Spatiotemporal mapping of population in Europe: The 'ENACT' project in a nutshell

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Abstract

Current knowledge of the spatial distribution of population is still very incomplete. It is based upon place-of-residence statistics and does not account for the fact that people shift between various locations in daily, weekly and annual cycles for reasons of shelter, work, leisure or fulfilling various necessities. Spatial mobility of people results in significant variation of local population densities, which is extremely relevant for a range of applications, from risk assessment to urban and regional planning. Despite the advances in computational capacity and data availability, spatiotemporal mapping of population remains challenging and the state-of-the-art is considerably thin. The ENACT project ("ENhancing ACTivity and population mapping") is an ongoing applied research project aiming at producing consistent, seamless, multi-temporal, high-resolution and validated population density grids for Europe that take into account major daily and seasonal population variations. This paper provides an overview of the project, with focus on the data sources and methodologies being developed and applied to derive the first EU-wide multitemporal population density grids.

Key-words

Population density; Spatiotemporal mapping; Big Data; Data fusion; High-resolution; Tourism; Europe

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1. Introduction

Population is a crucial variable for the social sciences, the geosciences, and for policy support in many domains. Yet, our knowledge of its spatial distribution is still nowadays very incomplete. Population is a temporally dynamic variable, with major shifts in its distribution occurring in daily and seasonal cycles, resulting in rapidly changing densities. Spatially detailed representations of residential population exist at European Union (EU) level since several years. While these maps can be used as proxies for night-time population distribution, the distribution of population for other time frames is practically unknown at almost every spatial scale. Consequently, all applied sciences and policy support that require spatially detailed information on population distribution must rely on a fractional and static representation of reality. Overcoming this large knowledge gap is the main goal of an on-going (2016-2017) research project at the European Commission Joint Research Centre – "ENhancing ACTivity and population mapping" (ENACT).

Ultimately, the ENACT project aims at developing and implementing a consistent and validated methodology to produce multi-temporal population density grid maps (or 'population grids', for short) for Europe. The final output of ENACT is a set of multi-temporal population grids that take into account the main seasonal and daily variations of population, consistent with the most recent censuses data (2011), and covering the whole of EU28. The target spatial resolution is 1 Km, which is sufficiently detailed for sub-regional and local scale analyses and applications. The target temporal resolution is day- and night-time for the 12 months of the years, hence resulting in a total of 24 population grids. These novel datasets are expected to not only expand the knowledge base of spatiotemporal population patterns across the continent but will be useful and straightforward (i.e. easy to use) inputs to applications in various fields. These include: assessment of human exposure to natural and technological hazards, assessment of resource use (e.g. energy and water), planning and modelling of transport, land use, regional economy and environment.

While the project is still on-going and the final outputs under production and validation, the purpose of this paper is twofold: to summarize the state-of-the-art of population mapping (Section 2) and to provide an overview of the ENACT project, the methodology, main challenges and advances concerning the spatiotemporal mapping of population distribution in Europe (Section 3).

2. State-of-the art

The European Commission Joint Research Centre (JRC) has a long experience in population mapping and modelling. Since the early 1990's it has contributed to revolutionizing the way population is represented and mapped at European level. From the early works of Gallego and Peedell (2001) to most recently Gallego et al. (2011) and Batista e Silva et al. (2013a), methods to map population have been experimented and refined, allowing the creation and update of maps representing residential population across Europe. Thanks to these early efforts, rudimentary – and to large extent ineffective – maps showing population density per administrative unit have been replaced by more realistic and useful depictions of population distribution at regular grid cell level, typically with a 100x100 meters resolution and usually referred to as 'population grids'. The data structure and high resolution of population grids allowed wider integration with other datasets in Geographical Information Systems (GIS), and thus have become indispensable datasets among both social and environmental researchers and spatial planners.

The main principle underlying the construction of such maps relies on the combination of two inputs: population counts usually available per administrative units or census zones, and a covariate of population distribution at higher spatial resolution. Examples of covariates include residential areas extracted from land use maps, building footprints, impervious surfaces, road network or even night-time lights from remote sensing imagery (for an extensive review of population estimation methods using GIS and Remote Sensing, see Wu et al. 2005). Using similar approaches, population estimates for the Urban Atlas polygons have also been created at the JRC at the request of DG REGIO (Batista e Silva et al. 2013b, Batista e Silva and Poelman 2016). In addition, the JRC has succeeded in modelling future population distributions at European level under different scenarios using the LUISA territorial modelling platform, given demographic projections, within-region migration and local potential for urbanization (Batista e Silva et al. 2013c, Lavalle et al. 2016).

Despite the many improvements introduced by different researchers over the years, European population grids are – still nowadays – essentially static maps of 'residential population'. Residential population refers to the number of people who declare to reside at a given location. As such, when mapping residential population we are essentially mapping the distribution of population during the night time, assuming that most people stay in their declared places of residence during the night for shelter and rest, and excluding the fraction of people who work outside their residences during night time. Maps of residential population have developed quicker due to easier access to data: all European National Statistical Institutes (NSI), at least once every ten years, systematically count the number of residents per census zone.

Residential population grid maps, although sufficient for a range of purposes, describe only a fraction of reality. The spatial distribution of people during the daytime or where people stay in different seasons is practically unknown for any spatial scale. Yet, such information is essential to a whole range of applications (Martin et al. 2010). The location of population during the day is determined by the location of economic, social and leisure facilities which pull population off their residences, driving commuting flows and other forms of daily trips. Daytime population distribution thus varies greatly from night-time distribution. Contrary to night-time population – which, as already mentioned, can be straightforwardly inferred by official statistics on residential population – it is much more challenging to infer daytime population distribution.

Addressing the needs of emergency response, compatible day- and night-time population grids have been produced in the mid-2000s for the USA (McPherson et al. 2004; Bhaduri et al. 2007). In Europe, such datasets have been mostly lacking, with only a few countries systematically collecting base data and modelling population distribution on the daily cycle (e.g. Ahola et al. 2007). More recent research (Martin et al. 2015; Martin et al. 2010; Aubrecht et al. 2014; Smith et al. 2016) has been increasing the resolution of the temporal component and/or including a seasonal dimension for limited regional areas by mining conventional data. Other authors have explored the contribution of non-conventional data such as mobile phone activity records (Deville et al. 2014; Tatem et al. 2014) or 'geotweets' (Patel et al. 2016) for population mapping in selected countries, a task which is not without shortcomings and challenges. A relatively straightforward approach was proposed to estimate day- and night-time population distribution at high resolution for the cities in Urban Atlas (Freire et al. 2015); yet its quality depends largely on that of ancillary datasets and availability of local parameters, and accuracy levels have not been assessed against independent sources.

The challenges posed by spatiotemporal mapping and modelling of population distribution cannot be addressed effectively by conventional data sources alone (e.g. official statistics and reference land use datasets). Significant advances in this field can only be attained if data from conventional data sources are combined with data from emerging, non-conventional data sources in a coherent methodological framework. Non-conventional data sources may include volunteered geographical information (Goodchild 2007), web-based social networks (Aubrecht et al. 2016), proprietary thematic databases, mobile phone operator data, or even navigation systems.

Data mining from such (big) data sources is becoming a common task in many geospatial applications. Craglia and Granell (2014) reviewed a range of projects leveraging citizen science or crowd sourcing in the area of environmental monitoring and smart cities application. Several projects demonstrate the benefits of combining official and non-official sources. These include for example the GEO-Wiki project focusing on global land cover validated by local people in game-inspired apps, and its urban application Cities Geo-wiki2 whose aim is to map the physical geography of all major cities in the world to link to weather and climate models. Another approach to augment local land use and building use databases with crowdsourced information is documented by Spyratos et al. (2014) who used data from 'Foursquare' to monitor the dynamic changes in building use in commercial areas. Other studies have also shown that thematic geospatial layers can be obtained from disparate data sources and integrated with existing land use maps for improved detail (Batista e Silva et al. 2013d; Jiang et al. 2015). One of the most promising data sources to estimate population density comes from mobile network operators. Several studies have documented the importance and usefulness of this data source (see for example Steenbrugger et al. 2014, and Deville et al. 2014), but one key problem remains data access, which is normally negotiated with the data providers by individual researchers for specific projects.

Until a few years ago, population grids were almost unknown to most researchers even in domains with a strong spatial dimension. But population grids gained momentum very rapidly, and have become mainstream input for many analyses. Eurostat, which was initially reluctant to publish population figures using non-conventional zoning systems, kicked-off the GEOSTAT project in 2010 to promote the production, dissemination and use of 'gridded' population among NSIs. However, despite all the referred advances, Europe still lacks a wall-to-wall, spatiotemporal model of population distribution.

The main challenges and associated with spatiotemporal population mapping can be outlined as follows:

(i) **Fast population dynamics**: People commute, travel, and migrate faster than ever before.

(ii) **Multifaceted concept**: During the night most of us are 'resident population'; during the day our (multiple) occupations are related to the (multiple) locations of probable presence.

(iii) **Data availability issues**: No official statistical sources exist. Daytime population needs to be inferred from multiple, indirect, and perhaps, emerging data sources.

(iv) **Thin state-of-the-art**: Few case studies, focusing on single countries, regions or cities, and often incomparable due to the use different methodologies and input data of different nature.

3. The ENACT approach

3.1 Main temporal and spatial specifications of ENACT population grids

As mentioned earlier, the final outcome of the ENACT project is a set of 24 population grids, each representing night-time or daytime for each month of the year. Despite the significant increase in temporal resolution vis-à-vis the state-of-the-art for EU-wide population grids (a single time window referring to night-time population distribution), the 24 population grids from ENACT are still discrete and not representative of all the daily, weekly or annual population fluctuations. In fact, each of the 24 population grids represents a 'typical' or 'average' working day of the month. The weekend variation is not addressed. The night-time slot represents an 'ideal' situation when everybody is assumed to be at home for rest/sleep, whereas the daytime slot refers to a situation when everybody is assumed to be at the location of their primary activity during core working hours (e.g. 9am-12am, 2pm-5pm). As such, intermediate daily variations of population are not taken into account (e.g. commuting, pre- or after-work activities, etc.). The reference year is 2011, to ensure consistency with the latest round of censuses.

The working spatial resolution of the population grids is 100m x 100m cells. However, the results will be aggregated and made available at coarser resolution (tentatively 1Km x 1Km grid cells) mainly due to the impossibility to carry a validation exercise at the working resolution. In fact, releasing the population grids at the working resolution could mislead users regarding the actual precision and accuracy of the product.

3.2 Data and methods

The methodology is structured in four main tasks or phases. Each task can be seen as an individual process, with inputs and output(s). Table 1 describes these tasks briefly, and refers to their main inputs, outputs, and methods. Some tasks run in parallel (1 and 2), while others have dependencies (task 3 depends upon completion of tasks 1 and 2, and task 4 depends on completion of task 3). Figure 1 shows the overall workflow of the project. The next subsections provide further detail for each task.

Table 1. Main tasks of the ENACT project, brief description, key inputs, outputs and methods.

Task / phase	**Description**	**Inputs**	**Outputs**	**Methods**
1. Regional population flows and stocks	Estimation of flows and stocks of various population subgroups per region (NUTS3) and per month.	Official statistics (Eurostat, National Statistical Offices)	Set of 12 tables, one per each month of the year. Each tables has x records = n rows (regions) x k population subgroups.	Search and assembly of statistical data; tabular operations supported by spreadsheet and statistical packages.
2. Activity mapping	High-resolution (100m x 100m) mapping of location of socioeconomic activities (e.g. places of residence, employment, study, leisure).	Geodata from multiple sources (proprietary, free/open/public/voluntary repositories).	'ENACT base map', consisting of a refined version of the CORINE Land Cover Map 2012, with improved spatial and thematic detail; Set of complementary layers (hotel room density, density of shops, schools, etc.).	Search and assembly of geographical data; geodata pre-processing and fusion, supported by GIS.
3. Population disaggregation	Creation of population grids by disaggregating regional population stocks to grid level using location of activities as spatial proxies.	Outputs of tasks 1 and 2.	Two population grids for each month of the year (total of 24 population grids).	Spatial downscaling supported by GIS.
4. Validation	Comparison of ENACT's outputs with population grids derived from independent sources or methods.	Output of task 3; population grids derived from independent sources or methods (e.g. Mobile Phone Operator Data).	Goodness of fit measures.	Pre-processing and harmonization of reference population grids; Calculation of comparison indicators, supported by GIS and statistical packages.

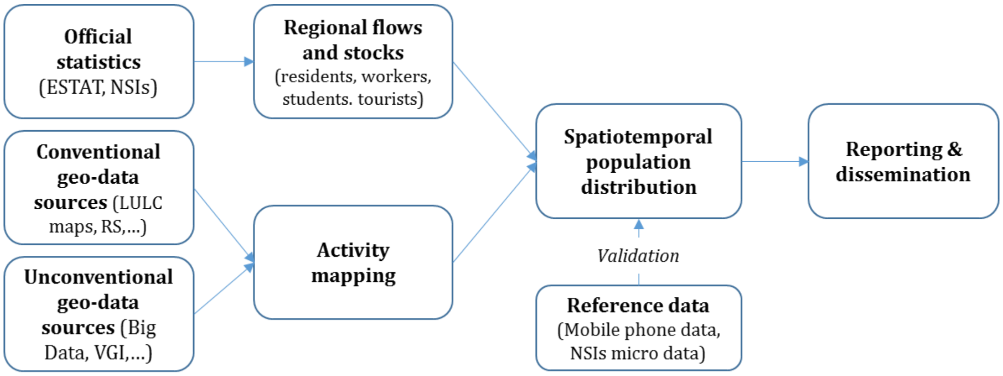

Figure 1. Overall project workflow.

3.2.1 Regional population flows and stocks

This task aims at constructing stocks of relevant population subgroups per month and per NUTS3 regions. There are a total of 11 population subgroups, as follows:

- Residents;
- Employees per 6 economic sectors;
- Students per 2 categories ('below tertiary education' and 'tertiary education and above');
- Non-active;
- Inbound tourists.

Residents, as the name indicates correspond to the number of registered residents within a region. This figure is obtained from Eurostat directly at NUTS3 level. *Employees* are broken down by the following broad sectors: Primary sector, Secondary sector, Construction, Private services (2 subgroups), and Public sector. The employment statistics were obtained from Eurostat and reflect the NUTS3 region of work. Gap filling was necessary to complete the available dataset from Eurostat. *Students* statistics reflect the region where students are enrolled in education institutions. Students are subdivided into 'below tertiary education' and 'above tertiary education and above', but in both cases, numbers were only available per NUTS2 regions. Students below tertiary education were distributed among the respective NUTS3 regions based on the proportion of the relevant population age-groups. Higher education students were downscaled to NUTS3 regions based on the number of enrolled students per NUTS3 available from the European Tertiary Education Register (ETER)[2]. The *non-active* population subgroup refers to population not working nor studying, and comprehends retired population, children not attending kindergartens, unemployed, and inactive working-age population. The aspect

[2] ETER-project, https://www.eter-project.com/

that holds together this population subgroup is the likelihood that its members hang around residential areas for a significant share of the daytime. The estimation of this stock per NUTS3 involved the combination of data from various Eurostat tables.

Inbound tourists are defined broadly as visitors (thus temporary residents) in the region for any purpose, leisure and business altogether. *Inbound tourists* were derived by following a set of calculation steps. First, annual no. of nights spent within a NUTS2 region (Eurostat) were disaggregated to NUTS3 regions based on the no. of bed-places per NUTS3 (Eurostat). Then, the NUTS3 annual no. of nights spent were broken down per month using regional (NUTS2 or NUTS3) seasonal curves constructed from data procured from every National Statistical Office (Figure 2 offers examples of seasonal curves for different regions). Finally, the average daily no. of inbound tourists is obtained by dividing the nights-spent per region and per month by the respective no. days in the month.

Also from the National Statistical Offices we obtained data allowing us to split inbound tourists in a country per country of origin. Tourists from countries outside the study area (i.e. EU28) constitute added population to the existing stock. Tourists from the same country (domestic) or from countries within the study area (non-domestic) had to be subtracted from their regions of origin to avoid double counting of total population within the study area. For example, the sum of inbound tourists from one country of origin (say, Germany) in all countries returns the total number of outbound tourists from that country (Germany). This number was then split per month and per NUTS3 region (based on the proportion of NUTS3 population). The total outbound tourists in a month from one NUTS3 region was finally removed from the stock of the various population subgroups proportionally to their size. In Figure 3 a visual representation of the flow of tourists between countries within the study area can be appreciated.

All in all, the seasonal variation of the total present population in a region is linked primarily to touristic flows, inbound and outbound. Figure 4 shows, for one alpine region in Austria, the monthly variation in stock of present residents and inbound tourists resulting from the above described calculation procedures.

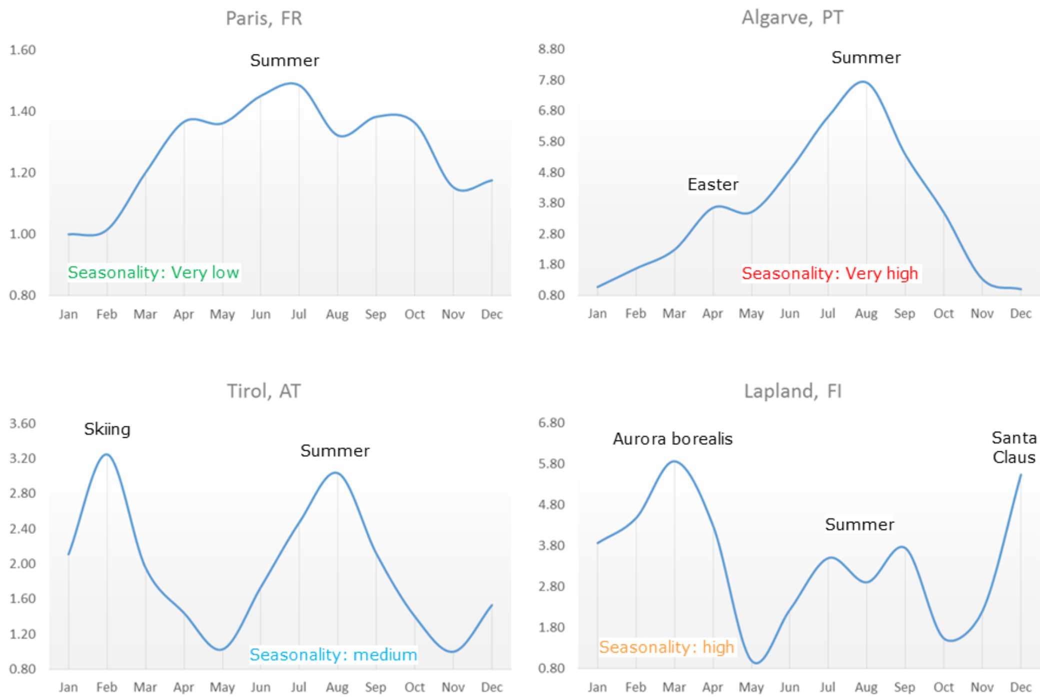

Figure 2. Seasonal profiles for four regions in Europe.

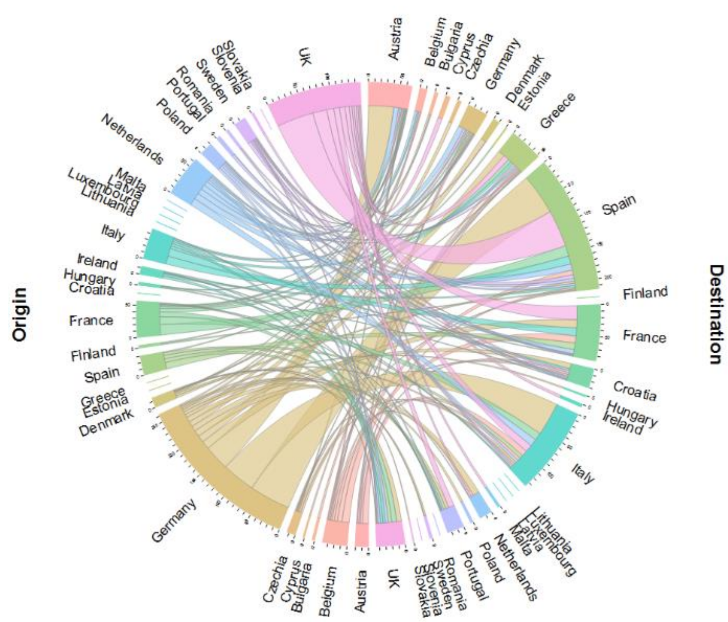

Figure 3. Origin-destination countries of non-domestic nights-spent.

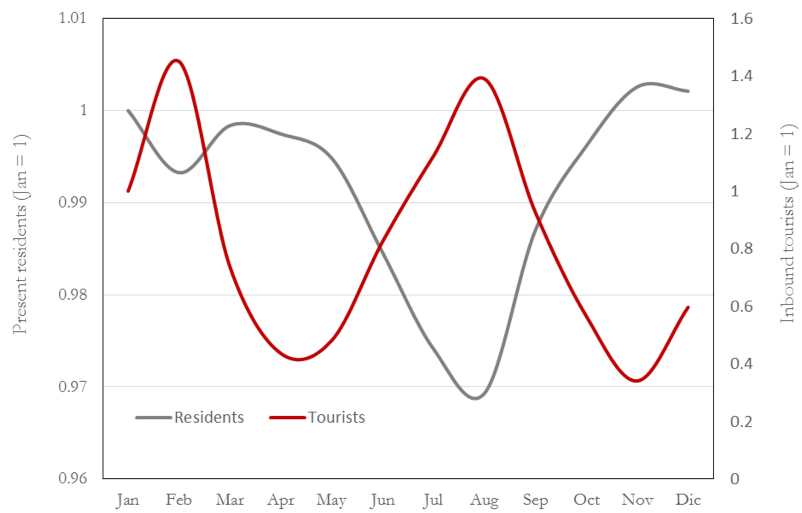

Figure 4. Monthly variation of the stock of present residents (axis on the left) and inbound tourists (axis on the right) in the region of Tiroler Unterland, Austria (NUTS3 code 'AT335'), indexed to the month of January.

3.2.2 Activity mapping

Determining the locations of probable presence of population is a major challenge. In fact, there is no one-stop shop for such multi-sector, highly detailed locations of activities. ENACT needs to resort to various sources, proprietary and open-source, conventional and non-conventional. Specific population subgroups (i.e. employed persons per sector, students, tourists, and inactive) then need to be allocated to locations of probable presence.

Land use and land cover (LULC) are widely used as ancillary variables (covariates) in fine resolution population mapping and modelling. ENACT is constructing its own 'base map' for the disaggregation of population stocks from regional to grid level. The base map is a refined version of the well-known CORINE Land Cover map, version 2012 (CLC 2012). The refinement of CLC 2012 includes two key dimensions:

a) Spatial refinement;
b) Thematic refinement.

The *spatial refinement* consists in improving the spatial detail and geometric representation of the LULC classes. In practice, we reduced the minimum mapping unit from 25 hectares to 1-5 hectares (typically 1 ha for artificial surfaces, 5 hectares for all other LULC classes). The reduction was achieved by combining information from multiple geodata sources, and their integration with the original CLC 2012 in a sequential order. Input data have been selected and harvested upon compliance with the following criteria:

- Compatibility with CLC's LULC nomenclature (LULC class definitions);

- Reference year 2012 +/- 2;
- Higher spatial resolution than CLC 2012;
- Pan-European geographical coverage;
- Preferably free, open and documented data.

The input data sources are listed below:

- CLC products: CLC 2012 v 18.5, CLC Changes 2006-2012 and CLC Changes 2000-2006;
- Copernicus high resolution (HR) layers 2012: HR layer Forest type + Tree cover density, HR layer Permanent water bodies, HR layer Wetlands;
- TomTom Multinet 2014: Land Use layer + Built-up layer;
- JRC's European Settlement Map (ESM) (10m version, aggregated to 100 m reference grid);
- Urban Atlas 2012 (~ 700 Functional Urban Areas covered);
- OpenStreetMap (OSM) and TomTom Multinet 2014 as source of road network data.

The *thematic refinement* consists in increasing the breakdown of the LULC categories originally available in CLC. CLC uses a hierarchical nomenclature with 44 classes at level 3, however only 11 comprise artificial surfaces. The goal is to derive more specific subclasses of human activities, which then can serve as spatial containers of various population subgroups. A level 4 is therefore added to the CLC nomenclature (see table 2).

Methods based on cartographic overlay between the original map and ancillary layers are applied to derived classes 11XX, 122X, 124X, 1421, and 1422. However, the breakdown of class 121 is based upon a completely novel approach. After the spatial refinement step, each 121 polygon was geometrically intersected with the road network from TomTom to obtain a finer set of polygons (total of 0.75 million). Each resulting polygon is characterized by a number of explanatory variables (weighted sum of Points of Interest from 16 categories) and other contextual variables related to population density, land use/land cover in the neighborhood, and distance to key transport features). The sources of geodata to construct these explanatory variables include:

- Proprietary geographical data: TomTom Multinet (transport and miscellaneous Points of Interest), PLATTS (energy), EuroRegionalMap from EuroGeographics (miscellaneous);
- Open and public sources: European Pollutant Release and Transfer Register (location of industries);
- Volunteered Geographical Data: OpenStreetMap (miscellaneous Points of Interest).

For about 1/3 of all the class 121 polygons we have determined their ground truth class based upon detailed national land use maps for a selection of countries and regions (COS for Portugal, SIOSE for Spain, COSW for Wallonie, and DUSAF for Lombardy), as well as land use polygons obtained from OpenStreetMap and TomTom. All this information is then used by Machine Learning classifiers to construct an explanatory model which will then be used to classify 121 polygons without ground-truth in the level 4 categories.

In addition, the 'activity mapping' task includes the production of some complementary activity layers, such as those depicting touristic accommodation room density (constructed with data from online booking services), retail and food service density (constructed with data from TomTom Multinet Points of Interest), and location of schools. These additional layers were needed due to conceptual difficulties in integrating point-based data of hotels, shops, and schools in the polygon-based LULC map. These layers will play a key role in the subsequent spatial allocation of population subgroups such as tourists, students and shop workers and daytime clients.

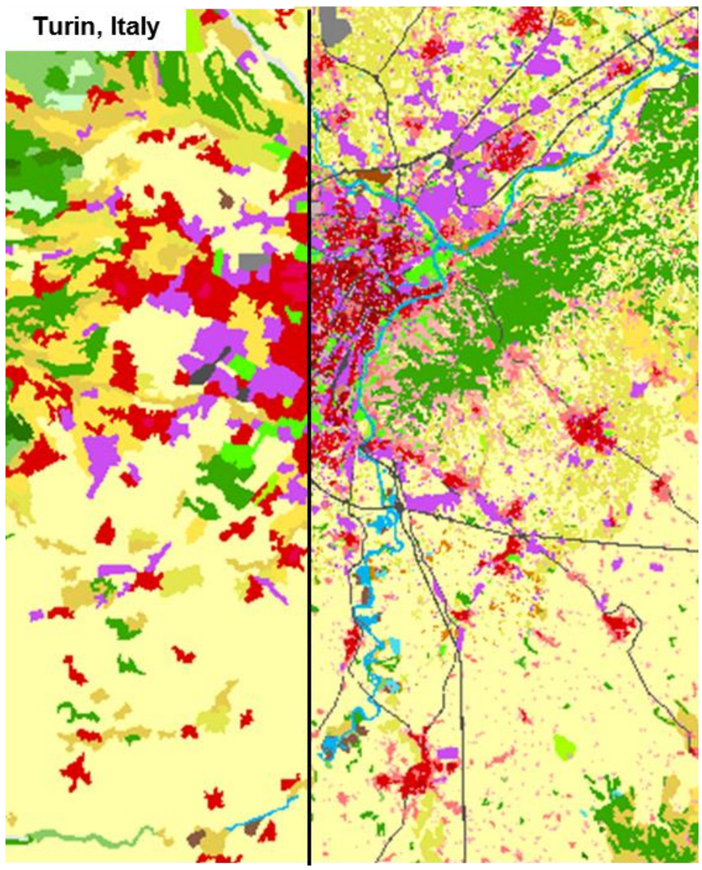

Figure 5. Differences between the original CLC 2012 (left) and the CLC after spatial refinement (right) for the area surrounding the city of Turin, Italy

Table 2. Nomenclature of CLC for artificial LULC classes. Hierarchical level 4 is added by this project.

Level 1	Level 2	Level 3	Level 4
1 Artificial surfaces	11 Urban fabric	**111 Continuous urban fabric**	**1111 Dense urban fabric**
		112 Discontinuous urban fabric	**1121 Medium density urban fabric**
			1122 Low density urban fabric
			1123 Very low density or isolated urban fabric
	12 Industrial, commercial and transport units	**121 Industrial or commercial units**	**1211 Industry**
			1212 Energy production, water supply, waste management
			1213 Commerce and private services
			1214 Public administration, defense and social facilities
			1215 Cultural facilities
		122 Road and rail networks and associated land	**1221 Road network**
			1222 Rail network
			1223 Train or ferry station
			1224 Other road and rail associated land
		123 Port areas	1230 Port areas
		124 Airports	**1241 Airport terminals and buildings**
			1242 Airport runway and associated land
	13 Mine, dump and construction sites	131 Mineral extraction sites	1310 Mineral extraction sites
		132 Dump sites	1320 Dump sites
		133 Construction sites	1330 Construction sites
	14 Artificial, non-agricultural vegetated areas	141 Green urban areas	1410 Green urban areas
		142 Sport and leisure facilities	**1421 Sport and leisure green**
			1422 Sport and leisure built-up
			1423 Touristic accommodation

3.2.3 Population disaggregation

Regional population stocks are disaggregated to grid level using the ENACT refined LULC map, and the complementary activity layers mentioned previously. The 'residents' population subgroup is assigned entirely to residential areas, while the stock of tourists is assigned to locations of touristic accommodation. Figure 4 shows the result of the disaggregation of tourists for four months. The sum of these 'gridded' residents and tourists will constitute the 'night-time' grid for each given month.

To produce daytime population grids, we allocate all population subgroups (excluding the 'residents') to the relevant LULC classes and in some cases the allocation is also based on complementary activity layers. The spatial allocation, or disaggregation, is governed by a probability matrix that establishes a link between each population subgroup and each LULC or activity class. This matrix is currently under construction using an expert survey approach. The disaggregation is further guided by the local built-up densities as per the European Settlement Map.

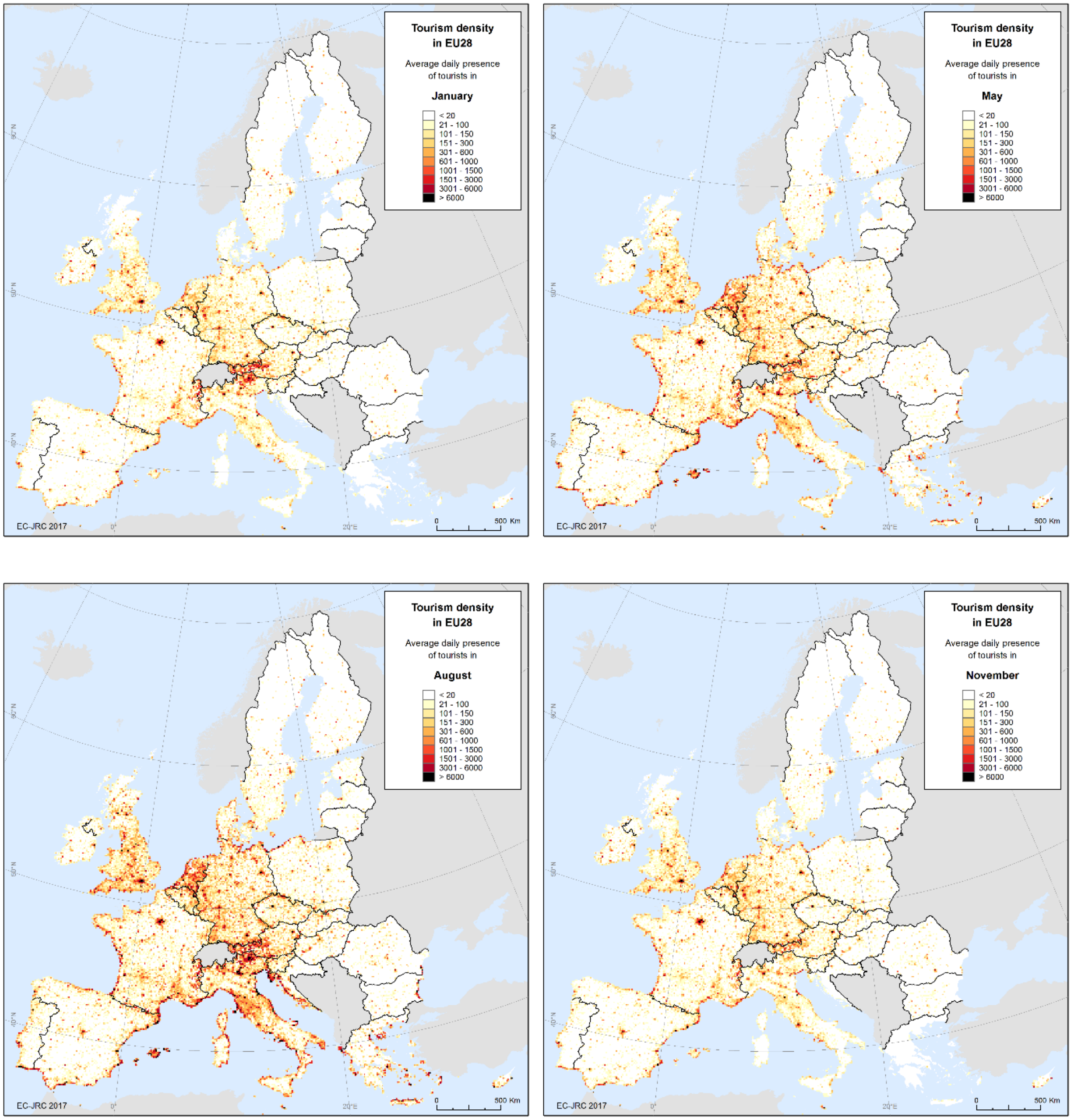

Figure 4. Tourism density grids of 10 Km^2 resolution for January, May, August and November.

3.2.4 Validation

The final challenge is to validate the produced multi-temporal population distribution grid maps. ENACT's outputs will be compared against reference data from independent sources such as multi-temporal population grids derived from mobile phone operator data or other sources (e.g. produced by other researchers), and official statistics and micro-data from National Statistical Institutes (NSIs) on the location of employment.

Collection of reference data for the validation exercise is on-going, so challenges associated with this task cannot be fully anticipated. One challenge, though, that will have to be addressed relates to the harmonization, or alignment of the reference data with the ENACT's population grids. Aspects to take into consideration in the data harmonization relate to the match of the temporal dimension, spatial resolution, as well as the variable of concern. For example, grids from mobile phone operator may refer to user density, rather than total population density. Options to deal with these mismatches may include variable rescaling or careful design of comparison measures based on relative densities across time and space, rather than absolute ones. Finally, and given the limited availability of reference data on spatiotemporal population, the validation will not cover the full extent of ENACT study area, but will inevitably be a patchy exercise.

4. Early conclusions and way forward

Although the project is still on-going, some preliminary conclusions can be drawn already. Multi-temporal modelling of population distribution is an exceptionally data-intensive task, especially for large study areas. Apart from the data required for the validation, the bulk of the input data required to progress in all project phases have been collected and processed. The assessment of regional population flows and stocks is complete, and the activity mapping is approaching its conclusion.

Currently, the groundwork for the 'gridding' of population is being laid by preparing a probability matrix linking population subgroups to the relevant LULC classes and activities. Information drawn from diverse data sources are being combined to fulfil the main goal of ENACT. Unfortunately, the inaccuracies present in each dataset will propagate and accumulate in the final product too. Knowing the accuracy of the produced dataset is necessary to inform the users of the product but also to determine the spatial scale at which it should be used. Therefore, designing a robust validation and quality assessment strategy will be no less important and challenging as the modelling per se. As it is likely that the quality and quantity of suitable input data will grow in future, it is also vital to attempt at developing a flexible modelling framework that could accommodate gradual data (and methodological) improvements.

Next advances carried in the context of this project, and most certainly ENACT's final results will be reported in forthcoming scientific communications and papers in relevant outlets.

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