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Disease burden among Ukrainians forcibly displaced by the 2022 Russian invasion

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The Russian invasion of Ukraine on February 24, 2022, has displaced more than a quarter of the population. Assessing disease burdens among displaced people is instrumental in informing global public health and humanitarian aid efforts. We estimated the disease burden in Ukrainians displaced both within Ukraine and to other countries by combining a spatiotemporal model of forcible displacement with age- and gender-specific estimates of cardiovascular disease (CVD), diabetes, cancer, HIV, and tuberculosis (TB) in each of Ukraine's 629 raions (i.e., districts). Among displaced Ukrainians as of May 13, we estimated that more than 2.63 million have CVDs, at least 615,000 have diabetes, and over 98,500 have cancer. In addition, more than 86,000 forcibly displaced individuals are living with HIV, and approximately 13,500 have TB. We estimated that the disease prevalence among refugees was lower than the national disease prevalence before the invasion. Accounting for internal displacement and healthcare facilities impacted by the conflict, we estimated that the number of people per hospital has increased by more than two-fold in some areas. As regional healthcare systems come under increasing strain, these estimates can inform the allocation of critical resources under shifting disease burdens.

refugee | conflict | health

Significance

On February 24, 2022, Russia began its invasion of Ukraine, triggering one of the largest mass migrations in Europe since World War II. Although the number and location of displaced individuals are available, there is limited information about their points of origin and health needs. This study estimates the burden of some of Ukraine's most prevalent diseases—cardiovascular diseases, diabetes, cancer, HIV, and tuberculosis—among forcibly displaced Ukrainians due to the 2022 Russian invasion. Our findings indicate regions where healthcare systems may face immediate strain and suggest critical targets for humanitarian aid within Ukraine.

The 2022 Russian invasion of Ukraine is the most extensive military operation that Europe has witnessed since World War II. As of July 15, over 6.1 million Ukrainians have fled their country, with more than 6.2 million internally displaced (1, 2), fueling a humanitarian crisis with lasting effects. The humanitarian needs range from essentials such as water, food, sanitation, and shelter to more complex needs, including preventative and critical healthcare, particularly in vulnerable groups such as unaccompanied children and those suffering from preexisting medical conditions. Chronic and infectious diseases among forcibly displaced Ukrainians pose immediate health risks and may contribute to strain on healthcare systems.

Although cardiovascular diseases (CVD), cancers, and diabetes are responsible for 79% of all mortality in Ukraine (3, 4), the country also has among the highest HIV and tuberculosis (TB) burdens in Europe (5, 6). Without international assistance, countries sheltering Ukrainians may be unable to provide adequate healthcare to meet the needs of refugees with such conditions. Inside Ukraine, the war continues to weaken the health system infrastructure, making healthcare delivery more challenging. Moreover, overcrowded shelters can amplify the spread of infectious diseases, further straining the healthcare system. Meeting the healthcare needs of internally displaced Ukrainians becomes increasingly challenging as conflict threatens to engulf the whole country and destroy healthcare facilities. Inadequate support for the healthcare needs of refugees and internally displaced persons (IDPs) with preexisting conditions can endanger lives and potentially fuel public health crises. Within days of the Russian invasion of Ukraine on February 24, multiple organizations began to deploy humanitarian aid (7). However, extensive fighting in some regions of Ukraine has impeded the delivery of aid (8). Combat has damaged critical infrastructure, increased the complexity of civilian evacuation, and resulted in intense overcrowding at IDP sites (8, 9). In a report published on March 1, 2022 from the United Nations Office for the Coordination of Humanitarian Affairs (OCHA), it was estimated that 12 million people may require assistance within Ukraine before June 2022. By the end of June 2022, 86% of this estimated target was reached (10, 11).

In this study, we evaluated the immediate and long-term needs of those who remain in the country with a rapidly deteriorating healthcare system and those who have left the country and may strain systems not equipped for the additional burden. Such evaluation requires assessing the number of refugees and IDPs with preexisting conditions. To estimate the burden of CVD, diabetes, cancer, HIV, and TB among Ukrainians impacted by the invasion, we developed a probabilistic framework—informed by data on the number of

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refugees, conflict events, and raion-level (i.e., district-level) disease burdens. We then mapped the displaced population within Ukraine and outside the country using data on geographical, social, and economic metrics. Finally, we combined these two estimates to infer disease prevalence among forcibly displaced Ukrainians at each destination.

Results

Heterogeneity in Disease Prior to the Invasion. Even prior to Russia invading Ukraine, there was substantial heterogeneity in prevalence across location, age, and gender observed relative to the national prevalence of the diseases considered in this analysis—CVD, diabetes, cancer, HIV, and TB (Fig. 1 and *SI Appendix*, Fig. S1). For example, the burden of CVD or cancer is disproportionate, skewed toward those aged 70 y and older (*SI Appendix*, Fig. S1 *A–C*). However, cancer prevalence exhibits more notable variation spatially than CVD (*SI Appendix*, Fig. S1 *A–C*). Similarly, diabetes affects the population aged 70 y and older more than children. Among this elderly population, there is an increased burden of diabetes among males compared to their female counterparts (*SI Appendix*, Fig. S1*B*). For HIV infection, adult males aged 44 to 59 y who reside in southern Ukraine are more likely to have the disease than females aged 50 y and older who reside in western Ukraine (Fig. 1 and *SI Appendix*, Fig. S1*D*). Similarly, the extent of the TB burden in Ukraine emanates from the southern and eastern regions, skewed toward the male population aged 40 y and older (Fig. 1 and *SI Appendix*, Fig. S1*E*).

Heterogeneity in Forcible Displacement. Aid organizations have reported numbers of forcibly displaced individuals for the six macroregions in Ukraine—North, East, West, South, Central, and Kyiv (Fig. 1*H* and *SI Appendix*, Figs. S3 and S7). Distance to conflict is specified to be a determining factor in the probability of displacement. We examined the additional role of age, gender, and socioeconomic status in explaining the reported displacement

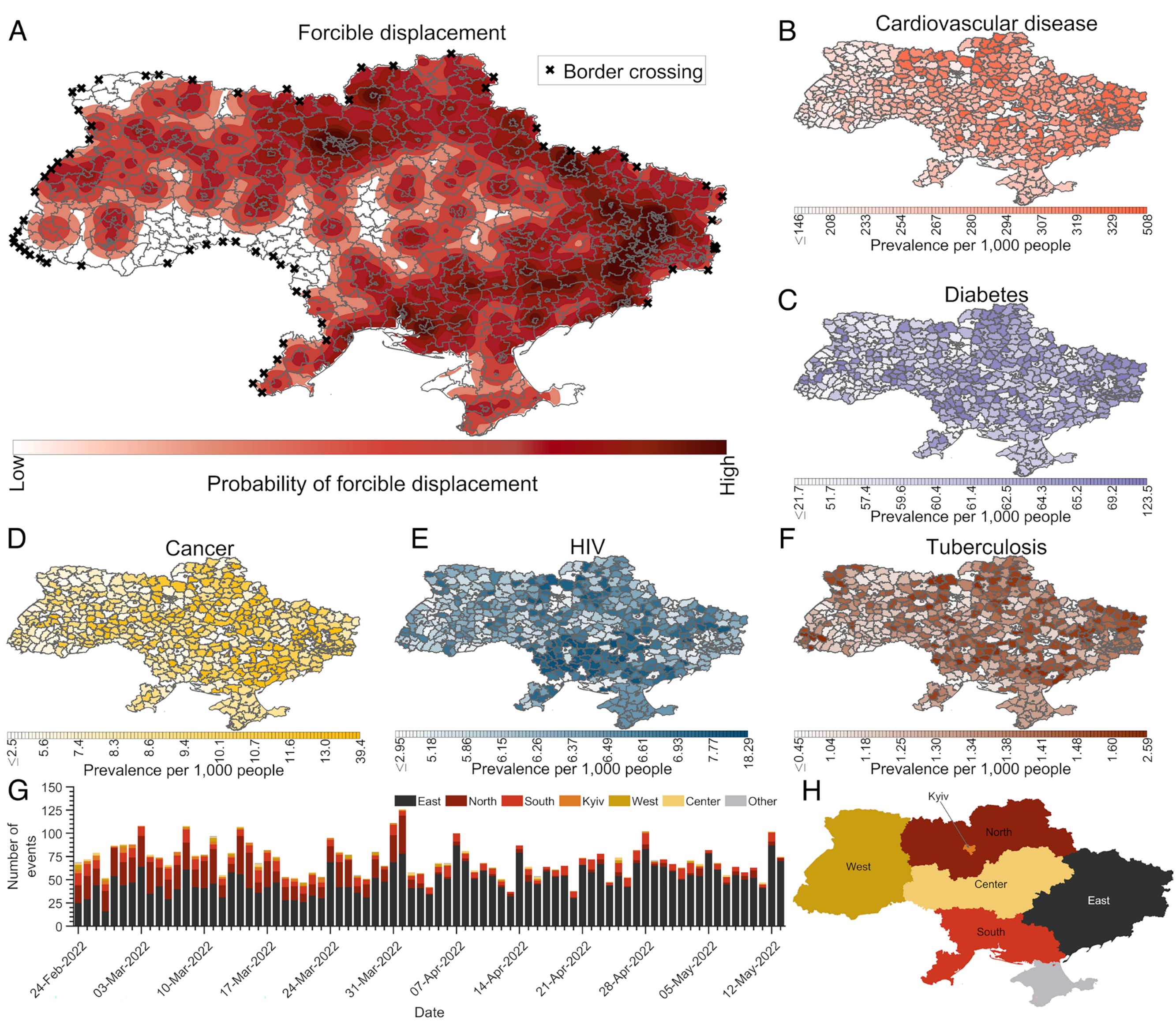

Fig. 1. The effects of disease burden and intensity of conflict within Ukraine on refugees. (*A*) The estimated average intensity of conflict under a $\log_{10}$ transformation from February 24, 2022, to May 13, 2022 (dark red = greatest intensity) based on reported conflict events (12) and reported border crossings (13) (black x). (*B–F*) The estimated prevalence per capita (light = low prevalence and dark = high prevalence) among Ukraine raions for (*B*) CVD, (*C*) diabetes, (*D*) cancer, (*E*) HIV, and (*F*) TB before the Russian invasion. (*G*) The daily number of conflict events reported by the ACLED inside and outside the six macroregions (black = East, dark red = North, red = South, orange = Kyiv, dark yellow = West, light yellow = Center, and gray = Other) between February 24 and May 13. (*H*) The geographical location of the six macroregions (black = East, dark red = North, red = South, orange = Kyiv, dark yellow = West, and light yellow = Center).

data of Ukrainians between February 24, 2022, and May 13, 2022. We determined the spatiotemporal probability of forcible displacement by fitting the model-estimated daily number of refugees and IDPs to the reported daily number of refugees between February 24, 2022 and May 13, 2022, as well as the number of IDPs reported on March 16, April 1, April 17, and May 3. Through model selection, we found that socioeconomic status of a location and age was the additional model variable that parsimoniously explained the substantial age- and gender-specific heterogeneity observed in the spatiotemporal displacement data (Fig. 1 and *SI Appendix*, Fig. S1*F*).

Over the first two and a half months of the invasion, the likelihood of forcible displacement has been highest in eastern and northern Ukraine and lowest in central and western Ukraine (Fig. 1*A*). Specifically, an individual residing in the Kyiv macroregion was 17.06 (95% credible interval [CrI]: 14.80 to 25.46) times more likely to flee home than someone from the West macroregion. Temporally, eastern Ukraine has consistently experienced at least 16 conflict events per day, averaging more than 49 events per day (Fig. 1 *G* and *H*). In northern Ukraine, over 85% of the conflict events occurred during the first 5 wk of the invasion and dissipated over the following 6 wk (Fig. 1 *G* and *H*). In the central and western parts of Ukraine, conflict events were sporadic, with a median of zero conflict events per day in each separate region (Fig. 1 *G* and *H*).

Disease Burden among the Forcibly Displaced. Combining the spatiotemporal probability of being forcibly displaced with estimates of raion-level disease prevalence (Fig. 1 *A*–*F*), we evaluated the burden of CVD, diabetes, cancer, HIV, and TB among the displaced. We estimate that the prevalence of CVD among the displaced population is 1,788.9 (95% CrI: 1,545.5 to 2,164.7) per 10,000; diabetes is 417.4 (95% CrI: 380.1 to 452.6) per 10,000; cancer is 66.8 (95% CrI: 59.4 to 80.3) per 10,000; HIV is 58.8 (95% CrI: 44.4 to 73) per 10,000; and TB prevalence is 9.3 (95% CrI: 8.1 to 10.4) per 10,000. In contrast, the national prevalence of these diseases is between 1.2% (95% CrI: −1.4 to 6.1%) and 44.5% (95% CrI: 25.8 to 61.7%) larger than that estimated among the forcibly displaced population.

Disease Burden among Refugee Population. Of the estimated 6.12 (95% CrI: 5.84 to 6.36) million Ukrainians fleeing the country between February 24 and May 13, 2022, we determined that 1,072,532 (95% CrI: 906,842 to 1,296,355) have CVD; 253,275 (95% CrI: 226,093 to 275,880) have diabetes; 40,011 (95% CrI: 34,844 to 48,079) have cancer; 35,694 (95% CrI: 26,855 to 44,428) live with HIV; and 5,625 (95% CrI: 4,844 to 6,357) have TB (Table 1 and Dataset S1).

The location of refugees reported as of May 13, 2022, is Poland, Belarus, Moldova, Hungary, Slovakia, Russian Federation, Romania, and other European countries. To determine the destination of Ukrainian refugees, we considered social connectedness, distance to the border, economic wealth, and perceived safety. Through the model section process, we identified social connectedness, distance to the border, gross domestic product (GDP), GDP per capita, and NATO status of the refugee country as the essential determinants of a refugee's final destination (Dataset S1).

The prevalence of disease among refugees was relatively similar for those entering Poland, Belarus, Moldova, Hungary, Slovakia, Russian Federation, Romania, and other European countries

Table 1. For the period between February 24 and May 13, 2022, the estimated number of refugees entering Russia, Poland, Belarus, Slovakia, Hungary, Romania, Moldova, and other European countries and internally displaced people (IDP) in Ukraine and the estimated number of refugees with CVD, diabetes, cancer, HIV, and TB and corresponding 95% credible intervals

Location	Total	CVD	Diabetes	Cancer	HIV	TB
IDPs	8,633,485 (7,881,366 to 8,898,878)	1,566,935 (1,292,321 to 1,845,102)	362,570 (314,063 to 389,702)	58,530 (49,604 to 67,911)	51,010 (37,187 to 61,872)	8,031 (6,739 to 8,924)
Poland	3,292,058 (3,139,930 to 3,420,255)	578,996 (489,317 to 699,099)	136,393 (121,733 to 148,589)	21,588 (18,790 to 25,901)	19,161 (14,404 to 23,833)	3,029 (2,608 to 3,422)
Romania	818,560 (780,539 to 853,678)	141,403 (119,379 to 171,159)	33,602 (30,025 to 36,688)	5,292 (4,625 to 6,385)	4,798 (3,610 to 6,005)	747 (643 to 845)
Russia	783,902 (747,377 to 813,827)	141,441 (119,722 to 169,747)	33,484 (29,849 to 36,500)	5,216 (4,535 to 6,229)	4,642 (3,493 to 5,780)	746 (642 to 843)
Hungary	650,748 (621,731 to 677,790)	112,228 (94,902 to 136,289)	26,542 (23,733 to 29,021)	4,209 (3,684 to 5,091)	3,778 (2,846 to 4,724)	589 (507 to 667)
Slovakia	403,041 (370,293 to 422,065)	67,667 (56,485 to 83,407)	15,984 (13,851 to 17,565)	2,564 (2,167 to 3,136)	2,301 (1,716 to 2,865)	353 (300 to 401)
Belarus	107,841 (102,294 to 119,073)	19,225 (16,220 to 23,463)	4,530 (4,052 to 5,024)	713 (624 to 862)	632 (476 to 797)	101 (87 to 117)
Moldova	51,309 (48,393 to 62,851)	9,164 (7,725 to 11,388)	2,172 (1,929 to 2,597)	339 (296 to 420)	303 (227 to 395)	48 (41 to 59)
Europe	13,743 (10,010 to 14,393)	2,408 (1,693 to 2,829)	569 (404 to 610)	90 (64 to 105)	80 (53 to 96)	13 (9 to 14)

(Dataset S1). Based on the maximum likelihood estimate, Slovakia was estimated to have the lowest prevalence of disease for refugees among all regions and diseases considered, while Russia was estimated to have the greatest prevalence for all diseases.

Disease Burden among the Internally Displaced Population. Based on the model parameterized to the number of IDPs reported on March 16, April 1, April 17, and May 3, we estimated 8.63 (95% CrI: 7.88 to 8.90) million IDPs by May 13 (Table 1). Of these IDPs, we estimate 1,566,935 (95% CrI: 1,292,321 to 1,845,102) to have CVD; 362,570 (95% CrI: 314,063 to 389,702) to have diabetes; 58,530 (95% CrI: 49,604 to 67,911) to have cancer; 51,010 (95% CrI: 37,187 to 61,872) to live with HIV; and 8,031 (95% CrI: 6,739 to 8,924) to have TB (Table 1 and Dataset S1).

To determine the destination of forcibly displaced Ukrainian in a specified raion, we considered social connectedness, perceived safety, and wealth. Through the model selection process, the extent of local conflict parsimoniously explained the spatial distribution of IDPs across the macroregions of Ukraine (Dataset S1).

Among these macroregions, the population size and disease burden were dynamic throughout the invasion (Fig. 2). We estimated that the West macroregion exhibited the largest increase in population (23.55%; 95% CrI: 21.71 to 24.64%), while the Kyiv macroregion was determined to have the greatest reduction in population (87.76%; 95% CrI: 83.05 to 93.96%) (Fig. 2*A*). Qualitatively, this trend persisted when examining the temporal disease burdens in the macroregions (Fig. 2 *B–F*). We found that the age distribution of the population, as well as those with a specific disease in a macroregion before the invasion, remains relatively stationary for the different macroregions except Kyiv (Fig. 2). The age distribution in Kyiv shifted toward a more elderly population as there was a notable reduction in the younger population, as seen across all diseases (Fig. 2).

Impact of Displacement and Conflict on the Healthcare System. The impact of the invasion on the local health system is dependent on ensuing population movement and access to healthcare facilities. Analyzing the distribution of IDPs at the more granular raion level, we found that the concentration of IDPs is near the country borders in the West and South macroregions (Fig. 3*A*). In contrast, the estimated concentration of IDPs in the North macroregion is to the exterior macroregion toward the West. Within the East macroregion, the concentration of IDPs is in the raions located near the borders of the Center macroregion (Fig. 3*A*). Of the 1,038 reported locations of hospitals in Ukraine, we estimated that 171 (95% CrI: 156 to 185) are inaccessible due to conflict as of May 13. The Kyiv and East macroregions were the two most affected by conflict, with 53.62% (95% CrI: 46.89 to 62.78%) and 32.02% (95% CrI: 29.47 to 34.26%) of their hospitals deemed inaccessible due to conflict (Fig. 3*B* and Dataset S1).

To measure the strain of the invasion on the local healthcare system, we calculated the number of people per hospital pre- and postinvasion. Of the 343 raions containing a hospital, an estimated 68.80% (95% CrI: 67.64 to 72.01%) have at least a 5% increase in the number of people per hospital and 27.70% (95% CrI: 25.95 to 28.57%) to have a reduction in the burden (Fig. 3*C* and Dataset S1). At the level of the macroregions, the West macroregion was estimated to have the greatest increase in the number of people per hospital, despite experiencing the least amount of destruction in hospitals (Figs. 2*A* and 3*D*). Among the West, Center, Crimea, and North macroregions, the burden of disease on the local healthcare system increased across all categories (Fig. 3*D*). Within the South macroregion, there is an increased burden with respect to CVD, diabetes, and cancer; in the East macroregion, we estimated that the burden increased moderately for CVD and cancer (Fig. 3*D*). Kyiv macroregion is estimated to have the greatest reduction in the number of people per hospital (Fig. 3*D*). This reduction for Kyiv is due to the extensive decrease in the population relative to increased inaccessibility to healthcare facilities (Figs. 2*A* and 3 *A–C*). To retain the same number of people per hospital as preinvasion, the West macroregion requires 62 (95% CrI: 57 to 64) additional hospitals, 37 (95% CrI: 34 to 39) in the Center macroregion, 4 (95% CrI: 4 to 4) in Crimea, and 2 (95% CrI: 0 to 4) in the North macroregion (*SI Appendix*, Fig. S12). Despite a decrease in the burden with respect to the general population for some macroregions, we estimated that for CVD, diabetes, and cancer, there can be additional hospitals required to alleviate the burden at the regional level (Fig. 3*D* and *SI Appendix*, Fig. S12).

Discussion

Assessing the potential healthcare needs of Ukrainians displaced by the Russian invasion requires knowledge of where the individuals originated within Ukraine, demographic characteristics, and the spatial–demographic disease prevalence. We constructed a probabilistic framework to infer the origin locations and demographic characteristics of those forcibly displaced. We then quantified the burden of CVD, diabetes, cancer, HIV, and TB among refugees and IDPs. Our analysis up to May 13, 2022 highlights the importance of accounting for the spatial and demographic heterogeneity in disease prevalence in evaluating shifting disease burdens and distributions of healthcare needs. Specifically, integrating these heterogeneities, we found that disease prevalence among refugees and IDPs was typically lower than national prevalence before the Russian invasion. Inside Ukraine, healthcare capacity is rapidly deteriorating with the destruction of healthcare facilities. Despite depopulation in regions of conflict, we found that the devastation of hospitals in those regions has resulted in a reduction in per capita healthcare resources. The interplay between changing population demographics, disease burdens, and destruction of healthcare facilities lead to dynamic healthcare needs, influencing the optimal distribution of humanitarian needs.

Prior studies have included conflict in their analysis by assuming that spatial intensity is based only on the conflict at specified borders, such that conflict beyond the immediate border area is assumed to have no impact on forcible migration. In contrast, our probabilistic modeling framework determines the likelihood of displacement at a granular level—providing a scale of continuity for the impact and intensity of the conflict. The rapid escalation of combat in Ukraine generated a surge of displacement, thereby causing a backlog of individuals attempting to flee the country. However, prior models of forcible displacement do not consider individuals transitioning from being internally displaced to refugees (14–20). By accounting for this transition in our model, we more accurately identify the origin locations of the forcibly displaced population to improve temporal understanding of the spatial distribution of IDPs and refugees.

The disease burden in Ukraine is heterogeneously distributed spatially, as well as across age and gender. However, the likelihood of forcible displacement is also heterogeneous across spatial and demographic factors, which will influence the disease prevalence among the forcibly displaced. In our analysis, locations of active conflict were the primary driver forcing individuals to flee their homes. We also examined the importance of age, gender, and socioeconomic status of individuals in deciding whether to leave.

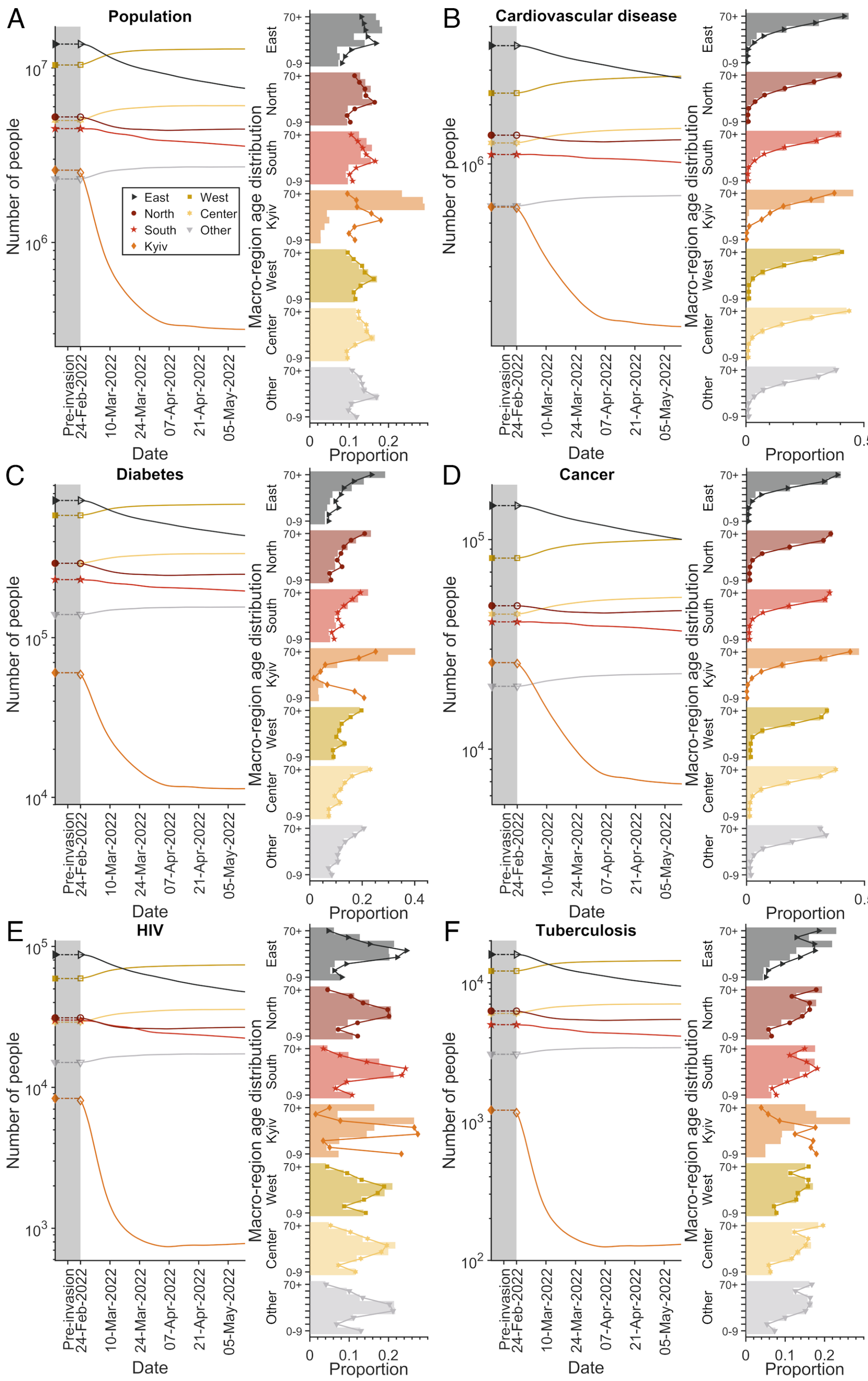

Fig. 2. Disease among individuals in Ukraine. Among the West (dark yellow square), South (red star), North (dark red circle), Other (Crimea; gray triangle), Kyiv (orange diamond), East (black triangle), and Center (light yellow hexagram) macroregions in Ukraine, the temporal change in the number of people (*Left*) and age distribution (*Right*) up to May 13 for the (*A*) total population and those with (*B*) CVD, (*C*) diabetes, (*D*) cancer, (*E*) HIV, or (*F*) TB. The comparison of the age distribution among the different macroregions is preinvasion (lines) to that estimated for May 13, 2022 (histogram bars). Ages are stratified as 0 to 9, 10 to 19, 20 to 29, 30 to 39, 40 to 49, 50 to 59, 60 to 69, and 70+ years.

Consistent with prior survey studies outside the 2022 Russian invasion of Ukraine (21–23), we found that age and socioeconomic status explain the forcible displacement data stratified by location, age, and gender well. Although disease-dependent probability of displacement was not implemented, its effects on displacement are likely reflected implicitly through the selected

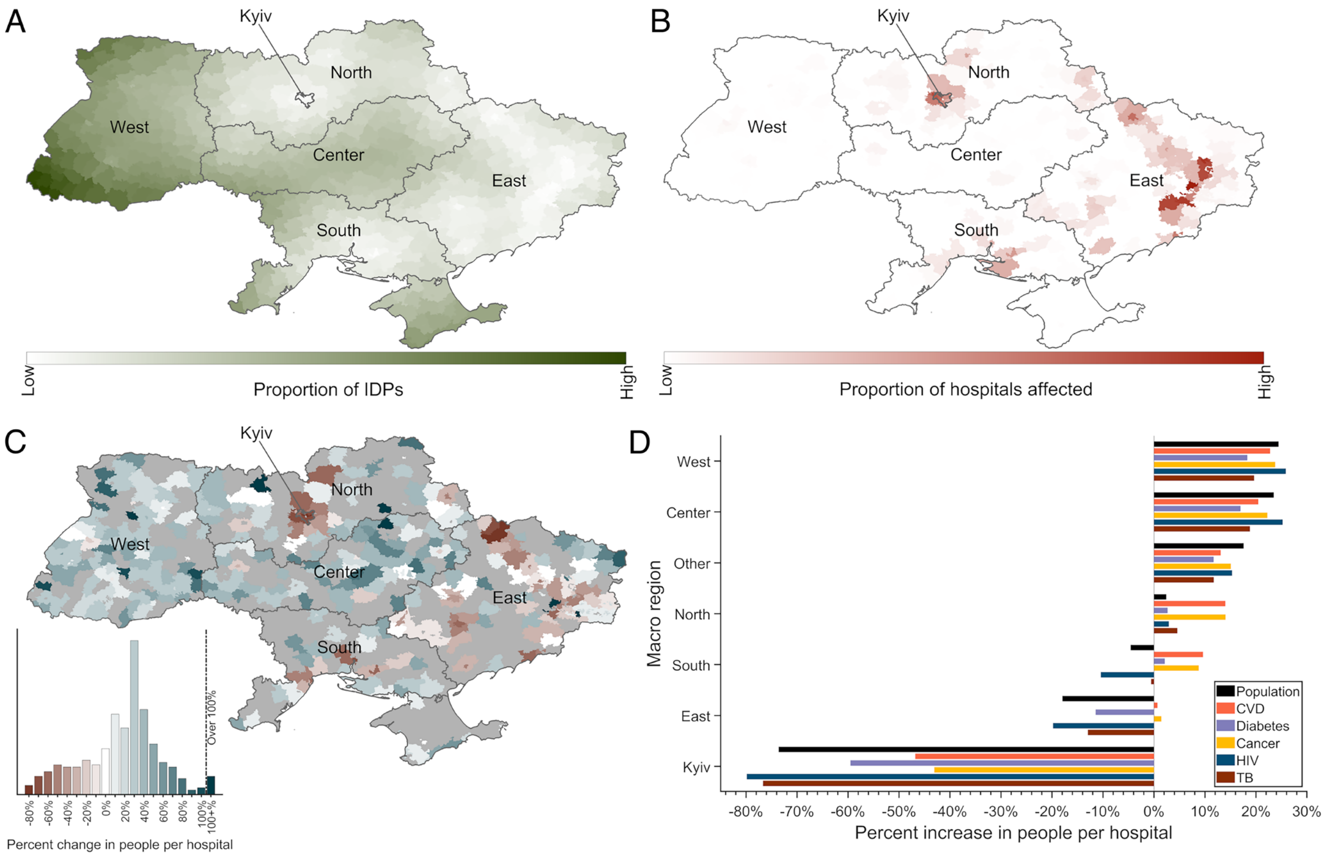

Fig. 3. Public health implications of the Russian invasion. Based on reports from March 16, April 1, April 17, and May 3 for IDPs among the macroregions of Ukraine, (*A*) the estimated destination distribution of IDPs among the 629 raions as of May 13. (*B*) The proportion of hospitals affected by conflict in each raion (white = low proportion and dark red = high proportion) over the course of the invasion. (*C*) The relative change in the number of people per hospital compared to that determined preinvasion for raions containing a hospital (brown = reduction, white = no, dark green = increase, and gray= no hospital). (*D*) The percent increase in people per hospital for each macroregion relative to the number of people per hospital prior to the Russian invasion for the total population (black), as well as those with CVD (red), diabetes (purple), cancer (yellow), HIV (blue), and TB (brown).

factors of age and socioeconomic status. Given the imposition of martial law by the Ukrainian government, one would have expected gender to play a more prominent role in determining the probability of forcible displacement. However, model selection ruled out any model consisting of age and gender together as the best model candidate. This outcome could have stemmed from our assumption prohibiting males aged 18 to 60 y from displacement due to martial law. In reality, there are exemptions for martial law (24). Thus, the selection of age and socioeconomic status may have averaged out these exemptions in the age class between 18 to 60 y to best explain the observed data.

Estimating disease burden among the forcibly displaced using a crude approximation to national prevalence was found to overestimate prevalence for most diseases. However, heterogeneity is critical to the analysis because some diseases disproportionately impact different demographic groups. By combining the heterogeneities in disease prevalence and displacement, we more accurately reflect the disease burden in the forcibly displaced population. Specifically, cancer and CVD burdens occur primarily among the elderly, who are less likely to relocate. TB and HIV disproportionately impact adult men younger than 60 y, who may be prohibited from leaving the country under martial law restrictions. In contrast, young females and children, who constituted most of the displaced population during the early phases of the war, are less likely to suffer from chronic conditions. Direct assessments of healthcare needs through surveys for each refugee would be a time- and resource-consuming process which could impede and delay aid to those in need. Smaller random sample surveys alleviate some logistical issues (25) but could struggle to quantify the burden of low-prevalence high-risk diseases. In our analysis, for example, we estimated the prevalence of TB to be 9.19 per 10,000 refugees. However, a survey with a minimum sample size of 3,258 individuals would be required to detect at least one TB infection with a 95% probability. Another challenge is that the results from such surveys can quickly become outdated due to the dynamic nature of the humanitarian crisis. Therefore, the probabilistic modeling framework developed in this study provides a complementary approach to rapidly evaluate and estimate evolving healthcare needs during shifting sociopolitical situations.

Previous modeling frameworks (14–20) have analyzed forced migration integrating factors such as population density, socioeconomic characteristics, and intensity of conflict in other locations. Nevertheless, the application of these frameworks to post-Soviet states has not occurred. After individuals are forcibly displaced, a multitude of factors influence the choice of their destination. However, the influence of these factors on the decision-making process is unclear. The rapid early influx of refugees into neighboring countries overwhelmed social and healthcare services. For example, the population of Warsaw, Poland, increased by 20% within a few weeks of the Russian invasion (26), while the number of refugees residing in Moldova amounts to the size of the second-largest city in the country (27). Among neighboring countries hosting refugees, we explored the influence of social connectedness, economic wealth (GDP and GDP per capita), perceived safety (NATO status), and distance to the border from the location in Ukraine. The identified factors that parsimoniously explained refugees' choice of country (ranked from most to least important) were NATO status, GDP, distance to the border, social connectedness, and GDP per capita. We found that there were several simpler models that were not significantly different (ΔAIC < 2) than the best model selected. Each factor influences the distribution of disease burden among countries, reflected by the amount of dispersion from the model estimates of the number of refugees with a disease. The most notable variability in the estimated total disease burden was in Moldova and Belarus. Regarding disease prevalence among refugees, factors dependent on the origin location (e.g., distance to the border) will integrate heterogeneity into disease prevalence among refugees heading to a country. Nonetheless, disease prevalence among refugees for all diseases remained relatively robust irrespective of the choice of the model that determines the destination country.

Asylum in neighboring countries was transient for some as they dispersed across the globe. As a result, even nonneighboring countries have felt the strain of the refugee crisis throughout the Russian invasion (28–30). While our results estimate the disease burden among the refugee population, expansion of the model to include further migration from neighboring countries can provide insight into dispersion of disease burden more broadly. Many of these countries hosting Ukrainian refugees may be unable to handle additional waves of immigration as they are already at or have surpassed capacity. The care available to residents and refugees has been spread thin. In the short term, volunteers were available. However, more stable aid is required, with refugee aid centers being overworked and overwhelmed and depleting housing options (29, 31). Poland, for example, is struggling to maintain efficiency in its services for refugees and their citizens (32). Moreover, those with complex chronic conditions entering Moldova must be transported to other countries in the European Union to receive proper care (33). With the ensuing winter months and Russia targeting power and gas sources, a large wave of Ukrainian refugees is expected (30). Refugees are already disproportionately distributed across Europe, causing animosity between countries (29, 34). For example, Moldova—one of the poorest countries in Europe—was housing more refugees per capita in the early stages of the invasion than other neighboring countries (33, 34). Most recently, the Czech Republic has had more refugees than France, Italy, and Spain combined, with the German state of Baden-Wurttemberg hosting more refugees than France (29). The long-term concern is the antirefugee tensions in the host countries, with issues already arising (33, 35, 36). Given the extensive burden of chronic conditions among Ukrainians, the long-term goals should also be focused on alleviating any additional patient burden on the healthcare system.

To infer the destination of the IDPs within Ukraine, we considered several factors such as social connectedness, conflict, and wealth. The extent and location of conflict were the critical components in identifying the location of IDPs. As a result, the selected model estimated a dramatic reduction in the population in Kyiv due to decreased flow of IDPs into the region. However, despite intense combat near Kyiv, the capital of Ukraine was one of the top five oblasts in hosting IDPs affected by the war (37), which is likely attributed to the increased opportunities for employment and social services in urban centers (38). Inclusion of other factors such as areas under Russian control, total capital per capita, and social connectedness also provided insight into the destination location of IDPs in our analysis and can improve the estimates of population changes in all macroregions (Dataset S1). All IDP destination models were relatively robust in their estimate of disease burdens for the different macroregions of Ukraine, except for Crimea. The estimated disease burden in Crimea highly depends on the extent of Russian influence/control on an individual preference in seeking safety in Ukraine. Excluding Crimea, the Kyiv macroregion had the greatest dispersion among the model estimates for absolute disease burden, with the estimated prevalence being relatively robust across models. The similarities between the destination country for refugees and location of IDPs are evident—forcibly displaced people prefer safe areas with economic prosperity and are less influenced by their social connection to an area.

As reports and our analysis highlight, the war has affected the Ukrainian health system, particularly facilities located in conflict-intense regions. Our analysis relied on the only available information that was the number of hospitals. However, incorporating heterogeneity in hospital capacity can improve the estimation of disease burden on the local healthcare systems. For example, rural regions have fewer physicians and nurses relative to urban centers (39). Many hospitals near the war front in eastern Ukraine during the early stages were small and rural. Most doctors and nurses in the area fled the conflict and the number of wounded from war limited capacity in the hospitals (40). With fewer staff members, smaller patient capacity, and a rapid increase in the population, the rural healthcare systems could quickly become overwhelmed. In the context of our results, regions where bed capacity is relatively homogeneous, our current results would be relatively robust. In areas where bed capacities are heterogeneous across hospitals, the burden becomes more sensitive to the hospitals affected by conflict.

While we calculate the disease burden among the forcibly displaced for some of the most prominent diseases in Ukraine, a more accurate assessment of healthcare needs requires accounting for the type of care necessary for the patient. For example, cancer treatment depends on the stage and type of cancer at the time of diagnosis. Also, there may be immediate or long-term consequences due to delayed care. Delaying chemotherapy treatment of colorectal cancer, the most prevalent cancer in Ukraine (41), by 4 wk increases the probability of death by 13% (42). In contrast, interruption of HIV treatment may not immediately impact the individual. Limiting access to diagnostic and treatment centers can be particularly concerning for diseases which heavily rely on these components for effective population-level control. For example, during the COVID-19 pandemic, there was a 30% decrease in the diagnosis and treatment of TB, producing a surge in transmission (43). Moreover, the inoperability of pharmacies further impacts access to medications due to constraints on supply and staffing shortages. Among IDPs surveyed, only 64% reported that all local pharmacies remained operable (37). In addition, increased costs and lack of medication availability have prevented people from receiving their medicine (44). As the war prolongs, estimates indicate that the proportion of Ukrainians living below the poverty line will increase to as high as 60% (44), limiting access to healthcare needs further among the forcibly displaced.

Our estimates for disease burden could be improved further if data on the locations of specialty hospitals were available. Limiting access to these specialty hospitals can profoundly affect patient care and the proportion of the population impacted (45). For example, the National Cancer Institute is Ukraine's leading center for oncology. It caters to the most complicated cases from across the country. Due to its specialization in oncology and quality of care, patients prefer the National Cancer Institute over the care they receive at regional oncology centers (39). In terms of HIV treatment, there are 400 sites across the country, with a regional center in each area. Nevertheless, the locations of these centers across regions are not uniform, possibly requiring rural patients to travel (39). With the extent of conflict in urban areas and HIV at-risk populations more likely to be discriminated against in rural areas, many patients could go without treatment (39). Considering all factors impacting access to care and healthcare capacity, our results only provide a conservative estimate to quantify the increased burden on the local healthcare systems.

At the population level, disruption of disease surveillance measures heightens risks of outbreaks going undetected and thus unmitigated. As in prior epidemics with heightened conflict, the damage to healthcare infrastructure can exacerbate the disease burden (46). In particular, the unmonitored spread of infectious disease among trapped populations could broadly disseminate disease throughout Ukraine upon extraction from the war zone. Despite international humanitarian laws that protect medical operations during armed conflicts, attacks on healthcare personnel and facilities have been deliberate (47, 48). Since the Russian invasion, the World Health Organization has confirmed over 200 attacks on health facilities throughout Ukraine (48). Through a combination of the destruction of hospitals in areas of heavy conflict and an influx of IDPs, we found that the disease burden per hospital increased across all six macroregions of Ukraine. For those trapped in regions with active conflict, access to treatment and care may be even more challenging. In a recent survey, roughly 33% living in a conflict zone stated that their access to care had been reduced compared to 22% across Ukraine (44). Moreover, our analysis suggests that the elderly and low-socioeconomic status families are less likely to flee their homes than others, implying the trapped population may have a higher burden of chronic noncommunicable diseases (e.g., CVD, cancer, and diabetes). Thus, with this burden and the greater likelihood of patient frailty, the level and timeliness of care needed for these individuals becomes more pertinent in conflict-intense regions.

Our framework is applicable to other chronic and infectious diseases, mainly with preventive efforts impeded in most of the country. For example, roughly 36% of Ukrainians have received a COVID-19 vaccine (49). Additionally, overcrowded IDP sites may exacerbate widespread COVID-19 transmission, with case-fatality rates elevated by inadequate care. Polio outbreaks are another recent concern, particularly given Ukraine's low polio vaccination coverage (50, 51). Before the invasion, there was 20 confirmed polio cases in western Ukraine in the regions of Rivne and Zakarpattia (52). The invasion has halted polio surveillance and a campaign aiming to vaccinate 140,000 children against polio (53, 54). Furthermore, limited access to clean water and the deterioration of sanitation and hygiene alongside crowded conditions increase the threat of new disease outbreaks (55). The extension of our methodologies to similar humanitarian crises or other public health crises will depend on the availability of relevant data. For example, the framework presented here could also be utilized to assess the risk of disease outbreaks from vaccine-preventable diseases among displaced populations.

With the Ukrainian refugee crisis reported as the fastest growing in Europe since World War II (56), there is an urgency to scale up healthcare aid. Our results inform resource allocation to regions with the greatest unmet needs. With the continuing influx of refugees from Ukraine and the diversity of medical needs, the existing public health infrastructure in neighboring countries is already experiencing increased strain. As conflict prolongs in Ukraine, a shifting mosaic of disease burden within the country and crumbling healthcare infrastructure could lead to a public health catastrophe extending beyond Ukrainian borders. Mitigating this crisis will depend on countervailing effects of international resource mobilization and optimal distribution of humanitarian aid.

Methods

Daily Probability of Being Forcibly Displaced across Ukraine. An individual may be forcefully displaced on a given day based on the anticipated intensity and proximity of fighting. We account for the anticipated intensity of conflict at a location by incorporating both daily conflicts and past combat. Similarly, an individual residing closer to the locations of attacks is expected to have a higher probability of being forcefully displaced than those residing further from conflict regions.

We constructed a grid across Ukraine at a spatial resolution of approximately 10 km^2, which consisted of 6,125 locations ($i \in \{1, \ldots, 6125\}$). We computed the great circle distance $d_{i,j}(t)$ (57, 58) between the grid location i and the location for conflict event j that occurred on and before day t (12). We specified the probability that an individual of socioeconomic status f, gender m ($m = 0$ indicates female and $m = 1$ denotes male), and age class a will be forcibly displaced from grid location i and on day t as follows:

$$P_{i,m,a,f}(t) = p_{m,a,f}\left(1 - \prod_{k=t-(D-1)}^{t} \prod_{j=1}^{c(k)} \left(1 - \Omega(k)C\exp\left\{-\frac{d_{i,j}(k)^2}{2\sigma^2}\right\}\right)\right), \quad [1]$$

where $c(t)$ is the number of conflict events on day t, $p_{m,a,f}$ is the maximum probability of forcible displacement for socioeconomic status f, gender m, and age class a, C is the kernel scaling parameter, σ is the kernel dispersion parameter, D is the window in which conflict events influence forcible displacement, and $\Omega(t)$ is step function to account for saturating effects of conflict, where $\Omega(t) = 1$ when $t < t_S$ and $\Omega(t) = \omega$ otherwise. Male individuals between the ages of 18 and 60 y are required to stay in the country by the martial law implemented during the ongoing war in Ukraine. When accounting for both age and gender in the model, males in the age group of 20 to 59 y are assumed to not become refugees or IDPs. We account for it by setting $p_{m,a,f} = 0$, when $m = 1$ and $a \in [20, 59]$. Otherwise, if accounting only for age, then $p_{m,a} = p_a$, and if only accounting for gender, then $p_{m,a} = p_m$. Since the distribution of socioeconomic status among the population within a grid point was unavailable, we assume it to be homogeneous across age and gender. Thus, the socioeconomic status is only heterogeneous with respect to the location in Ukraine.

The number of forcibly displaced individuals of socioeconomic status f, gender m, and age class a from grid location i on day t is the product of the number of those individuals remaining and the probability of their forcible displacement on that day. Among the forcibly displaced, a proportion φ become IDPs, while the remaining $1 - \varphi$ becomes refugees. Among those who are already IDPs, a proportion Φ become refugees.

Using the Akaike information criterion (AIC) model selection, we determined the importance of including socioeconomic status, gender, and age in determining the probability of forcible displacement. For each model, we calibrated the kernel dispersion parameter and the window in which conflict events influence forcible displacement.

Mapping Country of Refuge for Ukrainian Refugees. We considered several factors of the destination location–Poland, Hungary, Belarus, Romania, Moldova, Russia, Slovakia, and other countries in Europe not neighboring Ukraine–that may act as an attractor for a forcibly displaced individual from a specified location in Ukraine. These factors consisted of social connectedness, economic strength, NATO status, and distance to the border crossing.

The preference for one country over another could be influenced by the extent of friends and family in the country. The intensity of social connectedness between the Ukrainian oblast and the destination country was quantified using the Social Connectedness Index–an anonymized snapshot of active Facebook users and their friendship networks (59). Expecting that a higher-income country may be better equipped to accommodate refugees, we measure the economic strength of a country using both GDP (a reflection of overall wealth) and GDP per capita (indication of living standards) (60, 61). We speculated that refugees will tend to enter NATO member countries (62) over those who are not in the organization. Countries with a shorter travel distance would likely receive greater preference over those with longer travel distances. The number of border crossing points and the median distance to these crossings were used in measuring the preference to travel to the country (13). For each factor, we determined country-specific weights and combined them to determine the probability of an individual seeking refuge in a particular country (*SI Appendix*, *Methods*). The set of attractors used in the analysis was determined through the AIC model selection. Furthermore, we compute the AIC-associated model weight to quantify the importance of each factor in determining the country of refuge.

Mapping the Location of Internally Displaced People. Movement of the forcibly displaced within Ukraine was restricted to the granularity of the raion level. The probability of an IDP seeking safety in a raion was determined using social connectedness (59), economic strength (63), distance to conflict, and whether the area is under Russian control.

Similar to refugees, social connectedness to a raion and the economic strength of a raion can make it a preferred destination for an IDP. Additionally, individuals fleeing would prefer regions where there has been less active fighting, which we quantified using the minimum distance to conflict events averaged over the last week (12). We also speculated that raions under partial or full Russian control could deter IDPs from seeking safety in the area (64). Combining the raion-specific weights of each attractor, we calculated the probability of an individual seeking safety in a particular raion (*SI Appendix*, *Methods*). The set of attractors used in inferring the destination of IDPs was determined through AIC model selection, with the importance of their inclusion quantified using AIC model weights.

Disease Prevalence among Refugees and the Internally Displaced. To estimate the number of people in age class a and gender g living with a specified disease in a raion, we used the national number of people with the disease (3, 41, 65–68) and raion–age–gender-stratified mortality data (3) to distribute the burden. We then determined the raion-level prevalence of the disease for each gender and age class. This geospatial age- and gender-specific prevalence was used to determine the disease burden among the forcibly displaced population.

Accessibility to Healthcare Facilities. The accessibility to a healthcare facility was quantified by the average intensity of conflict surrounding the healthcare facility (i.e., proportional to the value of displacement kernel at the site of the hospital). We normalized this intensity using the maximum average intensity of conflict across Ukraine (i.e., proportional to the value of the displacement kernel at the site of conflict events) to construct a proxy for the probability the healthcare facility is inaccessible. Specifically, we assume that hospitals where the average intensity of conflict is closer to this normalizing constant are more likely to be inaccessible compared to those with a lower average intensity of the conflict. Summing this measure across all healthcare facilities, we estimated the number of healthcare facilities inaccessible due to the invasion.

Data Sharing. The daily number of Ukrainian refugees between February 24, 2022 and May 13, 2022 was reported by the United Nations High Commissioner for Refugees (1). The number of Ukrainian IDPs was reported by the International Organization for Migration for the dates March 16, April 1, April 17, and May 3 (69–72). Conflict data for the period of analysis were obtained from the publicly available dataset provided by the The Armed Conflict Location & Event Data Project (12). All data are publicly available and provided in an online repository with computational scripts (73).

Data, Materials, and Software Availability. Previously published data were used for this work (Data sources (58–63, 65, 66, 39, 3, 67, 68, Stop TB Partnership. UKRAINE TB dashboard [Internet]. [cited 2022 Aug 3]. Available from: https://www.stoptb.org/static_pages/UKR_Dashboard.html, Hospital locations OpenStreetMap. HOTOSM Ukraine Health Facilities (OpenStreetMap Export) [Internet]. Humanitarian Data Exchange. [cited 2022 Mar 2]. Available from: https://data.humdata.org/dataset/hotosm_ukr_health_facilities, 1, 69–72, 57, Demographics UNFPA. Ukraine – Subnational Population Statistics [Internet]. Humanitarian Data Exchange. [cited 2022 Apr 6]. Available from: https://data.humdata.org/dataset/cod-ps-ukr).

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