAIN (KOPAN HPP) KHERSON OBLAST

Date: 2021.04.24
Source: WV03
Ground Sampling Distance: 38 cm
Off-Nadir: 26.2932°

There is no apparent damage to the facility or the surrounding area.

ELEVATOR: GLOBAL GRAIN (KOPAN HPP) KHERSON OBLAST

Date: 2022.04.26
Source: WV03
Ground Sampling Distance: 36 cm
Off-Nadir: 24.7453°

Several buildings have sustained total or near-total damage within the facility. Impact craters appear to be visible in the field southwest of the facility site.

SHIPPING COMPLEX:
NIKA-TERRA GRAIN TERMINAL
MYKOLAYIV OBLAST

Date: 2022.05.21
Source: WV02
Ground Sampling Distance: 50 cm
Off-Nadir: 27.320982°

There is no apparent damage to the facility or the surrounding area.

SHIPPING COMPLEX: NIKA-TERRA GRAIN TERMINAL MYKOLAYIV OBLAST

Date: 2022.07.05
Source: WV03
Ground Sampling Distance: 48 cm
Off-Nadir: 38.344563°

Three of the four facility buildings located by the waterfront appear to have sustained total damage. A building east of these now-roofless structures appears to have sustained damage to its north-end roof.

SILO COMPLEX: PORTTRANSBUD (OVRUCH BRANCH RISE) ZHYTOMYR OBLAST

Date: 2022.02.14
Source: WV02
Ground Sampling Distance: 50 cm
Off-Nadir: 37.1811°

There is no apparent damage to the facility or the surrounding area.

SILO COMPLEX: PORTTRANSBUD (OVRUCH BRANCH RISE) ZHYTOMYR OBLAST

Date: 2022.02.27
Source: WV02
Ground Sampling Distance: 50 cm
Off-Nadir: 28.7099°

Dark markings consistent with charring or absent roofing are present on at least six of the facility's silo tops. The greatest apparent damage is observed to the silo in the center row, second from the right (east).

SMALL-SCALE CROP FACILITY:
DAFETY SFH
DONETSK OBLAST

Date: 2022.03.12
Source: WV02
Ground Sampling Distance: 50 cm
Off-Nadir: 26.9844°

There is no apparent damage to the facility or the surrounding area.

SMALL-SCALE CROP FACILITY:
DAFETY SFH
DONETSK OBLAST

Date: 2022.08.01
Source: WV03
Ground Sampling Distance: 43 cm
Off-Nadir: 33.6127°

Damage to the facility and surrounding (ostensibly residential) infrastructure appears consistent with effects of artillery and/or missile fire. There is damage observed to the facility's silo tops and several other buildings have also sustained damage. Impact craters are visible in fields surrounding the facility.

Appendix II: DAMAGE IDENTIFICATION PROCESS

A routine process was followed by all assessment team analysts to identify potential damage at each crop storage facility with a common and consistent applied process. If damage was identified on any given facility site, and this damage was not visible prior to 24 February 2022, it was then determined whether the apparent sustained damage could be attributed to conflict. The availability of pre-invasion imagery and patterns of visible damage to an analyzed structure were required for a site to be classified as conflict-afflicted damage.

- *Availability of pre-invasion imagery*: Baseline imagery prior to 24 February 2022 was used to determine the general condition of the facility's infrastructure and enabled analysts to establish with greater certainty whether instances of damage took place before or after the invasion of Ukraine by Russia and Russia-aligned forces.
- *Pattern of visible damage*: Visible locus of apparent direct impact (on a roof or on the ground) with indications of damage spreading beyond that single point. This may include, but is not limited to, gradually smaller markings and/or perforations in roofing, or a perimeter of rubble consistent with damage caused by artillery and/or missile fire. The visual profile of unforced structural dilapidation is not consistent with this pattern of damage.

Further, the exterior condition of the analyzed structure and visible surrounding damage were also considered throughout the analysis of the sites.

- *Assessment of structural condition*: Analysts assessed the general condition of the facility's exterior structure as seen through VHR imagery – any indications of disrepair or heavy wearing may suggest that some apparent instances of post-invasion damage were not conflict-related.
- *Apparent damage within 400 meters of the analyzed facility*: Damage to surrounding buildings, in addition to damage sustained by the facility itself, may indicate that the analyzed site falls within a wider area of bombardment. The structural condition of these surrounding buildings prior to any visible damage was also considered.
- *Potential charring and smoke*: Instances where darkened patches of land and/or infrastructure can be seen around areas of apparent damage can be indicative of the incendiary effects of explosive artillery/missile fire. Smoke apparently emanating directly from areas of supposed damage can also be indicative of this. In addition to the analysis of VHR imagery, OSINT research was conducted to determine whether any fires or other notable non-conflict-related events took place at any given facility.