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

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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 Oak Ridge National Labs (ORNL), concludes with high confidence that approximately 21.5% of Ukraine's estimated 57 million tonnes of crop storage capacity has been impacted by conflict since Russia's full-scale invasion of Ukraine in 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 currently control approximately 10 million tonnes of Ukraine's crop storage capacity. At least an additional 3.06 million metric tonnes[1] of storage capacity has been destroyed or visibly damaged since 24 February 2022. Yale HRL has identified 73 crop storage facilities visibly damaged in areas currently under Ukrainian control. The damaged facilities constitute more than 17% of all crop storage capacity in the regions most subjected to bombardment since the invasion and at least 5.3% of Ukraine's crop storage capacity nationwide. 41 of the damage affected facilities are found in only three of the twelve oblasts included in the scope of this assessment.

The assessment also concludes that at least 59 of the 73 facilities (81%) 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 still significant. Proximity to transportation infrastructure should be considered relevant to any future analysis of visibly damaged crop storage facilities attempting to a) differentiate between indiscriminate and 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 statistically significant 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 427 of the more than 800 crop storage facilities determined to likely have been in range of Russia-aligned forces bombardment since February, 2022. Ukraine has more than 1,300 crop storage facilities. The change detection analysis was supported by the collection and review of open source data relevant to alleged attacks on these facilities. A custom built object detection algorithm 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 because of the following five factors: 1) Access to a 2019 dataset identifying all certified crop storage facilities; 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 February 24, 2022; 4) Deployment of a target-tailored object detection

[1] N.B. This report uses metric tonnes.

algorithm to capture facilities not included in the 2019 dataset; and 5) Robust cross-corroboration of multiple apparently damaged facilities with a diverse area of open source data.

I. ASSESSMENT CONTEXT, TARGETS, AND DESIGN

a) Assessment context

Millions of vulnerable people around the world rely on Ukrainian agricultural products for basic survival 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 and its proxies on 24 February 2022.[2] 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.[3]

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. Since Russia invaded Ukraine, the price of wheat in Africa has risen by 45%, according to the African Development Bank.[4] 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.[5]

Much attention has rightly 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.[6] However, Russia and its proxies' 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.[7] Insufficient storage could interrupt or severely limit the next planting cycle, including winter wheat, which is the majority of Ukraine's wheat crop.[8]

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[2] 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.

[3] 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

[4] 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.

[5] 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/.

[6] Reuters. "Grain Exports from Ukraine Helping to Push Prices down -U.N. Spokesperson," September 7, 2022, sec. European Markets. https://www.reuters.com/markets/europe/grain-exports-ukraine-helping-push-prices-down-un-spokesperson-2022-09-07/.

[7] 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/.

[8] 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.

The destruction of these facilities may constitute a war crime and a crime against humanity.[9] Intentional destruction of agricultural infrastructure may constitute a violation of Article 54(2) of the 1977 Additional Protocol I of the Fourth Geneva Convention. 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.[10]

b) Assessment targets

Russia-aligned forces have allegedly been damaging and destroying Ukraine's crop storage facilities since a full-scale war began on 24 February. Silos, grain elevators, grain bins, and other critical crop storage infrastructure have been visibly damaged by an apparent combination of indiscriminate and targeted bombardment from multiple weapons systems, including artillery, long-range missiles, aerially-dropped ordnance, and other munitions.[11]

These grain-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. Grain 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.

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.

[9] 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 [accessed 7 September 2022]

[10] lnternational 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, available at: https://www.refworld.org/docid/3ae6b36d2.html [accessed 7 September 2022]

[11] 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 grain facility ©2020 Maxar Technologies

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

Figure 1. *Example of grain facility morphology. Fig.1. A 241 tonne capacity shipping facility Brooklyn-Kyiv-ZPK[12] in Odessa. Fig.1.B 9.5 tonne capacity rural operation Safety SFH near Verkhoyansk. Fig.1.C Prometeus Artsyz Elevators, a 50k tonne capacity facility in Artsyz. Fig.1.D. Zhelev SS and the Kamysh-Zaryansky Elevator Company, a 150k tonne facility in Komysh-Zoria.*

Grain 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 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. Grains must be cleaned and stored under a specific range of temperature and moisture

[12] Note: The Elevatorist entries often abbreviate sections of facility names.

parameters to ensure that it is safely stored.[13] Grain storage must be able to keep grain dry, maintain uniform temperature and prevent insects and other pests such as birds and rodents from accessing the grain.[14] Therefore, grain storage facilities must maintain sufficient ventilation, insulation, moisture and temperature controls, space, and cleanliness to store grain safely.[15] An increase in temperature or moisture content beyond the optimal levels will reduce safe storage time and increase the rate of grain spoilage.[16] 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).[17] 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.

c) Assessment design

Yale HRL, working with its partners in the Conflict Observatory and the Oak Ridge National Laboratory (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 assessment's intended purpose is to provide policymakers, international agencies, donor governments, and most importantly, the farmers themselves 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 February 24, 2022. Given the large 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 since the invasion. Just over half of all facilities (427/816) identified within the AOI were imaged as part of the assessment.

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[13] 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.
[14] *Ibid* 375
[15] *Ibid*. 380
[16] 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.
[17] 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.

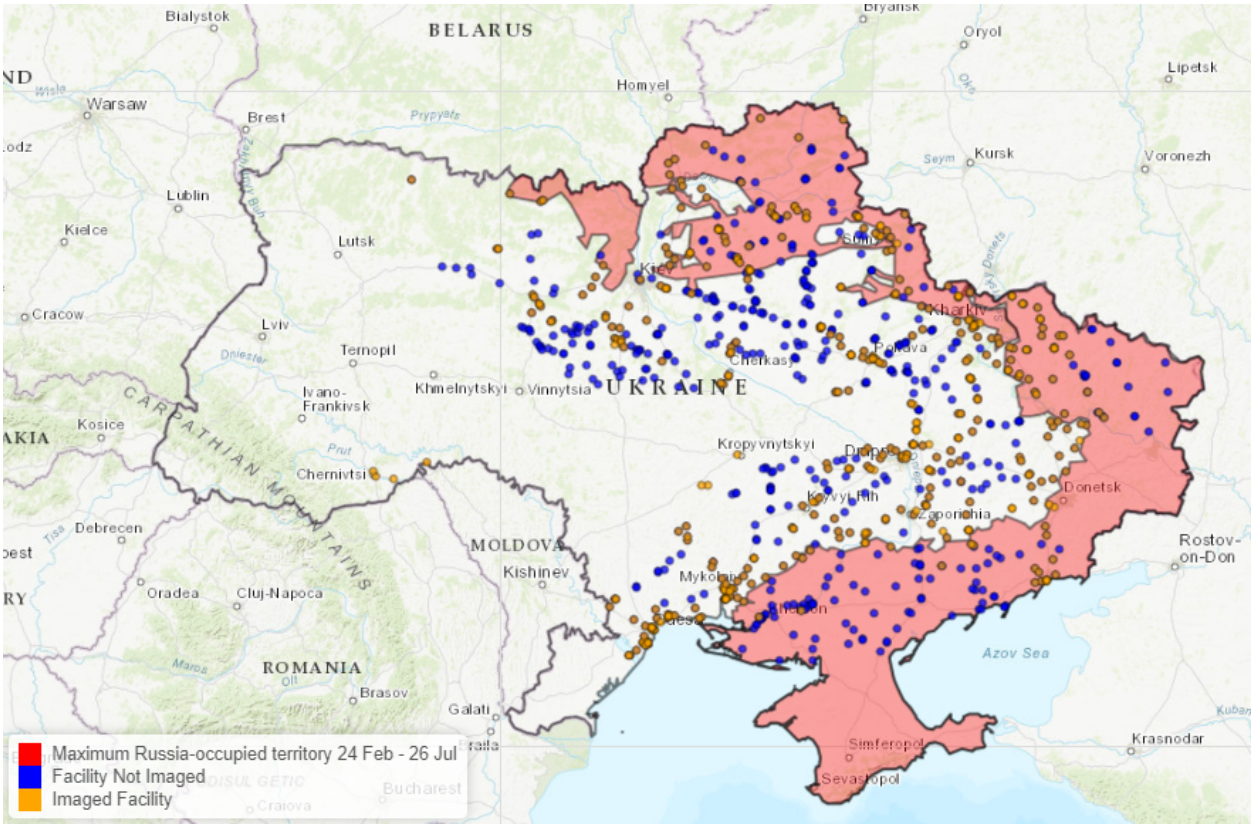

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Figure 2: *Post-Invasion Imagery Availability of Facilities in Areas of Interest.*

A 2019 dataset of certified crop storage locations scraped from The Elevatorist website by the US Department of Agriculture, a now no longer publicly available data source, provided the locations of at least 1,378 crop storage facilities. The object detection algorithm ORNL custom built and tested in collaboration with HRL enabled the assessment team to rapidly detect potential facilities not included in The Elevatorist dataset. Open source information of any alleged attack on a crop storage facility was collected, translated, and corroborated to the extent possible. 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.

Commercial imagery providers were tasked with collecting as many sites as possible within the AOI of areas most likely to have been affected by bombardment 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.

II. SUMMARY OF KEY FINDINGS

a) 73 damage-affected facilities identified by assessment

The assessment identified 73 facilities as affected by damage caused by bombardment or other modes of combat occurring after February 24, 2022. The damage-affected facilities represent 17.1% of the total available storage capacity of facilities analyzed as part of this assessment's AOI. These facilities account for 3.058 million tonnes of Ukraine's national storage 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) [18] 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.

[18] https://www.alcis.org/ *For more information please see Part III, Assessment Methodology, Challenges and Limitations, d) Identifying an Area of Interest.*

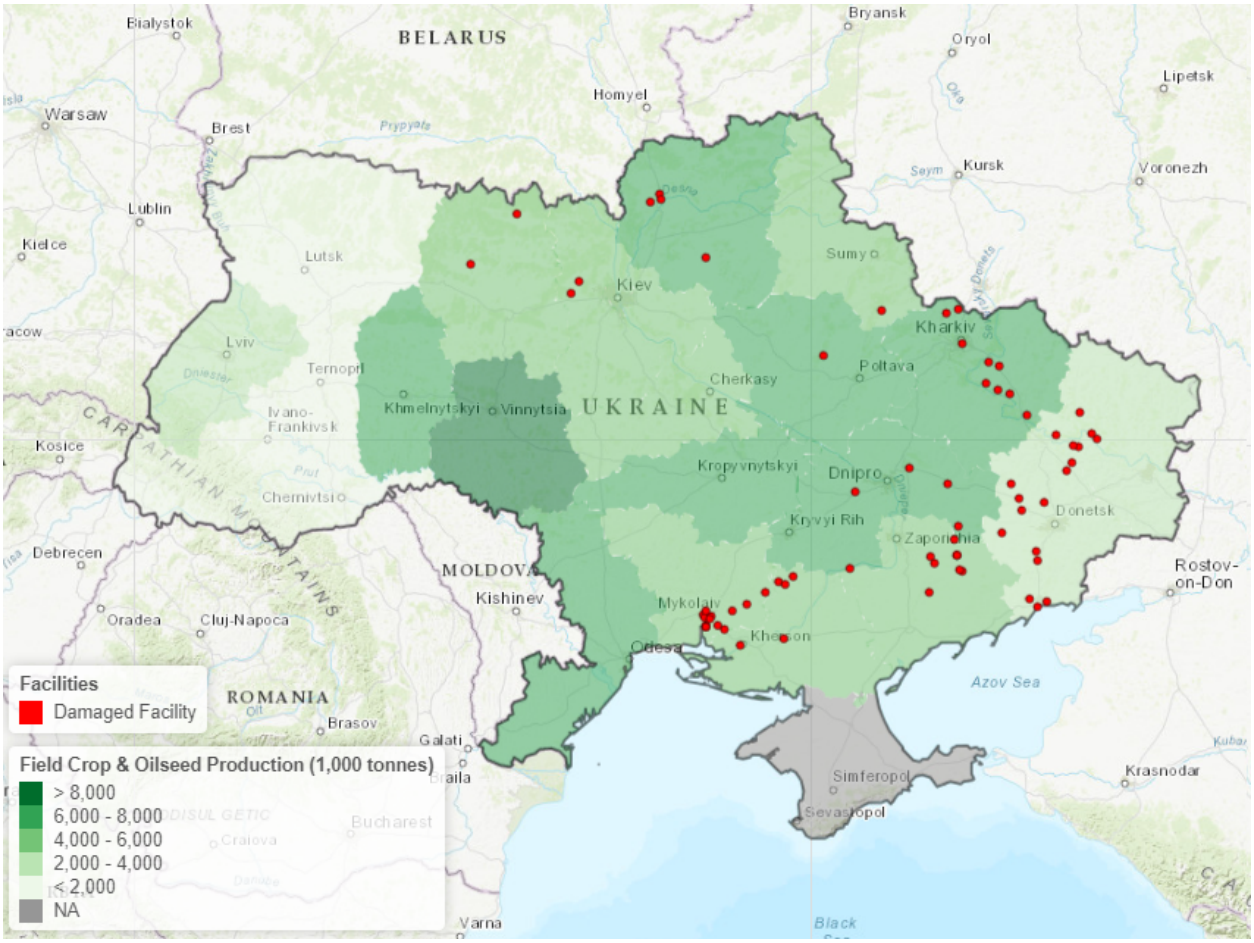

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Figure 3: *Damaged Facilities and Ukrainian Agricultural Production by Oblast.*[19]

b) 12 million tonnes of Ukraine's ~57 million tonnes of storage capacity impacted by conflict

At least 12,140,900 tonnes of Ukraine's total national storage capacity has been affected after Russia's invasion of Ukraine in February 2022. Prior to Russia's war of choice, Ukraine had an estimated 57 million tonnes of storage capacity, according to the Elevatorist dataset. That number is now 45.5 million tonnes or less, according to this assessment.

This figure is the combination of the amount of storage capacity damaged in areas under Ukrainian control and the storage capacity lost to Russia's occupation of Ukrainian territory between March and July 2022, as defined by the AOI for this assessment (see AOI definition in Section III). The 73 damage-affected facilities identified by this assessment account for at least 3.058 million tonnes of storage capacity, 1.11 million tonnes of which are in areas controlled by Russia and its proxies as of July 2022. The storage capacity within damaged facilities alone represents over 5% of Ukraine's total national

[19] 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.

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.

Approximately 9.08 million tonnes of the impacted storage capacity has been under the territorial control of Russia and its proxies between March and July, 2022. 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. Thus, nearly 9.1 million tonnes of storage capacity have been captured by Russia within the past six months, which is approximately 15.7% of Ukraine's national storage capacity recorded in the Elevatorist data set.[20] Territorial control of facilities determines export control and market access - when grain 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.

c) Three oblasts contain the majority of damaged facilities

The top three most affected oblasts represented in this assessment both in terms of number of facilities damaged and overall tonnage compromised are Mykolaivska, Zaporizka, and Donetska, respectively. 41 of the 73 facilities that appear damage-affected are within these oblasts. The other 32 facilities identified by the assessment are present across nine other oblasts. These other oblasts had fewer than ten damaged facilities and fewer than 300,000 tonnes of affected storage capacity each. It is important to note, however, that disparities in imagery collection across oblasts may have affected these totals. Until all known facilities in the Elevatorist dataset are imaged, as well as all facilities identified by the ORNL object detection algorithm built for this assessment, these numbers should be considered initial results.

[20]HRL concludes that one facility (Elevatorist: Karakubskoe HPP) in our data set was located in Donbas previously to 24 February. Thus, the invasion of Ukraine by Russian and Russian-aligned forces resulted in a loss of an additional 10.2 million tonnes.

Table 1: Damage by Oblast[21]

Oblast	Number of Facilities in Oblast	Number of Facilities in Analyzed AOI	Number of Facilities Visible through Satellite Imagery	Number of Facilities Classified to have Sustained Conflict-Adjacent Damage	Affected Tonnage (1,000 tonnes)
Mykolaivska	70	56	42	13	1,046
Zaporizka	55	55	19	10	489.8
Donetska	36	36	36	18	458.5
Kharkivska	87	87	65	9	299.9
Khersonska	59	59	6	6	185.2
Chernihivska	74	74	42	4	135
Dnipropetrovska	93	78	58	4	121.4
Zhytomyrska	54	45	14	2	111
Poltavska	109	100	28	1	100
Luhanska	23	23	3	3	71.9
Kyivska	70	70	25	2	22
Sumska	56	56	27	1	18
Total	786	739	365	73	3,058.7

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

The assessment team determined that 59 out of the 73 facilities (80.8%) identified as damaged were located along train routes or at shipping ports. HRL found 48 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 near the cities of Mykolaiv and Mariupol.

The assessment team cannot conclude a potential reason for this correlation based on the available data analyzed to date. Hypotheses 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) 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.

[21] 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 transliterated from Ukrainian.

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.[22] Yale HRL analysts compared imagery of crop storage facilities, including those captured both before and after Russia's invasion of Ukraine, 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 is 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 algorithm developed and custom built for this assessment by Oakridge National Labs (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 algorithm 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)[23] across multiple media sources to confirm the precise coordinates of a site and its function as a grain facility.[24]

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[22] 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.

[23] 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.

[24] 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 two data sources: the Elevatorist dataset and in algorithmic geolocation developed in partnership with ORNL. 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 grain storage facilities. The Algorithmic geolocation was conducted by visually inspecting geographic locations provided by ORNL for newly-identified grain storage facilities. For both methods, HRL analysts then 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 grain facilities was informed by two sources, the Elevatorist data set and through applying an algorithm developed, tested, and run by ORNL (*See Subsection c "Algorithmic detection" for more)*. At the onset of the conflict, the Elevatorist's dataset of grain 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 grain, agricultural production, approximately 76% of agricultural storage facilities in Ukraine, including a list of certified sites and subsequent storage capacity.[25] The Elevatorist data contains geographic coordinates, facility name, and storage capacity for 1378 grain and agricultural facilities across Ukraine capable of storing approximately 57.7 million tonnes. 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 process below*). The resulting subset of the original Elevatorist dataset contained 840 facilities with the capability of storing approximately 36.4 million tonnes. One facility was excluded from the count due because it was located in the Donbas region, which fell outside the AOI.

[25] 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.

Figure 4: Description of Data in Elevatorist Dataset

OID_	latitude	longitude	id	OBJECTID	rank	url	name	capacity_t

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) Identifying an Area of Interest (AOI)

Collecting recent imagery of the entire country of Ukraine was not found to be operationally feasible in the timeframe available to the assessment team. Thus, a geographic area of interest (AOI) was created by HRL analysts to narrow the scope of the assessment to areas believed to have been affected by the conflict following Russia’s invasion of Ukraine in February 2022. The first portion of the AOI consists of territory in eastern Ukraine occupied by Russia as of July 2022 stretching to territory formerly occupied by Russia in northern Ukraine as of March 2022. The second part of the AOI includes all storage facilities inside currently Ukraine-controlled territory within 120 km of both the eastern and northern occupied territories. Shapefiles of the respective occupied territory zones from July 2022 and March 2022 obtained from Janes were utilized in establishing the AOI.[26]

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

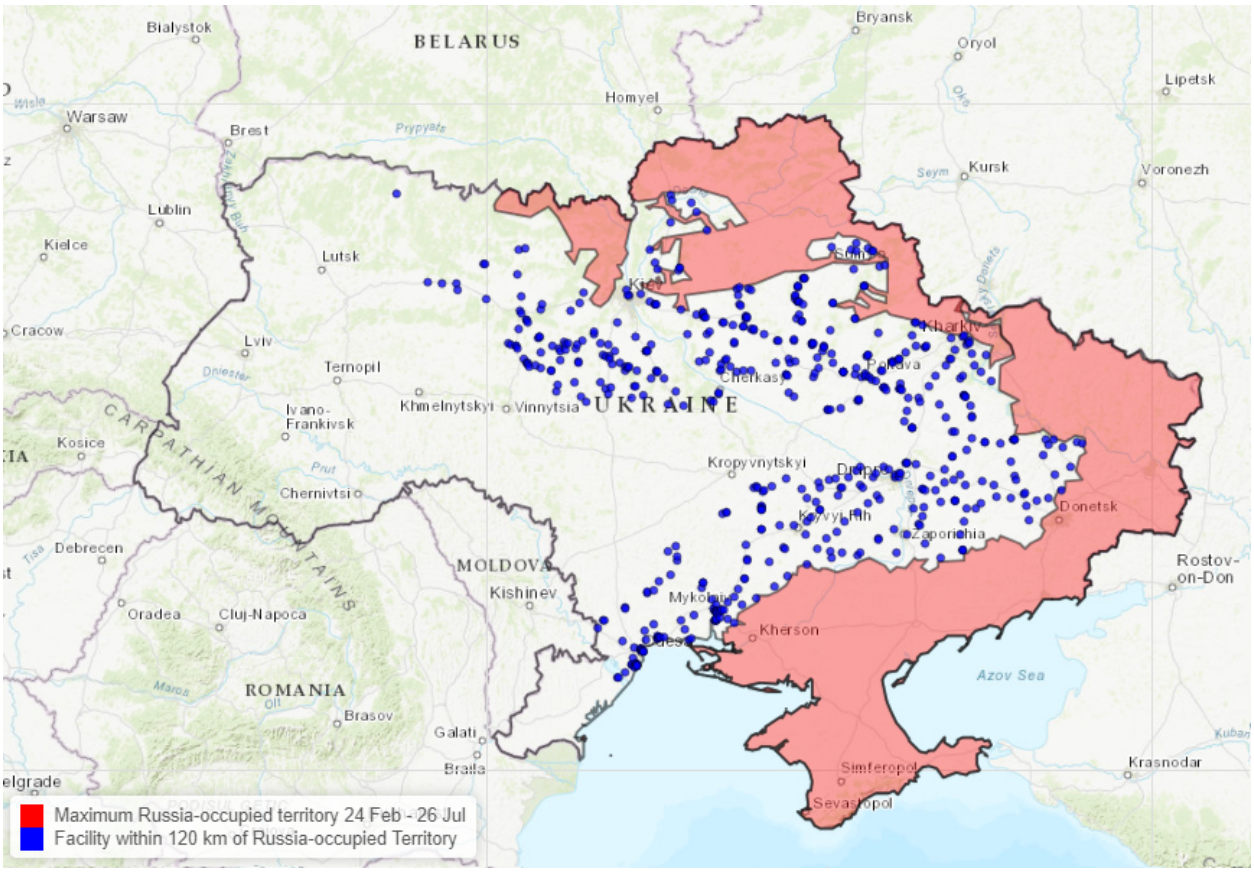

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Figure 5. *AOI Outside of Occupied Territory*: *AOI outside of occupied territories, represented by blue points, is at most 120 km adjacent to territory under occupation by Russia-aligned forces. AOI outside of occupied territories includes 564 grain facilities with a total storage capacity of 26,236,000 tonnes. 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.*

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.[27] 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.

This AOI of approximately 300,000 km^2 includes territory in 17 oblasts (Cherkaska, Chernihivska, Dnipropetrovska, Donetska, Kharkivska, Kyivska, Luhanska, Poltavska, Rivnenska, Sumska, Vinnytska,

[27]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

Volynska, Zhytomyrska, Khersonska, Kirovohradska, Mykolaivska, Odeska, and Zaporizka) and includes 840 grain-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 Russian-installed authorities exporting stored grain out of the region.[28,29] Collectively, these occupied facilities account for 10.2 million tonnes in capacity of grain storage across 276 facilities, which is 17.6% of total Ukrainian grain storage.

e) Algorithmic 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.

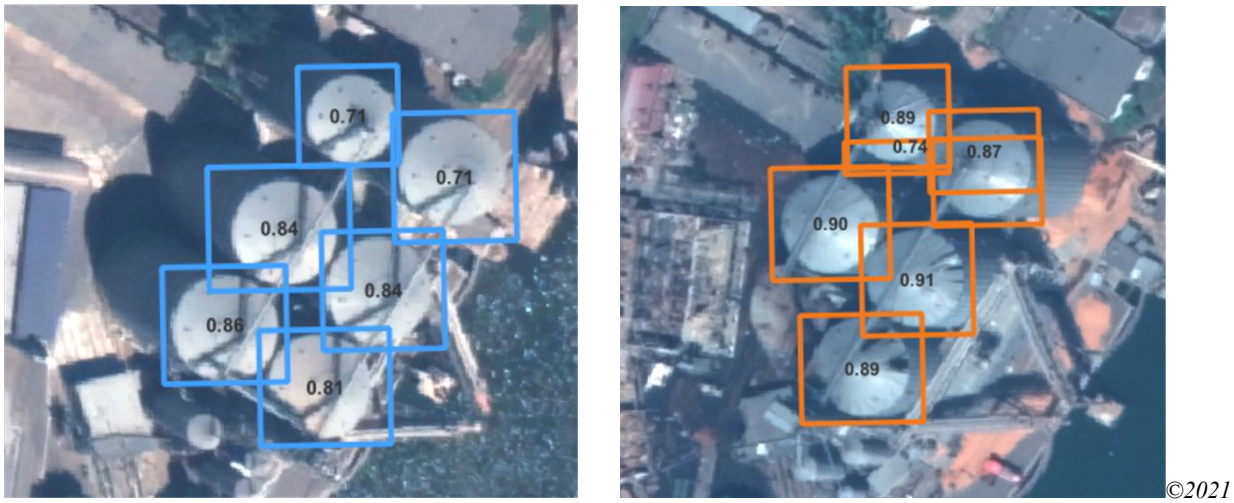

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Figure 6a and 6b. *Examples of damaged structures at Elevatorist:Mariupol ICC Grain terminal identified through comparison of pre-event and post-event detection by Oak Ridge National Laboratory. The blue squares indicate detection of silos at the grain 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 Grain 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

[28] 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/.

[29] 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/.

specified based on pre-observed imagery type statistics. The fine-tuned model was applied to images collected after February 24th, 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 percent split and evaluated with precision and recall metrics.[30] The evaluation yielded a precision of 83.6 percent and a recall of 73.9 percent. The optimal model detected an additional 37 agricultural facilities. These additional facilities included 19 grain facilities and 18 various farm types (e.g., chicken hatcheries, and various livestock).[31]

f) Crop storage facility damage scale

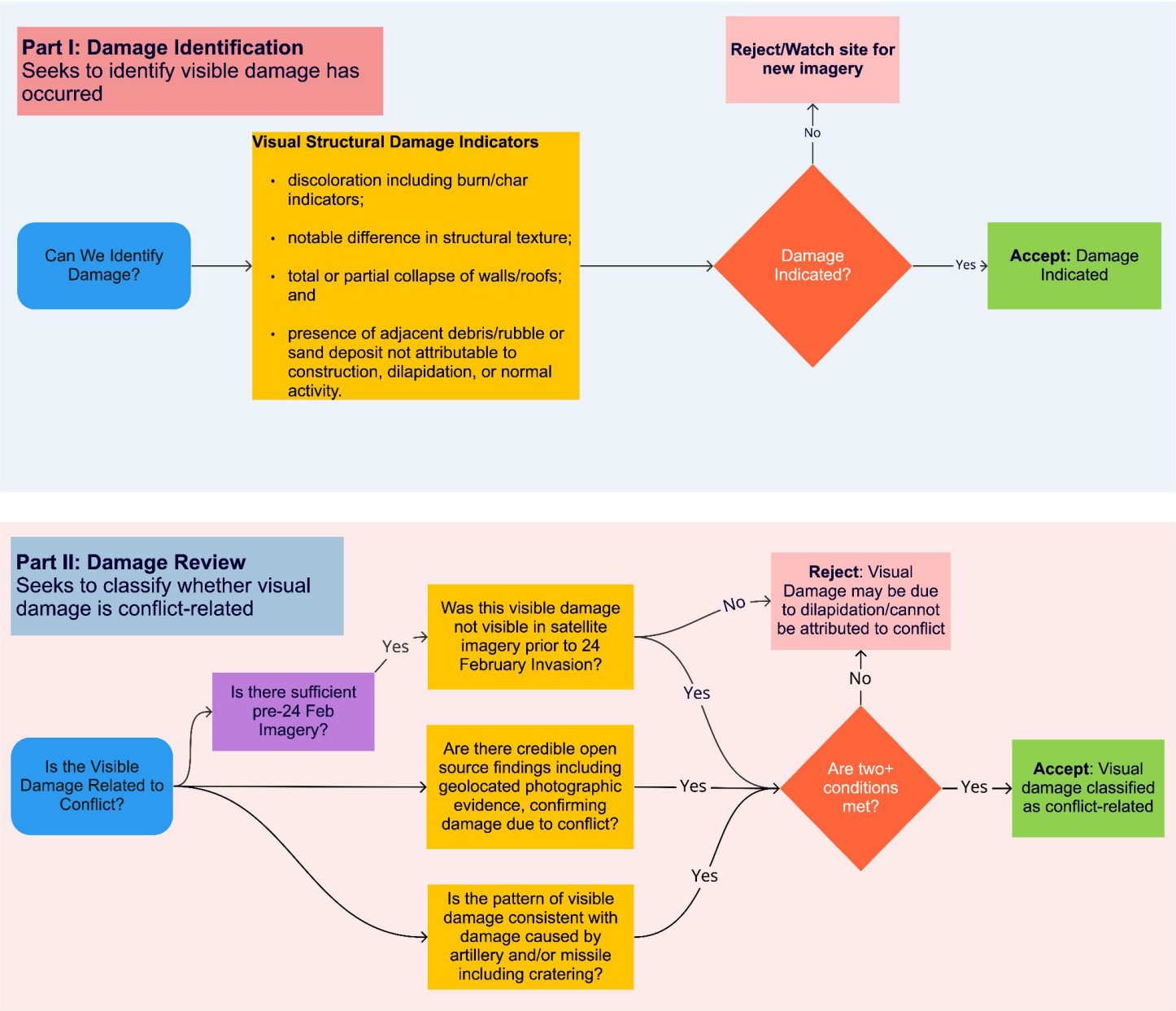
Yale HRL classified the evidence of damage to grain facilities on a binary scale as either "damaged" or "not visibly damaged". Indicators of damage included: discoloration to the analyzed structure, including indicators of possible burning or charring; notable difference in structural texture compared 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.[32]

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

[31] To estimate storage capacity for the 19 grain 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.

[32] 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[33]



[33] 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.

f) Limitations and challenges

The Yale HRL and ORNL assessment teams faced multiple limitations and challenges in the course of 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 52.3 percent of the AOI. ;
- The Elevatorist dataset was last updated in 2019 and is a list of certified grain 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 AOIs;
- 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 73 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 grain facilities. 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.

g) 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: Imagery Examples

Example 1: Recent bombardment at crop storage facility

Figure 8. *Orikhiv VSP Optimus Agro Trade Zaporizhzhia Oblast on 2022-05-11. There appears to be substantial smoke emanating from large areas of damage that is consistent with the apparent effects of heavy artillery and/or missile fire: collapsed roofs, severe charring, and substantial debris.*

Example 2: Damaged elevator facility

Figure 9. *Global Grain (Kopan HPP) in Kherson Oblast. Destroyed grain elevators surrounded by debris and discoloration on 2022-08-23. Impact of craters are visible south west of the compound.*

Example 3: Damaged silo complex

Figure 10. *Porttransbud (Ovruch Branch Rise) in Zhytomyr Oblast. There are dark markings on the tops of at least six of the facility's silos, with the greatest apparent damage to the silo in the second row, second from the right/east.Visible damage sustained by silos as of 2022-02-27.*

Example 4: Damaged crop storage facility at shipping complex

Figure 11. *SME Niko-Terra facility in Mykolaiv Oblast. Multiple structures within a grain facility compound have been visibly damaged. The structures in the western part of the complex are destroyed: roofing is either partially or entirely collapsed and extensive charring is visible as of 2022-07-05.*

Example 5: Damaged small-scale grain storage operation

Figure 12. *Safety SFH in Donetsk Oblast on 2022-09-06. Extensive damage is observable throughout the facility and nearby houses. Impact cratering can be seen in and around the facility.*

Appendix II: Damage Identification Process

A routine process was followed by all assessment team analysts to identify potential damage at a 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 Russian-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 - 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.

Further, the exterior condition of the analyzed structure and visible surrounding damage were additional indicators that were 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.