Supplementary Material: Producing population-level estimates of internal displacement in Ukraine using GPS mobile phone data

Anonymised for peer review

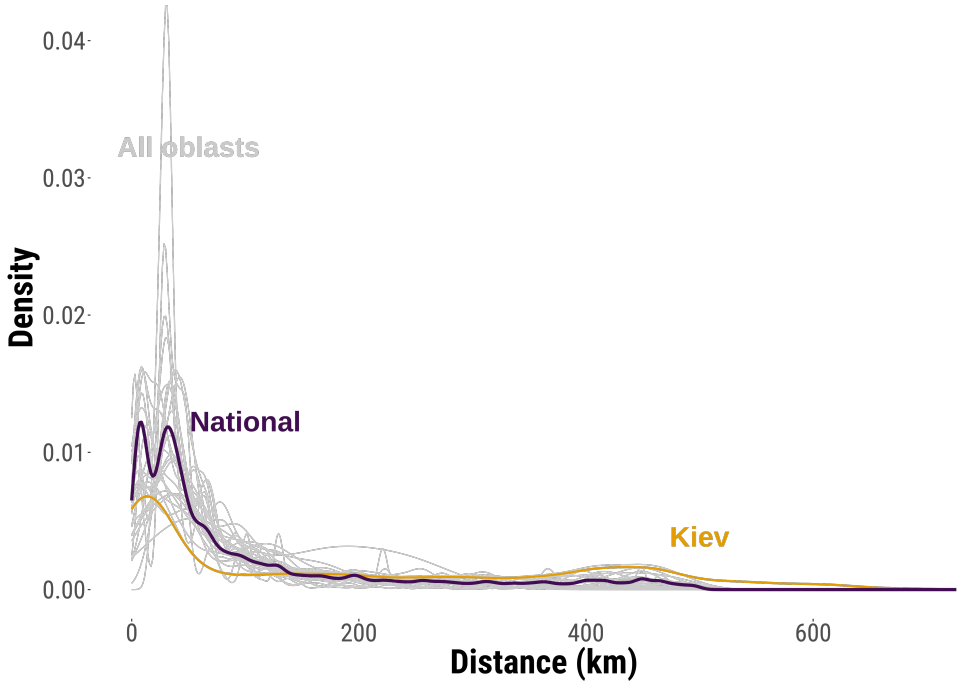
Supplementary Tables

Supplementary Table 1: National-level estimates of internal population displacement, February to August 2024. We assess the accuracy of our estimates of population displacement against published estimates produced by (1) IOM (International Organization for Migration) in the fourth column, and (2) Leasure and team in the fifth column. As described in the manuscript, IOM estimates are based on a telephone survey of 2,000 individuals each month. Leasure et al's estimates are based on data from Facebook's Advertising Platform. Unlike these efforts, and as described in the Methods section, our estimates are based on GPS mobile phone data. For our comparative assessment in this section, we report national estimates including and excluding Crimea. We use the former for our main analysis in the manuscript, and use the latter for our analysis here as these estimates are the most comparable to those produced by the IOM and Leasure et al which do not consider the Crimea oblast and Russian-occupied areas prior to the 2022 invasion. Our national-level estimates display a relatively high degree of correspondence with IOM estimates, particularly from March to July, and they tend to be higher than those produced by Leasure et al. by approximately 250 thousand people across the time series. The difference with estimates produced by Leasure and team may be explained by the fact that they are affected by power outages in the Donetsk and Luhansk regions, resulting in no or very small estimates for various dates after March 2022 and multiple locations. Supplementary Figures 2-4 capture this absence of estimates.

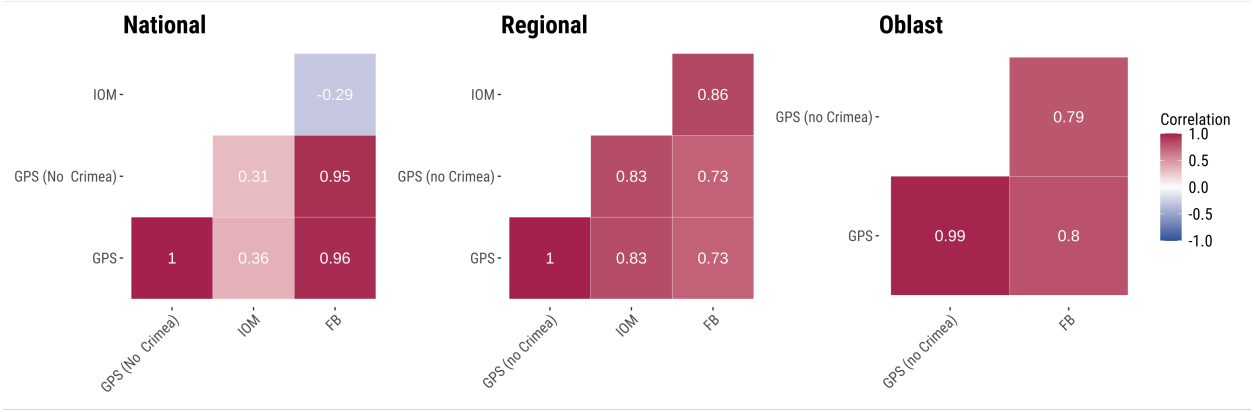
Month	Median Displacement	IOM Mean Estimate	Difference
February	3,436,536	NA	NA
March	6,191,498	6,478,000	-286,502
April	7,389,048	7,423,000	-33,952
May	7,526,610	7,581,500	-54,890
June	7,234,083	6,275,000	959,083
July	6,930,409	6,645,000	285,409
August	9,273,980	6,975,000	2,298,980

Supplementary Figures

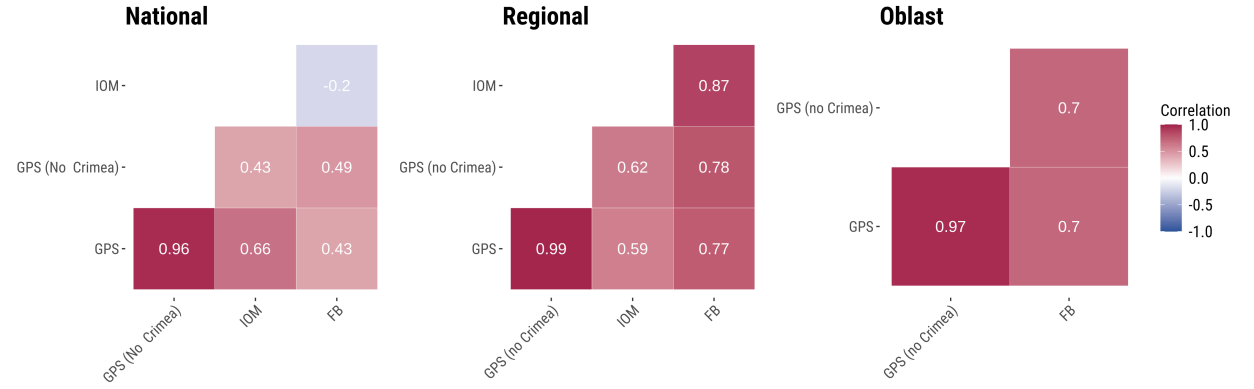
Supplementary Figure 1: Distribution of distance travelled relating to internal population movements. We analyse the distribution of distance travelled, computing the Haversine distance in kilometres based on centriods between areas at the raion level. We compute the distance for all moves, involving the home location as a starting point, temporary locations and the "final" destination area (i.e. where people spent most time away from their residential area). The results indicate that most people travelled less than 100 kilometres and most moves involves a displacement away from the home location. These results suggest that most people move do not move that far from their home location. While this is a common observed pattern for intentional moves, it is less expected for forced displacements. The distance profile for all moves is similar to that of return movements (Fig.3 reported in the manuscript). This suggests that most displacements are made to their "final" semi-permanent destinations.



Supplementary Figure 2: Correlation of coefficients based on based on three data sources: GPS, IOM and FB estimates, Pearson and Spearman, national regional and oblast level estimates. We measure the overall correlation between our GPS estimates and those derived by IOM and Leasure and team from FB data. We compute Pearson and Spearman correlation coefficients for estimates at three geographical levels: national, regional and oblast levels. Again, we cannot evaluate our estimates at the raion level as no comparable estimates for the period of analysis were published for our assessment. The results reveal a high degree of correspondence between our estimates and those produced by IOM and Leasure and colleagues across Pearson and Spearman correlations across the three levels of geography in our analysis.

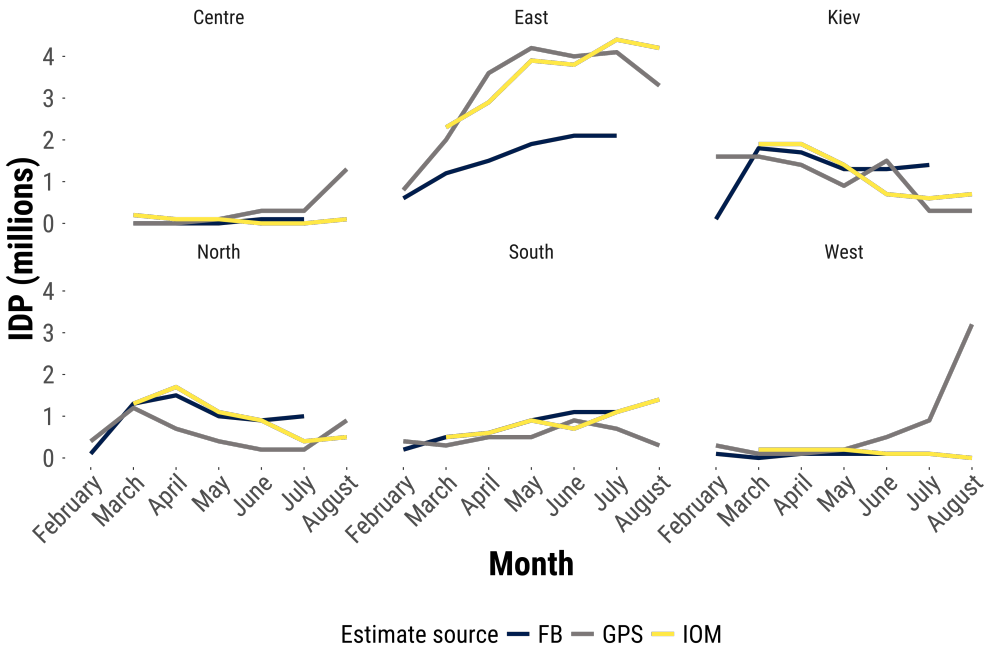


(a) Pearson's correlations

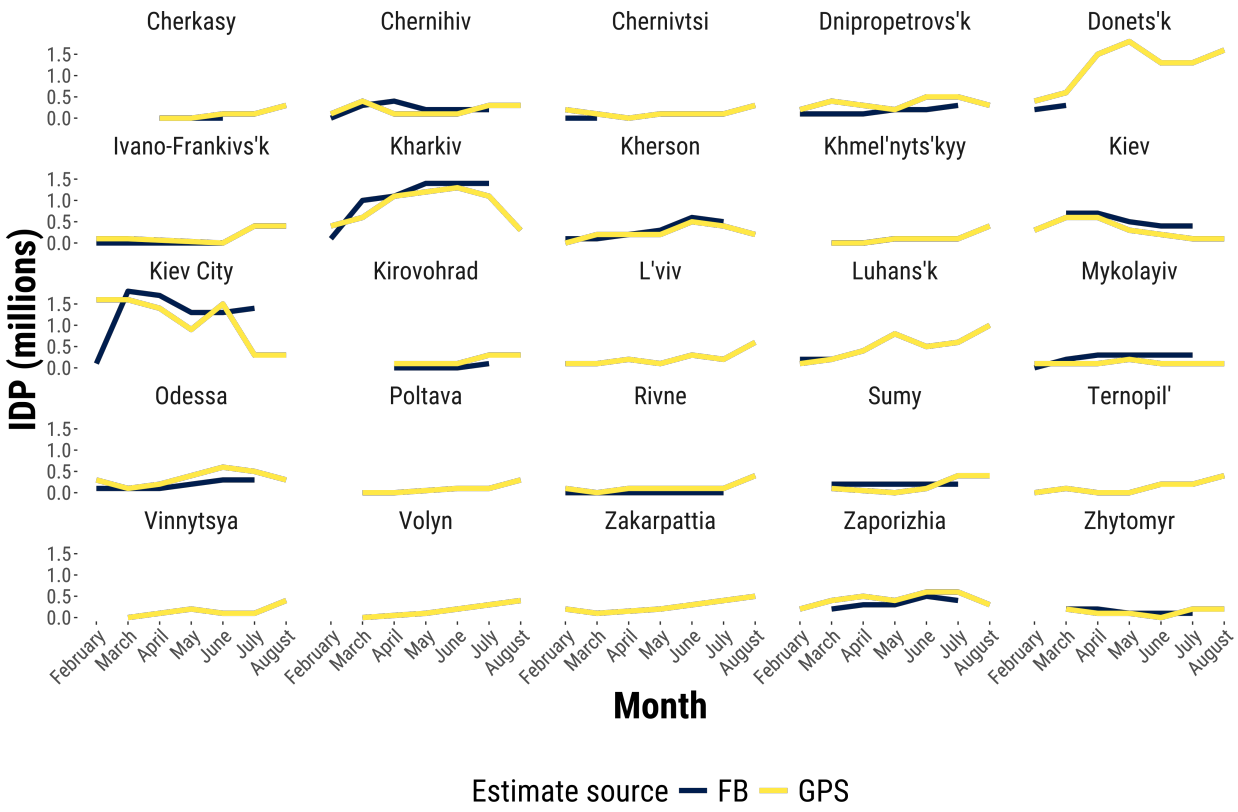


(b) Spearman's correlations

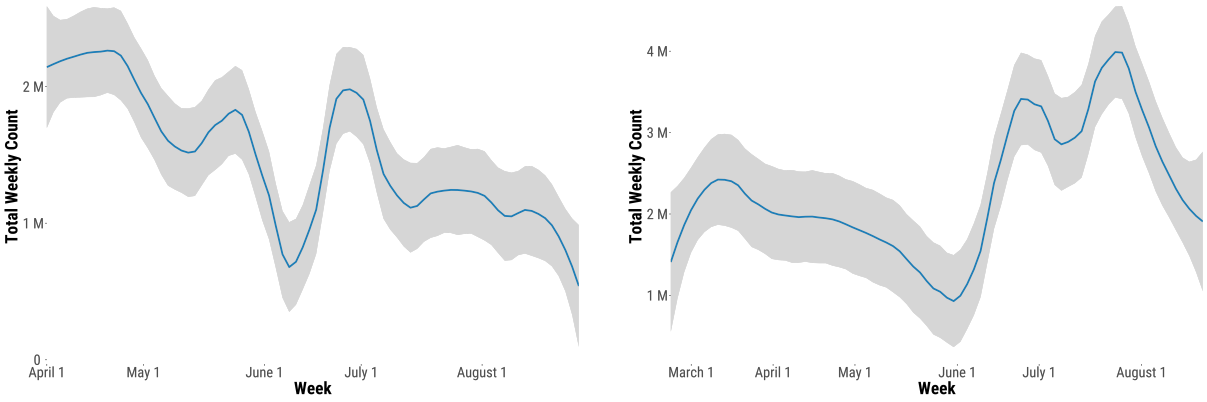
Supplementary Figure 3: Regional-level estimates of internal population displacement, based on three data sources: GPS, IOM and FB estimates, February to August 2022. We compare our GSP-based estimates against the survey-based IOM and FB-based Leasure et al estimates for macro-regional areas. We assess two dimensions of these estimates: (1) their level, and (2) temporal. We expect them to display a similar scale and temporal trend of displacement. As expected, all three sets of estimates are largely consistent with small discrepancies. The most notably systematic difference is against the FB-based estimates for the East region. As explained in the manuscript, this reflects the fact that Leasure et al.'s estimates are affected by power outages in the eastern regions of Donetsk and Luhansk resulting in zero or small population counts for the period of analysis. Additionally, our GPS-based estimates display a larger number of population displacement for western areas, capturing return movements from these regions to Kiev and northern regions as Russian troops withdrew from these areas. We note that FB-based estimates are only available until July so discrepancies between our GPS-based estimates and those based on FB data are not observable, and the identified differences for July and August are specific to our and IOM's estimates.



Supplementary Figure 4: Oblasts-level estimates of internal population displacement, based on two data sources: GPS and FB estimates, February to August 2022. We also compare our GSP-based estimates against the FB-based Leasure et al estimates at the oblast level. IOM have no published oblast-level estimates for the period of analysis. Oblast comprises the most detailed geography at which internal population displacement are published for the period of analysis. We acknowledge that the IOM have started producing raion-level estimates more recently but they are not openly accessible. As above, we assess two dimensions: (1) the level, and (2) temporal alignment of the set of estimates. Our GPS-based and the FB-based estimates show a remarkable degree of correspondence. We note that FB-based estimates are not available for some oblasts and time periods as a result of power outages.



Supplementary Figure 5: National-level estimates of return movement using two methods. As described in the Methods Section, we compare two approaches approaches to estimate the number of return movement. These approaches are based on the methods used by: (1) the IOM; and, (2) Leasure and team. We compare both sets of estimates and considered that the latter approach provides more reasonable estimates: 1) the IOM approach generates estimates suggesting a decline in the number of returns from over 2 million to around 500 thousand; 2) it produces return estimates displaying an increasing trend, within the range of 1 million in February 2022 and 4 million July 2022; and, 3) Leasure el at approach produces estimates indicating an increasing trend of return moves over time. The latter is what we expect based on existing information, anecdotal evidence and news reporting. At the same time, we consider a decline in the number of the number of IDP to be unrealistic. As Russian troops withdrew from northern Ukraine, we have visual and information evidence to suggest that many people returned to Kiev and northern areas in June and July 2022. Additionally, the IOM estimates uses a two-week period to define returns; that is, a returnee is an individual who have left and return to their home location after a two-week period. Our definition indicates that the mean duration time of return moves is nine weeks.



(a) IOM-based approach

(b) Leasure et al-based approach

Supplementary Figure 6: Number of weeks spent away from the place of residence before returning. We examine the distribution of weeks before a return move to a home location occurred. The IOM definition defines that a return occurs after people have spent two weeks away from their home location. Our evidence indicates that the average number of weeks before a return is observed is nine weeks after people moved away from home. A very small percentage of people (less than 3%) appears to make a return to their home location after two weeks away from home.