War and Science in Ukraine *

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Abstract

We discuss the impacts of the Russian invasion on Ukrainian science. Using newly collected data, we show that the war has already had significant effects on science in Ukraine: research papers produced by Ukrainian scientists declined by about 10%, approximately 5% of the most prolific scientists are publishing with a foreign affiliation, 22% of top universities have faced destruction of physical capital, and international collaborations with Russian scientists have declined by more than 40%. Drawing upon the economics of science and innovation literature, we highlight three primary channels through which wars impact science: 1) the loss of human capital, 2) the destruction of physical capital, and 3) reductions in international scientific cooperation. The evidence from the literature on the long-run effects of losing human or physical capital indicates that shocks to physical capital can be remedied more easily than shocks to human capital. Our new data also suggests that human capital shocks are the main drivers of the reduction in Ukrainian research output that has occurred since the beginning of the war. Hence, reconstruction efforts should be focused on supporting scientists to continue in the research sector and to return to Ukraine after the war has ended.

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1 Introduction

Science in Ukraine has a rich history and a well-developed infrastructure with numerous research institutions and universities. On February 24, 2022, Russian troops started a full-scale invasion of Ukraine, which disrupted ordinary life and also had a profound impact on the country's universities and research institutes. The conflict disrupted the normal functioning of these institutions, and many scientists have been forced to relocate to other parts of Ukraine or even abroad.

In this article, we present new facts on the impact of the war on Ukrainian science. We then draw on the economics of science and innovation literature on war and other crises to point to the channels through which science is affected by war and conflict. We also discuss potentially effective ways to mitigate its negative impact on science and to aid reconstruction after the end of the war.

Only in retrospect will we be able to evaluate the full impact of the war on Ukrainian science. Nevertheless, it is becoming clear that the conflict has already significantly impacted the country's scientific community. To study this medium-run impact, we collect data from *Clarivate Web of Science*, ORCID, and other sources. These data allow us to explore the impacts of the war on scientific production, on the emigration of Ukrainian scientists, on the destruction of physical capital in Ukrainian universities, and on changes in international collaboration patterns of Ukrainian scientists.

Our newly collected data reveals a notable decline in research output produced by Ukrainian scientists since the beginning of the war. Between 2021 and 2022, the number of papers already declined by about 10 percent (see Figure 1).[1] As scientific papers tend to be published with significant delays, and as the first two months of 2022 were not yet affected by the war, the decline shown in Figure 1 likely underestimates the medium to long-run effect of the war on Ukrainian scientific production.

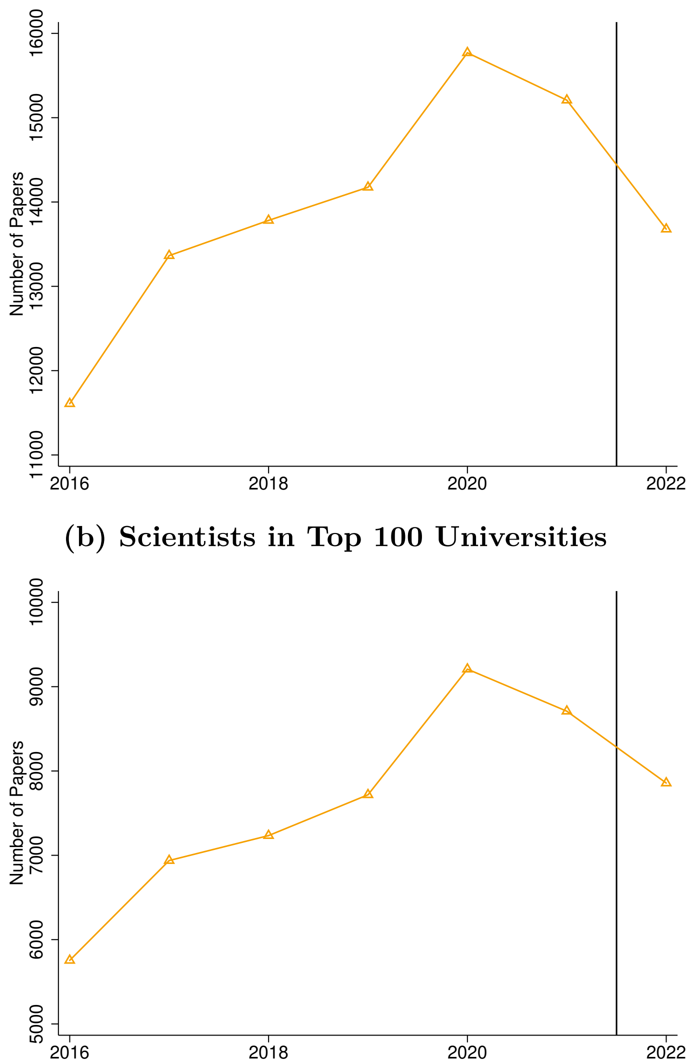
Three primary channels may drive this decline in scientific production. First, the war has had a devastating effect on human capital, i.e., the scientists carrying out research in universities and laboratories. Many scientists have been forced to flee their homes and relocate to other parts of Ukraine or abroad. Others have joined the army to fight in the war or were directly killed in the war. Second, the war may have affected physical capital as classrooms, laboratories, libraries, and other essential

[1] As of May 2023, the *Web of Science* continues to index papers that were published in 2022. As a result, the actual decline in the number of papers for 2022 may be somewhat lower than reported in data collected in May 2023.

Figure 1: Number of Publications by Ukrainian Scientists

(a) All Scientists

(b) Scientists in Top 100 Universities



Notes: The figure shows the total number of papers by Ukrainian scientists in the Web of Science. Papers with at least one coauthor affiliated with a Ukrainian research institution are counted. In panel (a), we report papers from any Ukrainian institution. In panel (b), we report papers with at least one coauthor affiliated with a top 100 Ukrainian university as measured by the Webometrics Ranking of World Universities by the CSIC Cybermetrics Lab.

facilities have been damaged or destroyed by bombings, shelling, and other forms of violence. War-related power outages have interrupted computers and experiments and may have thus reduced the effectiveness of existing physical capital.[2] Third, the war has also hindered the exchange of scientific knowledge and ideas, as travel restrictions and the general insecurity in the country have made it more difficult for researchers to attend conferences, seminars, and travel to work with coauthors.

In the rest of this article, we discuss the likely consequences of the shocks to human capital, physical capital, and to international collaborations by examining new data and by drawing on findings in the economics of science and innovation literature. Our newly collected data suggest that shocks to human capital, and a decline in international scientific cooperation, seem to be the main causes for the reduction of the research output of Ukrainian scientists. Shocks to physical capital have, as yet, only had a minor impact on research output. These short-run patterns mirror the effects of earlier wars and crises on scientific output. This suggests that lessons from earlier episodes of war and conflict provide substantive insights into Ukrainian science's trajectory, its challenges, and on appropriate interventions that could safeguard Ukrainian science for the post-war future.

2 War and Human Capital

As highlighted above, the war in Ukraine has already disrupted the lives of scientists in Ukrainian research institutions and universities. Many had to flee their homes, relocate to other parts of Ukraine or even abroad, or join the army.

Even in peacetime, it is challenging to measure cross-country migration rates. In the context of war, it is even more difficult to systematically measure relocations. Despite these challenges, a number of efforts have tried to estimate emigration rates among Ukrainian scientists. The Ukrainian Ministry of Science and Education estimates that approximately 6,000 of *all* 60,000 researchers, or 10%, left Ukraine since the beginning of the war (Irwin, 2023).[3] De Rassenfosse et al. (2023) report an emigration rate of 18.9% among a sample of scientists surveyed in early 2023. Other surveys have focused on Ukrainian academics who have already emigrated.[4] These surveys also indicate

[2]By January 2023, 40% of the energy system was reportedly damaged in the war https://www.reuters.com/business/energy/ukraine-introduces-emergency-power-cuts-east-southeast-2023-01-11/.

[3]This estimate includes scientific support staff and junior researchers.

[4]For example, Maryl et al. (2022) used an open-call combined with snowball sampling to survey 619 emigrants. Using an open-call approach, the researchers circulated and posted the survey link and did not try to make the sample representative of the population of scientists. Snowball sampling

that female scientists were more likely to emigrate and that many academics continue to work for a Ukrainian institution even though they are abroad (e.g., Maryl et al., 2022).[5]

The survey-based evidence suggests that the war has already resulted in a large emigration wave from Ukrainian universities. Such survey-based estimates potentially suffer from severe selection biases. Those who respond to surveys may not be a random sample of the population of academics. Hence, emigration rates may either be over or underestimated.

2.1 New Data on International Migration of Ukrainian Researchers

To overcome some of these challenges and to provide alternative estimates of emigration rates, we collect data for two samples of Ukrainian academics. First, we collect data on 535 elite Ukrainian scientists who were working in the top 100 Ukrainian research institutions before 2022. Second, we collect data on all 58,139 researchers with an ORCID ID who reported a Ukrainian affiliation in 2021.[6] These two datasets enable us to provide alternative estimates of international migration rates of Ukrainian scientists that are based on affiliations reported in publications and on affiliation changes reported in the ORCID database. On the one hand, such data may lead us to underestimate actual emigration rates because scientists may only publish with their new affiliation after a significant delay or because they may not update their ORCID profile. On the other hand, these data have the advantage that the estimates do not suffer from surveying a potentially selected sample of the population of Ukrainian scientists.

New Evidence on Emigration Rates Among Elite Scientists

To obtain our sample of elite scientists, we focus on the top 100 Ukrainian institutions, as measured by the Webometrics Ranking of World Universities by the CSIC Cybermetrics Lab.[7] We then collect information on the 10 to 20 highest-ranked academics

is a non-probability sampling method where earlier respondents recruit new respondents to form the sample.

[5]Similarly, De Rassenfosse et al. (2023) find that 74.6% of their survey respondents who had emigrated were women.

[6]ORCID stands for Open Researcher and Contributor ID and is a unique and persistent identifier of researchers. The ID is created and maintained by the researchers themselves and includes affiliation information.

[7]Ranking as of July 2022 from: https://www.webometrics.info/en/Europe/Ukraine.

in each of these 100 institutions who published at least one paper using an affiliation with one of the top 100 Ukrainian institutions in 2021.[8] We then classify scientists as having emigrated if they published a (working) paper in 2022 or 2023 with a foreign affiliation. For each of the 535 elite scientists, we search the *Web of Science* for papers that papers they published in with a foreign affiliation. Similarly, we search the arXiv website for working papers that they published in 2022 or 2023 with a foreign affiliation. We then classify elite scientists as emigrated if they published at least one (working) paper with a foreign affiliation in 2022.[9] Of course, this may underestimate the extent of international migration because migrants may not yet have published with a foreign affiliation. Alternatively, it may overestimate overall emigration rates because elite scientists generally have higher emigration rates (e.g., Becker et al., 2021) or because the foreign affiliation is only temporary.

In our data, 5.4 percent of these elite scientists have already emigrated since the beginning of the war (see Table 1, Panel B and Figure 2). Interestingly, women have slightly lower emigration rates in this sample than men (Figure 2). Emigration rates among elite Ukrainian scientists may, as yet, be relatively low for multiple reasons. First, since the imposition of martial law, men between 18 and 60 have been prohibited from leaving the country. Second, finding an attractive academic position abroad is difficult to organize in such a short time period, even for elite scientists. Third, Ukrainian scientists may have joined the military effort. Finally, they may feel a strong sense of attachment to their home country and culture, which could deter them from leaving. They may feel a responsibility to contribute to the scientific development of their country, especially during challenging times.

New Evidence on Emigration Rates Among Ukrainian Researchers with an ORCID ID

To complement the analysis of elite scientists with a broad sample of Ukrainian researchers, we analyze emigration patterns among researchers with an ORCID ID who reported a Ukrainian affiliation in 2021. There are no restrictions in obtaining ORCID

[8]We identify the highest-ranked academics by the total number of papers, as reported in the *Web of Science*. For the top 20 universities, we collect at most 20 academics; for the universities ranked 21-100, we collect at most ten scientists. Because some of the top 100 institutions do not appear in the *Web of Science* and because many of the top 100 institutions have fewer than ten researchers with at least one paper in 2021, the total number of scientists in this sample is 535.

[9]We also count them as emigrated if they list a Ukrainian affiliation in addition to the foreign one.

Table 1: **Summary Statistics Ukrainian Universities**

Panel A: University Level Data	
Number of universities	100
Percent with destruction	22
Percent relocated	5
Number of papers in 2021	8,709
Number of papers in 2022	7,857
Panel B: Scientist Level Data	
Number of scientists	535
Percent female	34.81
Percent emigrated	5.42
Panel C: Orcid Data	
Number of scientists	58,139
Percent female	56.07
Percent emigrated	0.20

Notes: The table reports summary statistics on universities and elite scientists. Panel A reports data for the top 100 Ukrainian universities. Panel B reports data for the 535 elite scientists from these top 100 universities. Panel C reports data for the 58,139 researchers with an ORCID ID who reported a Ukrainian affiliation in 2021.

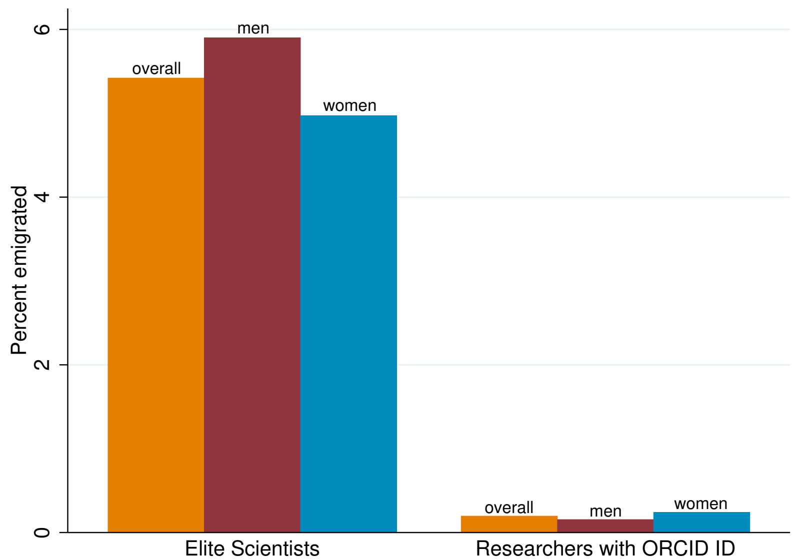
IDs. As a result, these data include professors at all levels of seniority, but also junior researchers such as PhD or Masters students and company-based researchers.

As researchers can update their profile on ORCID, the data may, in principle, be used to measure international migration of scientists (see, for example Bohannon 2017). At the time of writing, the newest available data from ORCID report affiliations for October 2022. This means that we can only measure very fast migration responses.

In the ORCID data, 0.2 percent of researchers had emigrated by October 2022 (see Table 1, Panel C and Figure 2). In this sample, we find higher emigration rates of female researchers (Figure 2).

These data suggest that in this broad sample of researchers, emigration rates are relatively low. Of course, as many of these researchers are young and/or worked in companies, they have fewer opportunities to find employment in a science-related job abroad.

Figure 2: Emigration Rates Ukrainian Researchers



Notes: The figure shows emigration rates of Ukrainian researchers. The first sample includes 535 elite scientists who were affiliated with a top-100 Ukrainian university in 2021. Emigration is proxied by publishing a (working) paper with a non-Ukrainian affiliation in 2022. The second sample includes 58,139 researchers with an ORCID ID who reported a Ukrainian affiliation in 2021. Emigration is proxied by changing to a foreign affiliation until October 2022.

Discussion and Comparison to Survey-Based Emigration Rates

The emigration rates in the two datasets are, as yet, relatively low. Our data may understate actual emigration rates for various reasons. First, many scientists kept Ukrainian affiliations even when they moved abroad. If they continue to publish using only their Ukrainian affiliation, or if they do not update their ORCID profile to account for double affiliations, we would not observe that they have moved abroad. Second, in the elite scientist sample, we would only observe them with a foreign affiliation if they published a (working) paper with the new affiliation.

Overall, it is difficult to get an accurate picture of short-term emigration rates among Ukrainian scientists. Whether true emigration rates are closer to the survey-based estimates or to the estimates from our data is difficult to evaluate. More representative, comprehensive, and longer-run data will have to be collected to measure the ultimate effect of the war on the scientific human capital stock in Ukraine.

2.2 The Effect of War and Conflict on Scientific Human Capital

The Effect of War-Induced Migration on Scientific Human Capital

The previous literature highlights that war, conflict, and economic turmoil can cause large emigration flows of academics. Over the course of history, such episodes have, for example, caused large emigration waves of Jewish academics from Nazi Germany and from countries that were occupied by German troops during the Second World War (Waldinger, 2012; Becker et al., 2021). Similarly, thousands of Russian, Ukrainian and other formerly Soviet academics emigrated abroad after the collapse of the Soviet Union (e.g., Borjas and Doran, 2012; Ganguli, 2017).

Emigration waves often have disastrous and long-lasting effects on universities in sending countries. In Germany and Austria, universities that lost more Jewish scientists because of Nazi persecutions did not recover for at least half a century (Waldinger, 2016).[10]

Previous research has also highlighted that one of the major effects of such emigration waves is the impact on young researchers. The resulting shortage of experienced mentors and role models for young researchers can have detrimental effects on their career outcomes and reduce the number of young people who enter scientific professions. The emigration of Jewish scientists in Nazi Germany, for example, reduced career outcomes of Ph.D. students in departments where high-quality mathematicians were dismissed (Waldinger, 2010). Similarly, the emigration of Soviet scientists after the collapse of the Iron Curtain harmed the careers of Russian Ph.D. students (Borjas and Doran, 2015; Ganguli, 2014).

The literature has also documented that network effects can make emigration self-reinforcing. Once the first group of emigrants has settled in their new destination, they attract other researchers from the professional network in their home country to their location (e.g., Becker et al., 2021; Ganguli, 2015). Because of such network effects, short-run increases in emigration rates can affect brain drain in the long run.

To summarize, the literature has documented significant and very long-lasting effects of losing scientific human capital in war and conflict situations.

[10] Other research has shown the mirror image of such effects: gaining leading researchers can lead to long-term positive gains (Agrawal et al., 2017).

Direct effects of War on Scientific Human Capital

In addition to emigration to foreign destinations, war and turmoil affect scientific human capital through other channels. Researchers may join the war effort (e.g., Iaria et al., 2018) or be displaced within the country. Moreover, the psychological toll of war can negatively impact scientists' ability to engage in scientific inquiry and innovation. Trauma, stress, and anxiety can impair cognitive function and decrease productivity and creativity. It has been shown that adverse life events, such as bereavements in the family, can lower productivity (e.g., Oswald et al., 2015). Finally, the direct loss of lives because of war action can deplete a country's scientific workforce.

The Effect of War-Induced Occupational Mobility on Scientific Human Capital

Furthermore, war may induce researchers to leave science to pursue other activities. Such occupational mobility may be caused by reductions in funding for research or by damages to physical infrastructure. After the collapse of the Soviet Union, for example, many researchers left the science sector because of low salaries and lack of materials and resources needed to do research (Ganguli, 2017).

However, wars and conflict can also provide opportunities for researchers to remain in science and to even accumulate further scientific human capital through targeted training programs and R&D investment. For example, a training program for medical school graduates in the United States during the Vietnam War, the National Institutes of Health "Yellow Berets" program, increased the likelihood that participants entered research-focused positions over purely clinical ones (Azoulay et al., 2021).

During WWII, the U.S. government made R&D investments via the Office of Scientific Research and Development (OSRD) by awarding contracts to firms and universities to conduct war-related research. The mandate of the OSRD's Committee on Medical Research was to mobilize medical researchers and pursue such contracts. These investments subsequently increased employment and entrepreneurship in high-tech clusters (Gross and Sampat, 2020; Gross and Sampat, 2022).

2.3 Lessons for Ukraine

Because of the large and often irreversible consequences of losing scientific human capital, the future of research in Ukrainian universities crucially depends on effective policies to preserve scientific human capital. As in other conflicts, the main threats to preserving scientific human capital are emigration, direct death and trauma caused by the war, and occupational mobility into sectors outside science.

Since the beginning of the war, there have been several initiatives to facilitate the emigration of Ukrainian academics. Many foreign universities have introduced fellowship programs for Ukrainian academics to travel abroad for short and long-term research stays (e.g., the University of Cambridge, and the University of Munich, to name just a few). Similarly, scientific societies have started many initiatives to support research visits of Ukrainian scholars at foreign universities (e.g., Shevchenko Scientific Society, the British Academy, and the Review of Economic Studies).

In addition, grassroots movements have sprung up to facilitate emigration. For example, *#ScienceForUkraine* an initiative that began on social media, now hosts a central database listing opportunities abroad for Ukrainian academics (e.g., Maryl et al., 2022). By June 2022, #ScienceForUkraine's database contained over 2,600 listings, with 16% of opportunities offered by German institutions, 9% by French and 7% by Polish institutions (Rose et al., 2022). These programs play an important role in safeguarding the livelihoods of Ukrainian academics. They are also a way of strengthening the scientific workforce of the host countries.[11]

Nevertheless, it will be essential to supplement such programs with efforts to preserve the human capital of Ukrainian universities, especially after the war has ended. A possible way are grants and virtual/remote/non-resident fellowship programs that support scientists who remain in Ukraine.[12] These types of fellowships that allow Ukrainians to remain in Ukraine while doing their research are already proliferating. They are funded by universities and other organizations (e.g., Scholars at Risk (SAR), Universities for Ukraine (U4U), Duke University, and the University of Massachusetts).

After the war has ended, it will be important that Ukrainian scientists who have emigrated abroad return to Ukraine. In other war and conflict situations, return migration has been relatively limited (e.g., Becker et al., 2021; Grüttner, 2022). Evidence from return migration in other contexts, however, points to potentially significant benefits to the home country in terms of knowledge spillovers and productivity gains (e.g.,

[11]A number of papers have documented that high-skilled scientists can have large effects on science and innovation in the host countries (e.g., Hunt and Gauthier-Loiselle, 2010; Kerr and Lincoln, 2010; Moser et al., 2014; Moser and San, 2022).

[12]Chhugani et al. (2022) also highlight the importance of remote opportunities for scholars in Ukraine.

Bahar et al., 2022, Kahn and MacGarvie, 2016, Fry and Ganguli, 2023).[13] Fellowships and large research grants to do science in Ukraine could be effective tools to encourage such return migration.

To aid the reconstruction of the Ukrainian university sector, it will also be paramount to keep individuals in the scientific sector. Because of the war, there have been significant budget cuts for universities and research institutes in Ukraine. These cuts have already resulted in the termination of funding for existing projects and layoffs (Gorodnichenko et al., 2022). Such layoffs often lead to irreversible occupational re-orientations that have the potential to reduce Ukrainian scientific human capital even further.[14]

Previous research has shown that after the collapse of the Soviet Union, small grants to close to 30,000 scientists funded by George Soros induced scientists to remain in science (Ganguli, 2017). During the current conflict, the Simons Foundation, for example, has funded grants to Ukrainian scientists, including salaries to 405 specialists and doctoral candidates to continue their research in Ukraine.[15] Such grants can be an effective and low-cost policy tool to reduce the outflow of academics into non-scientific sectors.

3 War and Physical Capital

3.1 Physical Destruction of Ukrainian Universities

The war in Ukraine has had a devastating impact on the country's scientific infrastructure. Because of the ongoing war, more and more universities have suffered from some physical destruction. As of March 2023, the Ukrainian Ministry of Education and Science reported that 3,145 educational institutions (such as schools and universities) had experienced physical destruction due to bombing and shelling.[16] For the same date, the ministry reported that 91 research and higher education institutes had been dam-

[13] However, evidence from an existing return migration fellowship program, China's Thousand Talents program, suggests that fellowships can help incentivize return migration of good - but not the highest-calibre - emigrants (Shi et al., 2023).

[14] On the other hand, there is some evidence that the Ukrainian government is currently prioritizing war-related research. This could potentially keep researchers in the scientific sector if such efforts were sustained.

[15] See https://www.nytimes.com/2023/01/25/science/ukraine-scientists-simons-foundation.html.

[16] The Ukrainian Ministry of Education and Science provides oblast-level information on the number of schools, colleges and universities that have been damaged since the beginning of the war (https://saveschools.in.ua/en). These data, however, do not list specific universities that were damaged.

aged, 4 had been destroyed, and 228 had had no damage (Irwin, 2023). This indicates that 29.4 percent of all research and higher education institutions had experienced at least some war-related destruction of physical capital. Estimates of the monetary value of damages are uncertain, but the National Academy of Sciences of Ukraine (NASU) estimated damages to research institutions of 0.5 billion hryvnias (approximately $13 million) as of October 2022 (Gorodnichenko et al., 2022).

As the ministry's data do not list specific universities, which would allow us to link damages to reductions in scientific output, we turn to the sample of top 100 Ukrainian universities discussed earlier. To obtain estimates of physical destruction among the top 100 Ukrainian universities, we search for news articles and other information on English-language and Ukrainian-language websites. It is important to note, that such articles usually do not report minimal damages. Hence, our measure of destruction measures relatively substantial damages. For example, the BBC reported that "a Karazin National University building in central Kharkiv caught fire after being hit by a missile".[17] Based on such information, we find that 22 of the top 100 universities have had some war-related damage (Table 1, Panel A). Many of the top 100 institutions are located in Kyiv, which experienced less war action than the areas in Eastern Ukraine. As a result, the share of damaged institutions is somewhat smaller for the top 100 universities than the overall share of 29.4% reported by the ministry. Moreover, the ministry's total includes research institutes as well as a larger group of universities, while ours includes only the top universities.

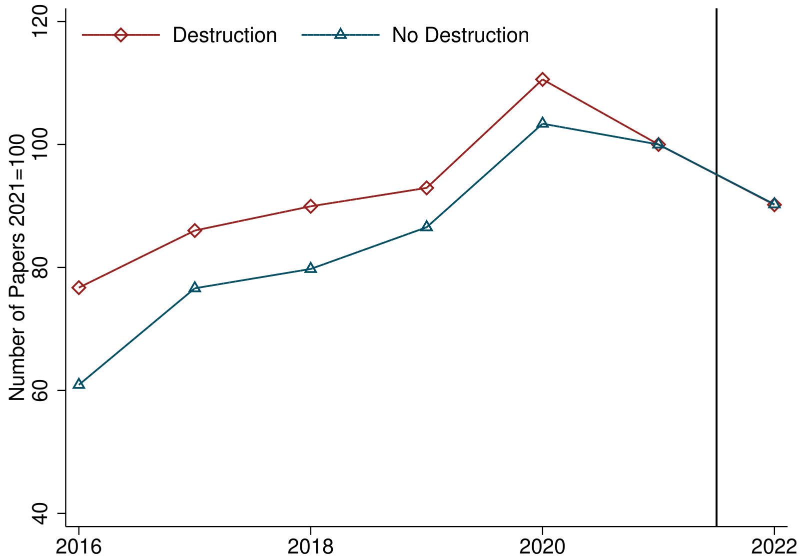
Has the Destruction of Physical Capital Affected Ukrainian Scientific Production?

To gauge the short-run impact of physical destruction on scientific production, we compare trends in the number of papers in universities with and without war-related destruction. For this analysis, we collect data from *Clarivate Web of Science* which allow us to count the number of papers published by at least one author with an affiliation in a top 100 university. We then analyze whether universities with destruction of physical capital experienced a stronger decline in scientific production than universities without destruction.

[17] https://www.bbc.com/news/av/world-europe-60585633.

To ease comparison, we normalize the number of papers in each group to 100 for 2021, the last year before the war.[18] Between 2021 and 2022 the total number of papers declined in both groups of universities (Figure 3). However, there was no disproportionate decline in universities that experienced physical destruction.

Figure 3: Number of Publications by Destruction of Physical Capital



Notes: The figure shows the total number of papers by Ukrainian scientists in the top 100 universities in the *Web of Science*. Note, for this analysis, we collect papers published by *all* scientists in these top 100 universities, not just the 535 elite researchers. To ease the comparison, we normalize the number of papers in each group to 100 for 2021. The red line shows the number of papers by scientists in those top 100 universities that experienced destruction of physical capital. The blue line shows the number of papers in the remainder of the top 100 universities that did not experience destruction of physical capital. For papers that were jointly published by scientists from universities with and without destruction, we proportionately assign papers according to the share of affiliations with and without destruction.

While these results suggest that physical destruction only had a limited impact on scientific production to date, it is important to note that there are significant publication lags in publishing research. As a result, the destruction of physical capital may not yet have visibly affected publication outcomes in 2022.

Nevertheless, these results suggest that the decline in Ukrainian scientific output between 2021 and 2022 was not predominately driven by the destruction of research

[18] In the appendix we report the equivalent figure without normalization (Figure A.1).

laboratories and other physical capital. Rather, it suggests that shocks to scientific human capital are the main source of the decline so far.

3.2 The Effect of War and Conflict on Physical Capital

Only a few papers have studied how the destruction of physical capital affects scientific output. The physical capital destruction of WWII reduced output of German and Austrian universities by about five percent in 1950. By 1961, most of the effects of physical capital destruction had dissipated, and universities destroyed during WWII produced as much output as those not destroyed (Waldinger, 2016). By 1970, universities that had been bombed even fared somewhat better than those that had not been affected, suggesting that bombed departments benefited from upgrading during postwar reconstruction. The evidence on the short and long-run effects of physical capital destruction during WWII suggests that shocks to physical capital can be remedied more easily than shocks to human capital.

While the loss of general physical capital can be overcome relatively quickly, recent research studying adverse events such as explosions or floods indicates that the loss of more specialized physical capital (e.g., equipment or material that has been developed by individual scientists for their specific research purposes, such as novel instruments or genetically engineered animals) is harder to overcome (Baruffaldi and Gaessler, 2021). This research also confirms that the replacement of obsolete physical capital can have positive effects on scientific productivity.

3.3 Lessons for Ukraine

The destruction of physical capital can affect scientific production, especially if destruction is at a larger scale, such as the WWII destruction in Germany and Austria. While the western parts of Ukraine have not experienced large-scale physical destruction, many cities and universities in the East have been heavily destroyed.

Rebuilding such physical infrastructure will be important to aid the reconstruction of Ukrainian universities and research institutions after the war. It is also important to remember that Ukraine's research infrastructure was already outdated and had little investment in recent decades (Gorodnichenko et al., 2022). This suggests that the investments made during the reconstruction will need to be even higher. However, the research on the destruction of physical capital also suggests that upgrading during reconstruction may have positive effects. This may even be beneficial for Ukrainian universities in the future. As discussed earlier, efforts to rebuild destroyed institutions must be complemented by funding for the scientists who work there.

4 War and International Scientific Cooperation

In addition to the loss of human and physical capital described earlier, the war has also hindered the exchange of scientific knowledge and ideas. Travel restrictions and the general insecurity in the country have made it more difficult for Ukrainian researchers to attend conferences and seminars and travel to work with coauthors.

Several international conferences that were scheduled to be held in Russia were cancelled or rescheduled in other locations. For example, the International Math Congress (ICM) was scheduled to be held in St. Petersburg in Russia in July 2022. In May 2022, it was announced that it would take place as a fully virtual event.[19]

Furthermore, interruptions of collaborations with Russian coauthors may have affected knowledge exchange between these two countries, which traditionally had strong scientific ties.

The consequences of such interruptions to international knowledge flows are twofold. First, science as a whole loses because scientists have worse access to knowledge that forms an input in their production of new knowledge. Second, such effects are more pronounced for scientists in countries that suffer disproportionately from the disruption of international knowledge flows (Iaria et al. 2018). In the current war it is likely that Ukrainian and Russian scientists are most affected.

4.1 The Effect of War on International Collaboration of Ukrainian Scientists

To study the short-run effects of the war on international scientific collaborations of Ukrainian scientists, we collect new data on international coauthorships from *Clarivate Web of Science*. The data contain all papers in the *Web of Science* that were published with at least one Ukrainian coauthor. For this analysis, we exclude papers without

[19] https://www.mathunion.org/icm/virtual-icm-2022. Already on February 24, 2022, American Mathematical Society (AMS) President Ruth Charney announced that "The AMS has no plans to send representatives to a meeting in St. Petersburg" and urged "the International Mathematical Union not to hold the ICM in Russia in July 2022." See: https://insidehpc.com/2022/02/american-mathematical-society-cancels-participation-in-2022-icm-conference-in-russia/.

international coauthors. This enables us to compute the share of coauthoring with authors from various countries among all internationally coauthored papers. We then calculate changes in coauthoring of Ukrainian authors with international coauthors between 2021 and 2022.

Coauthoring of Ukrainian authors with authors from Western Europe remained almost constant between 2021 and 2022 (see Figure 4). The share of coauthoring with authors from Eastern Europe increased by around 6 percent, while the share of coauthoring with authors in North America declined by about 4 percent. In sharp contrast, the share of coauthoring with coauthors in Russia declined substantially by more than 40 percent. This decline is even more dramatic if one considers that the Russian invasion did not commence until February 24, 2022, and that there are substantial publication lags in the sciences. The share of coauthoring with coauthors in Belarus declined by more than 30 percent.[20] In the appendix, we show longer-run trends in international coauthoring by Ukrainian scientists (Figure A.2). Notably, the patterns documented in this article are not an artefact of using data from *Clarivate Web of Science*. For example, Van Noorden (2023) shows similar changes using publication data from *Scopus*.

4.2 The Effect of War and Conflict on International Knowledge Flows and Scientific Collaboration

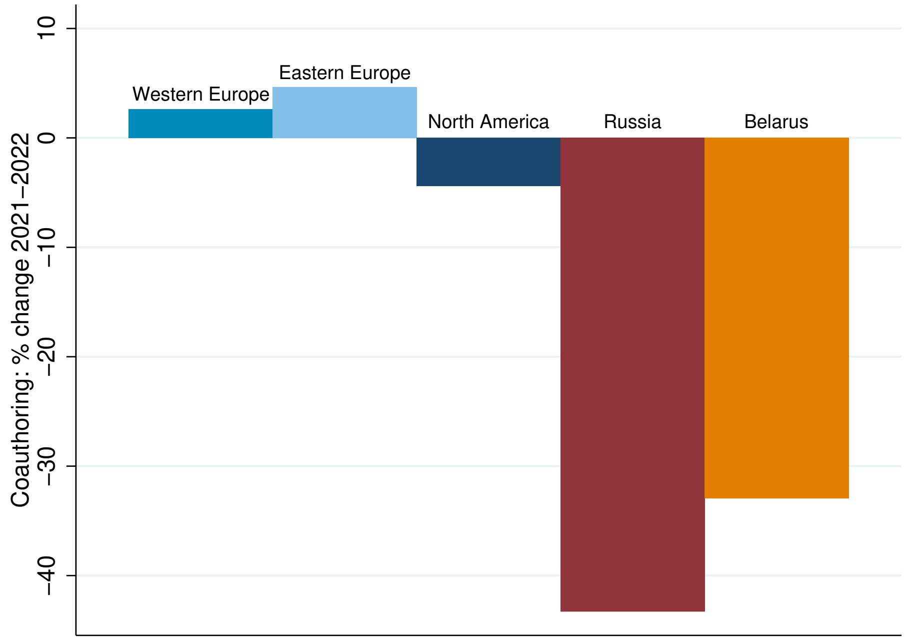
Prior literature has documented that wars can lead to severe disruptions of cross-border knowledge flows and international scientific collaborations. The Allied boycott against scientists from Central countries reduced international scientific collaborations during and after WWI (Iaria et al. 2018).[21] Scientists from Central countries were banned from attending international conferences, and the delivery of scientific journals to countries in the opposing block was severely delayed.[22] The decline in scientific collaborations

[20] It is important to note, however, that coauthoring with authors from Belarus is much rarer than with Russian coauthors (see Figure A.2).

[21] During WWI the world split into the Allied (United Kingdom, France, later the United States, and a number of smaller countries) and Central camps (Germany, Austria-Hungary, Ottoman Empire, Bulgaria). The involvement of scientists in the development of chemical weapons and other war-related research and the extremely nationalistic stance taken by many scientists pitted scientists in the two camps against each other and led to severe disruptions of international scientific collaborations.

[22] The importance of international conferences for exchanging knowledge has also been demonstrated by other research. The cancellation of a major political science conference due to a hurricane reduced the likelihood of collaboration with other attendees compared to attendees at similar conferences that did take place (Campos et al., 2018).

Figure 4: Share Among Foreign Coauthors (Percentage Change 2021-22)



Notes: The figure shows changes between 2021 and 2022 in coauthoring of Ukraine-based authors with coauthors from abroad. The figure is based on all papers in the *Clarivate Web of Science* with at least one coauthor from a Ukrainian university.

reduced the flow of scientific knowledge, as measured by citations to papers from the opposing block. As a result, scientists who were more dependent on foreign knowledge suffered severe reductions in their scientific productivity.

War and conflict have also disrupted international knowledge flows during other episodes. During the Cold War, there were significant barriers to scientific cooperation between the East and the West. Political tensions and ideological differences often made it difficult for researchers from opposite sides to collaborate or exchange information freely (e.g., Ganguli, 2015; Borjas and Doran, 2012). After the end of the Cold War, the subsequent immigration of Russian scientists to the United States increased citations by U.S. based researchers to Soviet-era work (Ganguli 2015). Similarly, book translations between the formerly opposing blocks increased dramatically after the fall of the Iron Curtain (Abramitzky and Sin, 2014).

War and conflict can also affect international knowledge flows by disrupting or breaking up international research teams. The loss of coauthors can have severe impacts on the research output of scientists (e.g., Borjas and Doran, 2015; Azoulay et al., 2010;

Jaravel et al., 2018; Poege et al., 2022).

4.3 Lessons for Ukraine

As shown above, the war has already disrupted scientific collaborations between Ukrainian and Russian scientists. Such disruptions can have long-lasting effects on scientific productivity, especially for those scientists whose research depends more on accessing international scientific knowledge.

Calls for boycotts have a long tradition in science.[23] However, the literature strongly suggests that such boycotts harm not only the boycotted scientists but also the boycotting ones (Iaria et al., 2018). As a result, boycotts slow down long-run scientific progress and are thus harmful for the scientific community as a whole. Furthermore, such boycotts harm the productivity of individual scientists whose research relies on the international knowledge that is cut off through the boycott. This would suggest that Ukrainian scientists themselves could suffer in such a boycott.

To mitigate the effect of reduced international scientific cooperation on Ukrainian science, programs to increase remote/virtual interactions with the international scientific community should be a priority. After the end of the war, questions will be raised regarding a potential return to scientific collaborations with Russian academics. Such a return to normal scientific collaboration will seem very far-fetched and maybe even inconceivable for many scientists in Ukraine. However, the historical evidence indicates that even after WWI, with millions of deaths and very severe involvement of scientists in developing chemical weapons and other military technology, the warring camps came together within less than a decade (e.g., Schroeder-Gudehus, 1973; Cock, 1983; Lehto, 1998; Iaria et al., 2018). Such reconciliation would benefit overall scientific progress.

5 Epilogue

In this article, we provide new evidence that the war in Ukraine has already affected science in Ukraine. These impacts will likely get worse if the war continues. Our data suggest that shocks to Ukrainian scientific human capital have already affected the output of Ukrainian universities, while shocks to physical capital have not yet

[23] See Blakemore et al. (2003) for a general discussion on the justification of boycotts in science. See Stone (2022) for a discussion of boycotts against Russian scientists since the Russian invasion of Ukraine.

visibly affected scientific production. Furthermore, scientific collaborations of Ukrainian scientists with Russian colleagues have declined dramatically since the war began.

Based on these findings and on our analysis of the economics of science and innovation literature, we argue that policies during the war and post-war reconstruction should prioritize the mitigation of shocks to human capital (and to scientists' access to international knowledge). Emigration and occupational re-orientation have long-run consequences, through network effects and through reduced training of young researchers. Such shocks, therefore, have the potential to leave scars that last for decades. It will thus be critical to support scientists who remain in the country and to incentivize return migration to Ukraine after the war has ended. Similarly, programs to keep researchers in the science sector while the war lasts can help alleviate shocks to human capital.

While calls to provide assistance for damaged facilities are important, such shocks to physical capital can be mitigated as long as sufficient funds for reconstruction are made available.

In this paper, we have focused on how the war in Ukraine impacts science *in Ukraine*, but the war also has important implications for other countries and global science. While it is outside of the scope of this paper, we briefly highlight some of these impacts that policymakers should keep in mind.

First, for other countries, trying to attract Ukrainian or Russian scientists may still be a goal, and a large body of prior research shows how other countries can benefit from the migration of high-skilled scientists (e.g., Moser et al., 2014). However, from the perspective of reconstructing science in Ukraine in the long-run, these approaches should be pursued with caution.

Second, the impacts of the war on Russia and Russian academics are still unclear. Many Russian scientists and tech workers fled Russia after Western sanctions and due to the partial mobilization of men aged 18 to 60 to fight in Ukraine. European countries, meanwhile, have made it more costly for Russians to travel to the EU and temporarily suspended visa issuance and introduced other immigration restrictions.[24] As a result, many Russian scientists and tech workers have emigrated to neighboring countries such Armenia, Azerbaijan, and Turkey, but more data is needed to understand these flows.[25]

[24] https://www.consilium.europa.eu/en/press/press-releases/2022/09/09/council-adopts-full-suspension-of-visa-facilitation-with-russia/.

[25] Wachs (2023) show that many of the most important Russian software developers have left Russia after the onset of the war. In the United States, the Biden administration initially asked Congress to amend the Immigration and Nationality Act to allow Russians with an advanced de-

To close, we stress that resources and expertise devoted to data collection to measure the effects of the war in terms of human and physical shocks will be needed to fully understand the effects of the war and to design effective mitigation and reconstruction efforts.

gree in a science, engineering or math field to apply for a visa without first obtaining an employer sponsor in the United States, but this was not pursued by the administration subsequently. See: https://www.cnn.com/2022/05/03/politics/visas-for-highly-educated-russian/index.html.

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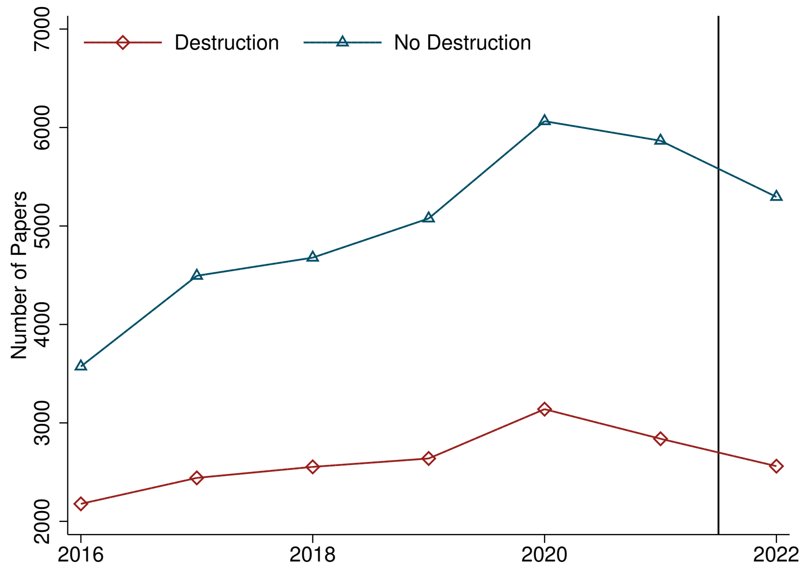
Appendix

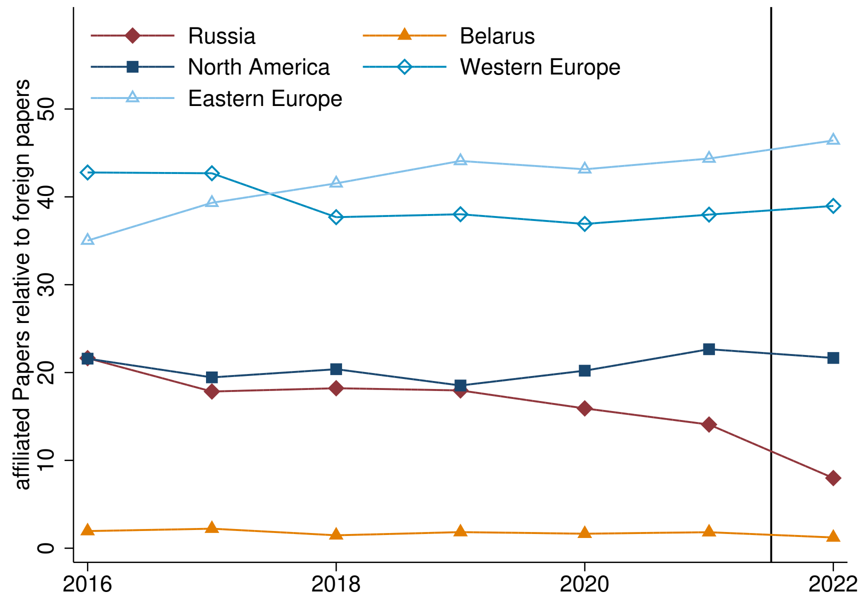
Figure A.1: Number of Publications by Destruction of Physical Capital - Absolute Levels



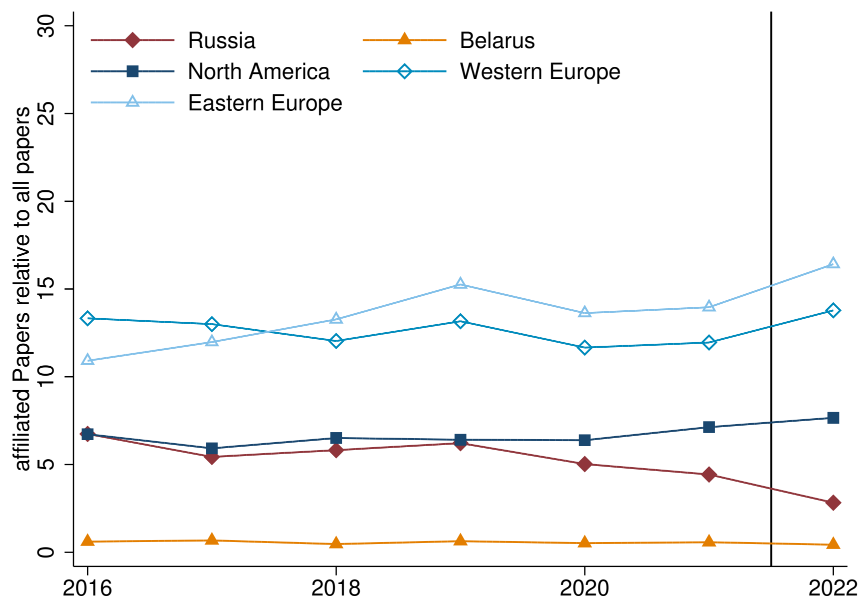
Notes: The figure shows the total number of papers by Ukrainian scientists top 100 universities in the *Web of Science*. It is the equivalent of Figure 3 without normalizing the total number of papers to 100 for the year 2021. As there are more universities without destruction, the total number of papers is higher in that group. The red line shows the number of papers by scientists in the top 100 universities that experienced destruction of physical capital. The blue line shows the number of papers in the top 100 universities that did not experience destruction of physical capital

Figure A.2: Share Among Foreign Coauthors

(a) Share Among All Internationally Coauthored Papers



(b) Share Among All Papers



Notes: The figure shows the share of papers coauthored with authors from various regions/countries from 2016 to 2022 using data from *Clarivate Web of Science*. Panel (a) reports data on all internationally coauthored papers. Panel (b) reports data on all papers, including those that were not coauthored with international coauthors.