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An open data index to assess the green transition - A study on all Italian municipalities

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A R T I C L E I N F O

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A B S T R A C T

This study introduces a municipality transition index based on open data and green transition principles. The Municipality Transition Index provides data and a succinct measurement of municipal attributes as defined by green policies at national and local level. We identify four dimensions of interest and 18 key performance indicators, defined at municipality level, and measure factors that directly and indirectly influence the green transition, with a focus on the Green Deal vision embraced by the European Union. The robustness and meaningfulness of the index is tested on a dataset covering all 7904 Italian municipalities.

Our results show that computation of the MTI on this sample produces a bell-shaped distribution, suggesting strong geographic disparities and a significant difference between cities, towns and rural areas. The results show the need for policies and tools tailored at municipal level and provide information for practitioners, policy makers and experts from academia, useful for designing tools to underpin investment planning in the framework of the recent National Recovery and Resilience Plan issued by the Italian government. This may be particularly useful for enhancing green-transition-enabling factors that may differ across regions, helping policymakers to promote a smooth and fair transition by monitoring the performance of municipalities as they address the challenge.

1. Introduction

Strategic and social planning, along with the management of environmental and energy transitions, play a central role in the current and future policy design of regions, cities and communities (Dall'O, 2020). At the same time, sustainability and circularity are fundamental goals of urban environmental evolution and the management of local services, assets and infrastructures. The Sustainable Development Goals of the United Nations are a blueprint for achieving a more sustainable future, including "making cities and human settlements inclusive, safe, resilient and sustainable", "ensuring sustainable consumption and production patterns" and "taking urgent action to combat climate change" by integrating related measures into national policies, strategies and planning.[1] The cities of today are distant from these goals. Urban areas occupy about 3% of the earth's surface and host >50% of the world's population, a figure expected to grow to 68% by 2050 (Lucertini and Musco, 2020). Cities produce 80% of the Global Domestic Product, approximately 70% of global CO_2 emissions and 50% of global waste (United Nations, 2019; Kennedy et al., 2015, Facchini et al., 2017; Merino-Saum et al., 2020).

To address these challenges, many recent studies have focused on measuring urban sustainability using different approaches, methods and metrics that embrace the concepts of sustainability, circularity, urban metabolism and smart cities (Dall'O et al., 2017; Brilhante and Klaas, 2018; Sáez et al., 2020; Sharifi, 2021; Maranghi et al., 2020; Kennedy et al., 2007). However, the need to define best practices and help policymakers address processes related to urban and regional planning reminds us that a unique and unambiguous set of strategies to reach these

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[1] http://www.un.org/sustainabledevelopment/sustainable-development-goals/.

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ambitious targets is still lacking (Maurya et al., 2020). Possible reasons include the complexity of the aspects and the wide range of competences involved, trade-offs between the need for concise and comprehensive measurements, the diversity of geographical and environmental contexts at regional and local level, and the different priorities, criticalities and potentials of cities in relation to their size and political and socio-economic context (Taylor, 2014). In addition, most studies on urban sustainability and smart cities have so far focused solely on large cities or towns with populations over 500,000. A significant part of the population (about 40%), especially in Europe, lives in non-metropolitan areas or towns with populations under 500,000.[2] This is also true of Italy, where studies focusing on urban sustainability mainly concern the large cities (e.g. Milan, Turin, Rome, Venice, Naples) or provincial capitals, while most of the population lives in towns and smaller cities.[3] Future strategies and policies based prevalently on large cities may be unsuited for the more numerous smaller cities and towns. These aspects reduce the availability of tools for planning and monitoring goals and action for the green transition as envisaged in the EU Green Deal (EU, 2021) and for energy transitions in which cities/towns and local communities both play a central role.

Success in achieving sustainable environmental policy objectives often depends on the ongoing engagement of civil society through local government arrangements that can evolve over time and respond to incentives and to increasing levels of community capability. Policies to cut CO_2 emissions and to promote digitalization, as well as smart-city and innovative design for local public utilities (waste, water, transport, etc.) being developed in many countries could benefit from scientific support for their definition and for their integration into appropriate monitoring. To address this need, we propose an index to measure the increasingly sophisticated strategies devised to effectively implement, manage and monitor the green transition of municipalities and urban regions in Italy. We use the term "green transition" to indicate a shift towards economically sustainable growth and an economy that is not based on fossil fuels and overconsumption of natural resources. This view is embraced by the European Union, whose Green Deal aims to achieve a sustainable economy that relies on low-carbon solutions and promotion of a circular economy and biodiversity. Thus the green transition encompasses measures that include green technologies and capacities, sustainable mobility, energy efficiency, renewable energy, adaptation to climate change, a circular economy and biodiversity (EU, 2021).

In the framework of the scientific community's efforts to develop indicators to measure city (Lucertini and Musco, 2020; Merino-Saum et al., 2020; Economist Intelligence Unit, 2009) and regional (D'Adamo et al., 2021) sustainability and circularity, the proposed method is the result of a search for a trade-off between the urgent need for shared approaches and tools and the current availability of open data and citizen science. We consider open data to be a fundamental resource for this monitoring task and for stimulating data-driven urban and planning and policy prioritization, as well as for promoting transparency and sharing policy decisions with the scientific community and citizens.

The aims of our study are: a) to design an index that incorporates the main elements and data concerning the urban green transition at municipality level for an entire country; b) to define a replicable method to assess local performance towards the green transition based on open data c) to identify critical aspects, geographical and social disparities and potential policy solutions to facilitate an effective and an equitable transition.

As a case study, we collected open data on digitalization, infrastructure, mobility, environment, energy and waste from all Italian municipalities. The results highlight regional and population size disparities, suggesting the need for tools to underpin the accurate investment planning envisaged by the National Recovery And Resilience Plan recently issued by the Italian government.[4]

The paper is organized as follows: Section 2 provides a brief overview of the literature and the main indicators developed; Section 3 presents the basic methods of the index and applies them to Italian municipalities. The results are presented in Section 4 and discussed in Section 5. Conclusions and future directions are detailed in Section 6.

2. Background and overview of the literature

The global adoption of a sustainable development vision in 1992 marked the beginning of a new era. It was recognized that people's needs and aspirations had to be balanced with healthy ecological and social systems. The pursuit of development, as such, could no longer be justified in solely economic terms without considering its broader environmental, social and sustainability impact. One approach has been to adopt new indicators of progress that complement and integrate traditional barometers of development which are mainly anchored in economic variables. Pioneering work on the development of these composite indicators (Stiglitz et al., 2010; Organization for Economic Co-operation and Development, 2011; CEC-COM, 2009) was followed by intense production of new indicators.

Composite indicators typically aggregate a variety of information about a sector and often provide a basis for its ranking, which in turn can enable comparisons of public policy outcomes. These indicators have the advantage of being inclusive and the disadvantage of sometimes being difficult to decipher and analyze because they condense messages that reflect a complex world. Composite indicators for sustainability studies at regional level have been applied in Europe (Paracchini et al., 2011) and Italy, where (Floridi et al., 2011) and (Ciommi et al., 2017) developed a framework of indicators to assess sustainability and wellbeing at NUTS-2 and NUTS-3 levels, respectively. Composite indicators span several dimensions and have also been used to monitor the progress of policy goals. For example, Costanza et al. (2016) used composite indicators to measure well-being at local level, while Biggeri and Ferrone (2022) proposed the Child Sustainable Human Development Index, a children-centered tool, to monitor sustainable human development covering several Sustainable Development Goals with a focus on emerging regions.

In Europe, regional competitiveness is one of the main objectives of regional policy and is considered fundamental for the promotion of cohesive and balanced regional development. According to Rogerson (1999), cities or regions base their competitiveness on the ability of local economies to achieve a high standard of living for their populations. The concept of competitiveness at regional or urban level is not simply related to the ability of local communities to obtain a high return from natural resources, labor and physical capital, but also includes the performance of governments and institutions (Turok et al., 2004). These aspects include urban amenities (Broxterman and Kuang, 2019), sustainable tourism (Lozano-Oyola et al., 2019) and regional inequalities (Sun et al., 2017), recently assessed using composite indexes. Regional competitiveness is also closely linked to innovation. Examples of the various approaches that highlight this link include the literature on industrial districts, extensively explored in Italy (Sforzi and Boix, 2019; Hervás-Oliver, 2021; Zanon and Verones, 2013), on Porter's industrial clusters (1998) and on science-technology parks, also known as Technopoles (Amirahmadi and Saff, 1993; Pittaway et al., 2004). This concept leverages geographical concentration of companies and firms to create economies of scale and scope, as well as agglomeration economies, with their corresponding benefits. In a global and technologically

[2] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Urban_Europe_%E2%80%94_statistics_on_cities,_towns_and_suburbs.

[3] The Italian population is distributed as follows: 23% in towns with populations >100,000, 47.5% in towns <20,000 and 31% in towns <10,000.

[4] Next Generation Italia https://www.governo.it/sites/governo.it/files/PNRR.pdf.

advanced scenario, besides the traditional determinants identified by Porter (2008), other factors, such as institutional quality, drivers of innovation, attention to sustainability and local-global interactions, therefore also need to be taken into consideration. Taken altogether, these factors become essential elements for local governments to determine and promote the attractiveness and prosperity of their areas.

The combination of human and social capital with institutional endowment therefore becomes a fundamental element in the creation of sustainable regional development paths, being a trigger factor through the (sustainable) transition process (Salvador and Sancho, 2021; Shapiro, 2006; Glaeser and Redlick, 2009).

Researchers have recently explored factors and determinants that play a key role in activating actors and resources that lead to spatial differences driving sustainability (Cappellano et al., 2022). Additionally, measuring social innovation, including innovation capacities and regional embeddedness, is now understood to play a key role in the process of sustainable transition (Krlev and Terstriep, 2022). In this perspective, promoting relationships between individuals, businesses and local institutions can increase regional competitive advantage. Policymakers must therefore confront new objectives and the needs of their communities including the dissemination of technologies, technological culture, sustainable development, environmental control and climate policies. This widens the concept of competitive and attractive regions and cities to include different aspects, such as quality of life, the environment, transport and so on. With these emerging trends in mind, progress towards accomplishing these important challenges needs to be measured and compared using new and more comprehensive analytical tools. With the availability of the recovery plan funds for Europe, the so-called Next Generation EU plan, decision-makers will more than ever require reliable data, figures and measures to underpin their strategies and monitor the progress achieved in the transition process. Increasing efforts are being made to quantify aspects of local and national performance in various fields and to compare them against a set of goals and targets (Surminski and Williamson, 2012), for use as a handy tool to highlight progress over time, assess performance in relation to national/regional pledges, and explore investment needs and institutional and infrastructural gaps.

To measure the evolving scenario related to sustainability and the ecological transition, several city rankings have been developed and adopted to specifically measure the environmental sustainability of European cities. Key examples include the European Green Capital Award, the European Green City Index and Urban Ecosystem Europe (Table 1). These rankings contribute to the assessment and development of environmental policy in European cities. However, city rankings only provide a partial picture of the situation in Europe, since only about 40% of the EU population lives in cities and 32% in towns/suburbs, while the rest lives in rural areas (Fig. 1). The European Union is solidly committed to making its cities and local communities more sustainable (European Commission, 2010). A dedicated indicator designed to capture this multifaceted scenario is therefore an important addition to the information available to policymakers and researchers.

2.1. Comparison with other indicators

Here we briefly describe the main characteristics of three existing indicators compared to the proposed Municipality Transition Index (MTI), to underline their main aspects and shortcomings. The existing indicators have important methodological differences, so that a city may have a high position in one ranking and a low position in another. However, object rankings are inherently problematic, and the data sources used in the European city-ranking exercise differ greatly across indicators (Table 1).

While these indicators are useful and highly informative, they compare major European cities in different countries and may provide biased results, as every city has its own social, economic and political landscape that obviously influences indicator outcomes and

Table 1
Comparison of MTI and the main Indices.

Indicator	Overall index attribute	Number of categories	Number of Indicators
Municipality Transition Index	Focus on all the municipalities in Italy to provide a picture of their sustainable transitions	4	18
European Green Capital Award (1)	The overall ranking is a technical combination of 12 separate indicators	NA	12
European Green City Index (2)	The European Green City Index measures the current environmental performance of major European cities and their commitment to reducing their future environmental impact by ongoing initiatives and objectives	8	30
Urban Ecosystem Europe (3)	Individual indicators are not aggregated into an overall ranking attribute	6	25

(1) Technical Assessment Synopsis Report - European Green Leaf Award 2022, Phrenos (2021).
(2) European Green City Index available here: https://assets.new.siemens.com/siemens/assets/api/uuid:fddc99e7-5907-49aa-92c4-610c0801659e/european-green-city-index.pdf.
(3) Maia Da Rocha S, Zulian G, Maes J, Thijssen M. Mapping and assessment of urban ecosystems and their services. EUR 27706. Luxembourg (Luxembourg): Publications Office of the European Union; 2015. JRC100016.

performances across dimensions. On the other hand, while cities are home to most of the EU population, the composition and distribution of domestic populations vary greatly from country to country (Fig. 1). Therefore cities may be representative of the main dynamics in countries such as Spain, Estonia, Netherlands and Portugal, where they represent most of the population, but less indicative of the status of other EU countries. The relative weight of the city, town and population also differs greatly across Europe. Countries such as Belgium, Czechia, Germany, Hungary, Croatia, Italy and Lithuania have a predominance of population in towns, suburbs and rural areas as opposed to cities. Yet it is necessary to measure and assess the results and performances of these peripheral areas in terms of their ability to cope with the sustainable transition.

In light of the urgency of policy response to the problem of global ecological deterioration and to the sustainability requirements of municipalities of all sizes, the aim of our Municipality Transition Index (MTI) is to help fill the gaps discussed above and to provide a more comprehensive picture of the current strategies of municipalities and regions to effectively implement, manage and monitor the green transition.

3. Method and case study

The MTI is structured in four dimensions: Digitalization (D), Energy, Climate and Resources (ECR), Sustainable Transport and Mobility (M), and Waste and Materials (W). Based on their impact on sustainability and economic circularity, these dimensions are divided into two groups: a) direct factors (ECR and W) and b) enabling factors (D and M). The former category incorporates tools to achieve better results in terms of sustainability and economic circularity, while the latter incorporates factors that can help and facilitate the implementation and monitoring of policies.

In turn, each MTI dimension is composed of several key performance indicators (KPIs), whose importance and weight can vary. In particular, the weight of a KPI is relatively high if it is subject to action by policymakers or if it is subject to political targets and environmental standards set by regulations and laws. As depicted in Fig. 2, the KPIs included in the MTI dimensions can be grouped as follows.

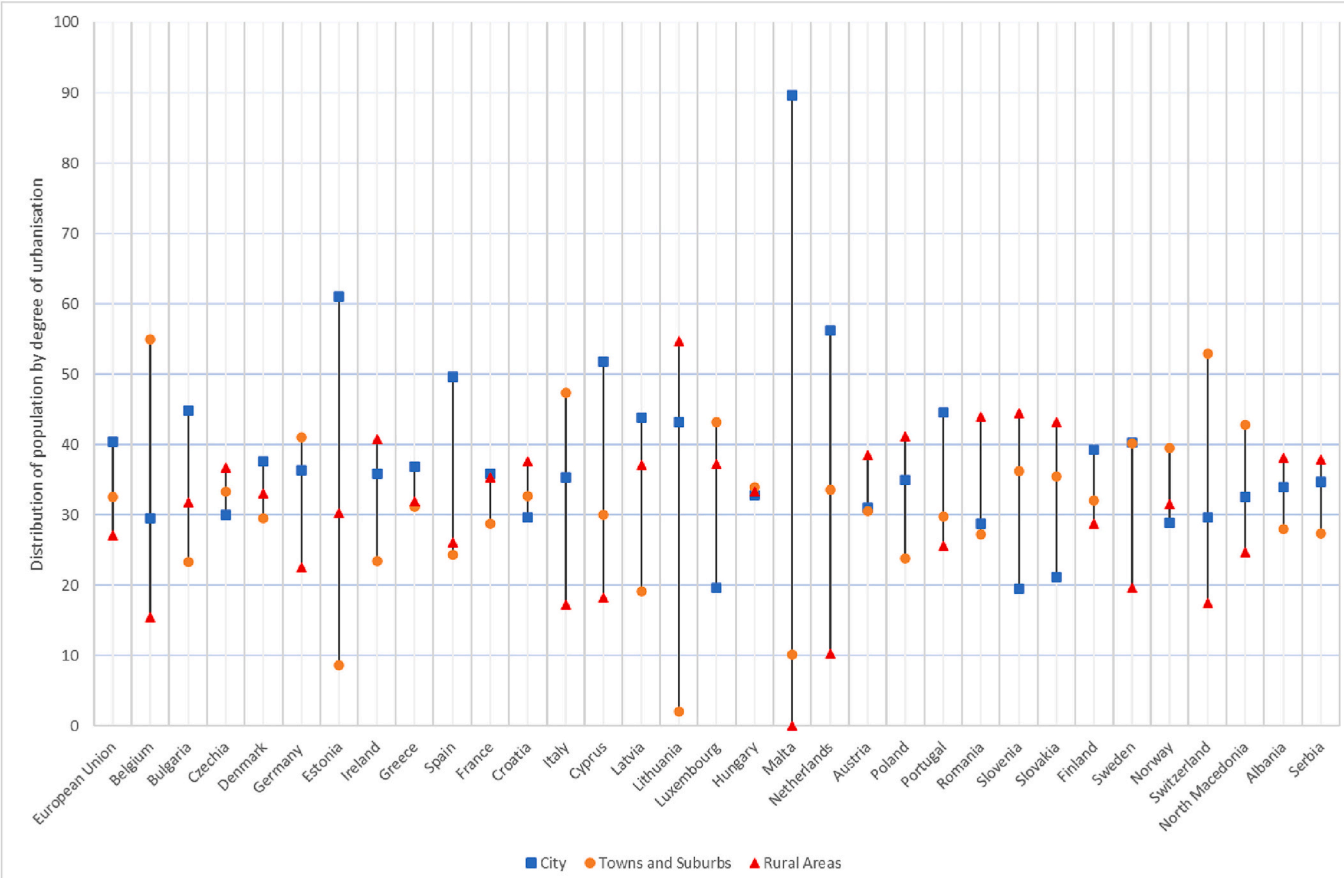


Fig. 1. Distribution of population by degree of urbanization, Total (Source: Eurostat, 2018).

Fig. 2. Dimensions and KPIs composing the Municipality Transition Index (MTI).

1. Digitalization (D)
   a. Broadband connection
   b. Public website and digital service accessibility
   c. Adoption of national digital enabling platforms: adoption of public digital identity systems (i.e. SPID in Italy) by public administration portals & services, adoption of national digital registries for resident populations by municipalities (i.e. ANPR in Italy)
2. Sustainable Transport and Mobility (M)
   a. Facilities for electric vehicles (e.g. charging stations)
   b. Pedestrian areas and infrastructure for bicycles
   c. Public transport and sustainable mobility
3. Energy, Climate and Resources (ECR)
   a. Resource use and infrastructure
   b. Air quality and emission reduction targets
   c. Renewable and low carbon energy sources
4. Waste and Materials (W)
   a. Input materials
   b. Waste production
   c. Separate waste collection

3.1. Adaptation and computation of the MTI for Italy

Considering Fig. 2 in the case of Italy, the Italian government recently defined the National Recovery and Resilience Plan (PNRR) in response to the EU Next Generation plan. It focuses on Italy's green transformation with ambitious policies in the following six areas:

1. Digitization, innovation, competitiveness, culture and tourism
2. Green revolution and green transition
3. Infrastructure for sustainable mobility
4. Education and research

5. Cohesion and inclusion
6. Health

We computed the MTI considering specific KPIs that are consistent with the PNRR. Table 2 shows the KPIs and the corresponding open data sources used to compose the database. We considered data and KPIs that cover points 1–3, which in our opinion are the most closely related to the concept of green transition.

Table 2 shows how the MTI was implemented for the case study of Italy and also shows information regarding the value assigned to each KPI and the targets we considered to calculate the index. More in detail, the information shown in the table is the type of KPI and current target. We categorize the data into different types according to the nature and objective of the KPI:

1) Binary: taking values 0 (e.g. false, no, etc.) or 1 (e.g. true, yes, etc.) when the municipality subscribes or implements a specific policy or is present in a database (e.g. signs the Covenant of Mayors).
2) Percentage: usually for material flows or availability of basic services.
3) Levels: the KPI takes values in a discrete set of integers (e.g. the level of accessibility of public digital portals or the level of commitment of climate reduction targets).
4) Number: usually expressing a threshold (e.g. concentrations of air pollutants).

To define an objective evaluation, we used the values of the target column as benchmarks to calculate the value of each KPI.[5] The target refers to current policies implemented to monitor or control the KPIs. Analyzing the targets, we note that most of them are not related to policies currently in force, ECR4 and ECR5 (air quality), W2 and W3 (separate waste collection and e-waste collection), Digitalization (D1 and D2) being the KPIs for which a policy is in force in Italy. Other targets are only recommended or under consideration by the Italian government or the European Commission. These are mainly related to climate reduction targets (ECR1, ECR2) and Mobility (M2, M3, M4) (for a comprehensive view of the target sources, see Section S1 of Supplementary Information). Other KPI targets are not linked to specific policy goals, despite being considered in the current EU Green-Deal-related documents.

Regarding weights, we follow (Ciommi et al., 2017) considering that weight values play an important role in the definition of the trade-off among the different KPIs in an Area. In particular, the weight associated to each indicator must reflect, as much as possible, not only its impact, but also the ability of policy makers to impact on the KPIs and the relevance of each KPI in the public policy. In the formulation of the MTI score, we considered slightly different values, a strategy also discussed in (Floridi 2011, and Chowdhury and Squire, 2006). A robustness check is performed to compare the current weights with the case of equal distribution (see section SI4 for details). We followed the same considerations when setting the Area weights, assigning a slightly higher value to the areas measuring ECR and Waste.

To set an upper bound for the MTI, we implemented a set of ideal targets that are the maximum or most desired value of each KPI. This choice has been successfully implemented in the literature (see Section 2) and was recently adopted by The Economist Intelligence Unit in the Global Liveability Index.[6]

Referring to Table 2, Starting with digitalization, D, we focused on local government and the availability of broadband connections. On the public administration side, there was sufficient good quality data on the accessibility of public digital service platforms and adoption of the personal digital identity system (SPID) in public portals for the purposes of the study, likewise for membership of municipalities to the National Digital Registry for Resident Populations (ANPR). For these KPIs, the data used - the most current available at the time of data collection and paper writing - is from 2021. Data on broadband cover held by the Italian telecommunication authority AGCOM includes the share of the population connected to the internet by connection speed (ranging from 7 Mb/s to over 100 Mb/s). We chose a threshold of 30 Mb/s, namely that of a high-quality ADSL2+ connection. This speed is specified by AGCOM as the minimum for a broadband connection that can ensure sufficient quality for web TV, remote working and education. The last data available for this KPI dates back to 2018.

For energy, climate and resources, ECR, we referred to the signing of the Covenant of Mayors and its adoption. Adoption was considered a measure of the municipality's level of commitment to European Commission targets, whereas mere ratification had less value in terms of commitment to 2020 or 2030 targets. Air quality is monitored by ISPRA, the technical body supporting the Italian government in the management of environmental data flows; data is available down to municipality level. For the case study, we considered concentrations of NO_2 and PM_{10}; $PM_{2.5}$ was discarded for lack of data and its high correlation with PM_{10} (Gehrig and Buchmann, 2003; Marcazzan et al., 2001). Ozone was also discarded because the data was not representative of the entire national territory. The data corresponding to ECR1–2 and ECR4–5 used in the computations date back to 2021. To monitor infrastructure efficiency, a lack of data at municipality level drove our choice to leaks in the water distribution system, since data on roads and electricity distribution is not available as open data. In Italy, the water distribution system is subject to regional policies and suffers from problems mainly related to aging infrastructure and lack of policy targets setting strict minimum quality thresholds (the Italian system leaks an average of 35–40% of the water conveyed, confirmed also in our data, which are from 2018). For energy, we focused on renewable energy self-sufficiency. To calculate self-sufficiency at municipal level, we referred to public data released by GSE ("Gestore dei Servizi Energetici") in 2021, the Italian public company in charge of monitoring renewable energy production plants. The self-sufficiency KPI, namely ECR3, is computed as follows:

$$ECR = \frac{R_{cap}}{H_{cap}} \quad (2)$$

where R_{cap} is the total photovoltaic and wind generator capacity in the municipality and H_{cap} is an estimate of the capacity demanded by all the households (N_h) in the municipality. Considering an average of 3.3 kW per household, $H_{cap} = N_h{*}3.3\,kW$, the self-sufficiency provides a measure of the extent to which currently installed renewable capacity meets the power demand of households in the municipality.

For the biophysical aspect of ECR, we referred to the recent scientific literature and EU policy actions that highlight the paramount importance of green areas, forests and biodiversity (Pascual et al., 2022; Oke et al., 2021; Markolf et al., 2018). A set of policies is currently discussed within the framework of the EC Nature Restoration Law (European Commission, 2022), a continent-wide comprehensive law considered a key element of the EU Biodiversity Strategy, which calls for the restoration of degraded ecosystems, with particular focus on those with the most potential to capture and store carbon and to prevent and reduce the

[5] See Supplementary Information for further details where, in particular, for each KPI's data, we indicate the open source available online and the year to which the data refers. Regarding the years, it should be noted that we used the most up-to-date data available at the time of data collection and paper writing, which took place in 2021. This means that, depending on the KPI, the years can range from 2018 (e.g. D3) to 2021 (e.g. D1, M1, etc). This is mainly due to two aspects: on the one hand, the availability of open data, and on the other hand, the usual time that some institutions take to collect and process data (waste data is released with a 2-year lag by ISPRA.

[6] https://www.eiu.com/n/campaigns/global-liveability-index-2021/.

Table 2
Definition of the KPIs and value levels used in the case study. Targets in bold indicate policies currently in force; targets in italics are recommended by institutions.

Dimension	Dimension weight	KPI code	KPI weight	KPI definition	Type	Target
Digitalization	0.2	D1	0.3	Presence in ANPR (public digital service registry for Resident Population)	binary	**yes**
		D2	0.3	Adoption of the National Digital Identity System (SPID) by municipalities in their digital portals, websites, services etc.	binary	*yes*
		D3	0.3	% of people with broadband connection (>30 Mb/s)[a]	%	*100%*
		D4	0.1	Accessibility of local government digital registries (i.e. websites, portals)	levels	high
Energy, Climate and Resources	0.3	ECR1	0.052	Covenant of Mayors - ratification	binary	Yes
		ECR2	0.252	Covenant of Mayors - Level of commitment	levels	2020–30
		ECR3	0.3	% local energy self-sufficiency (from renewables)	%	55%
		ECR4	0.1	Annual average concentration of PM10	threshold	**40 μg/m3**
		ECR5	0.1	Annual average concentration of NOx	threshold	**40 μg/m3**
		ECR6	0.1	% water leakage	%	low
		ECR7	0.1	Tree cover	%	10%
Mobility	0.2	M1	0.2	Pedestrian areas (m^2/100 persons	number	900
		M2	0.3	Charging stations (points/1000 persons)	threshold	***1* charging/1000 persons**
		M3	0.2	Cycleways (km/100 km^2)	threshold	100
		M4	0.3	Bus stops (number/100 persons)	threshold	1
Waste	0.3	W1	0.4	Per capita production of solid waste (t/person)	number	low
		W2	0.4	% separate waste collection	%	**65%**
		W3	0.2	Collection of e-waste	binary	**yes**

[a] The Italian government considers the limit of 30 Mb/s (https://www.ilsole24ore.com/art/banda-larga-casa-casa-ecco-mappa-aggiornata-ministero-AEEUGj7C), while FCC considers 25 Mb/s as threshold.

impact of natural disasters. We then introduced a specific KPI (ECR7) for tree cover in municipal areas, setting a policy goal of (at least) 10% of the area covered by trees (we used Copernicus data referring to 2020, see section SI1.3 for computational details).

For the mobility indicators, M, we focused on sustainable mobility and the availability of local public transport. Regarding electric vehicle charging point infrastructure, according to Motus-E, there were 11,834 charging stations in Italy in June 2021, but since this dataset is not openly available, we opted for the OpenChargeMap project[7] that counted 8242 charging station locations by crowdsourcing, i.e. 70% of the total, under an open license with daily updates.[8]

Regarding pedestrian areas, bike lanes and bus stops, features identified by specific tags (see Section S4.2 for details) were extracted by specific queries to the OpenStreetMap database.[9]

Finally, for waste, W, we considered direct factors that measure circularity, including the share of urban solid waste recycled, urban solid waste production per capita and collection. This data is available in the ISPRA database (data used are from 2019). Per capita solid waste production was considered from two perspectives: recycling and reduction of non-recyclable solid waste disposed of in landfills or incinerated. Finally, regarding e-waste collection, the KPI is considered binary in accordance with the current policy in force.

In the following Table 3, we report descriptive statistics for the KPIs that take numeric or percentage values when computed on the case study (all 7904 Italian municipalities). Notice that regarding M4 (number of bus stops), the missing data concern relatively small municipalities and, in fact, 75% of the municipalities that are missing have <3400 inhabitants. Moreover, they are mainly concentrated in sparsely populated and mountainous regions of the country. The extant literature acknowledges that data availability on mobility varies both between and within cities, particularly when using open data sources (Boeing et al., 2022; Basiri et al., 2019). While collecting valid and sufficient data related to the characteristics of urban mobility poses technical and practical challenges (da Silva et al., 2015), open data remains a valuable resource for policy evaluation and analysis (Barrington-Leigh and Millard-Ball, 2017). In fact, despite the challenges, the extant literature emphasizes that open data can support sustainable mobility studies and policy development.

With regards to KPIs of the type binary or levels, the following the binary and levels KPI, values are observed as follows:

1. D1: 96.7% of municipalities are present in the public digital service registry for resident population (ANPR), so take the value 1
2. D2: 86.7% of municipalities adopt the national digital identity system (SPID), so take the value 1
3. ECR1: 8.7% of municipalities have ratified the Covenant of Mayors, so take the value 1
4. ECR7: 77.0% of municipalities exceed the threshold of 10% for tree coverage, so take the value 1
5. W3: 90.4% of municipalities collect e-waste, so take the value 1. It should be noted that the original data provided by ISPRA contains the quantity of e-waste collected. However, since the current policy adopted is binary in nature, whereby a municipality is considered compliant if e-waste collection is active, the KPI we use is also binary in nature.
6. ECR2: the level of commitment of the municipalities in the Covenant of Mayors varies, as described in the following table between 0 41.3%; 1 50%; 2 0.5%; 3 1.8%;

4. Results

This section shows the results obtained computing the MTI of all Italian municipalities. In the first subsection, we show how the MTI values are distributed and how the single dimensions determine the final index. Next, we show the relation between the MTI and major socio-economic indicators. Robustness checks are reported in section S4 of the Supplementary Information.

According to the latest administrative boundaries, Italy has a total of 7904 municipalities. It became possible to compute the MTI of all Italian municipalities after the economic crisis caused by the COVID-19 pandemic, because the Italian government committed to a public investment plan aimed at promoting a country-wide green transition. The plan focused on circularity, digitalization and decarbonization of the energy system. Italian municipalities show a wide range of geographic, demographic and socio-economic characteristics. Table 4 shows the distribution of municipalities by population. Most municipalities (about

[7] github.com/openchargemap/ocm-data.

[8] https://www.motus-e.org/wp-content/uploads/2021/07/Istogramma-Storico-Giu-2021.xlsx.

[9] ISTAT is currently using OpenStreetMap as an experimental tool for the statistical analysis of road networks (https://www.istat.it/it/archivio/257382).

Table 3
Descriptive statistics of the KPI considered for the case study. Only KPIs with numeric and percentage values are reported.

	D3	ECR3	ECR4	ECR5	ECR6	M1	M2	M3	M4	W1	W2
count	7904	7904	7699	7742	7904	7904	7904	7904	4514	7904	7904
mean	0.25	0.27	25.14	27.03	599.21	0.12	29.27	0.46	0.30	0.64	0.25
std	0.36	0.29	6.10	9.72	341.04	0.26	41.89	0.17	0.32	0.19	0.36
min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
25%	0.00	0.07	20.50	21.00	265.64	0.00	0.00	0.35	0.06	0.55	0.00
50%	0.00	0.15	24.00	27.50	804.30	0.00	0.00	0.43	0.15	0.69	0.00
75%	0.64	0.36	31.50	34.50	900.00	0.08	71.34	0.51	0.43	0.78	0.64
max	1.00	1.00	35.70	47.40	900.00	1.00	100.00	2.99	1.00	1.00	1.00

Table 4
Percentage of municipalities by level of commitment in the Covenant of Mayors.

Level of commitment in Covenant of Mayors	Percentage of municipalities
0	41.3%
1	50%
2	0.5%
3	1.8%
4	6.3%

90%) are small towns with populations under 15,000, encompassing about 40% of the Italian population, i.e. about 25 million people. Few municipalities have populations over 100,000, and fewer than 700 are in the medium-size bracket. (See Table 5

It is therefore important to understand and track the manner in which Italian towns are involved in the green transition, since the Italian government will be investing significant resources in the coming years in green stimulus packages.

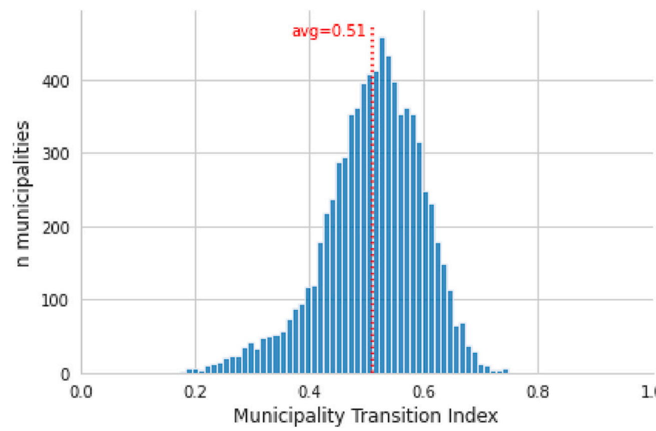


Fig. 3. Distribution of the Municipality Transition Index across Italian municipalities.

4.1. Computation of the MTI in Italy

Fig. 3 shows the distribution of the MTIs of Italian municipalities, where the ideal case takes a value of 100 (reported as reference point). MTI distribution appears to be bell-shaped around a mean value of about 0.51. The standard deviation is 0.093, while the maximum and minimum values are 0.76 and 0.14, respectively (see Table for the statistical description of these values). Interestingly, the distribution does not show significant asymmetries or kurtosis, confirming that the MTI calculated on many cases does not introduce biases that may lead to misinterpretation of the results.

The map in Fig. 4 shows the distribution of the MTI in Italy. The map highlights some regional differences: low MTI values are mainly found in the south-western regions, the inner center (coinciding with the Apennines) and in one southern region. The north-eastern and the Adriatic regions generally have higher MTIs. The islands generally show medium to high values.

For a better perspective on the composition of MTI, Fig. 5 shows the geographic distribution of the four dimensions. Fig. 5(a) shows a consistent divide in Digitalization between the urban regions of the north, the central regions and the south, which except for the eastern region and Sicily, generally take values in the low bracket. Fig. 5(b) mapping ECR does not mirror the disparity observed in Digitalization, showing medium to high values distributed evenly across the regions.

Table 5
Number of Italian municipalities and population distribution according to municipality size.

City size (population)	Number of municipalities	Total population	Percentage of population
< 5000	5521	9.8 M	16.6%
5000–15,000	1651	14.1 M	23.8%
15,000-100,000	688	21.5 M	36.3%
>100,000	44	13.8 M	23.3%
Total	7904	59.2 M	

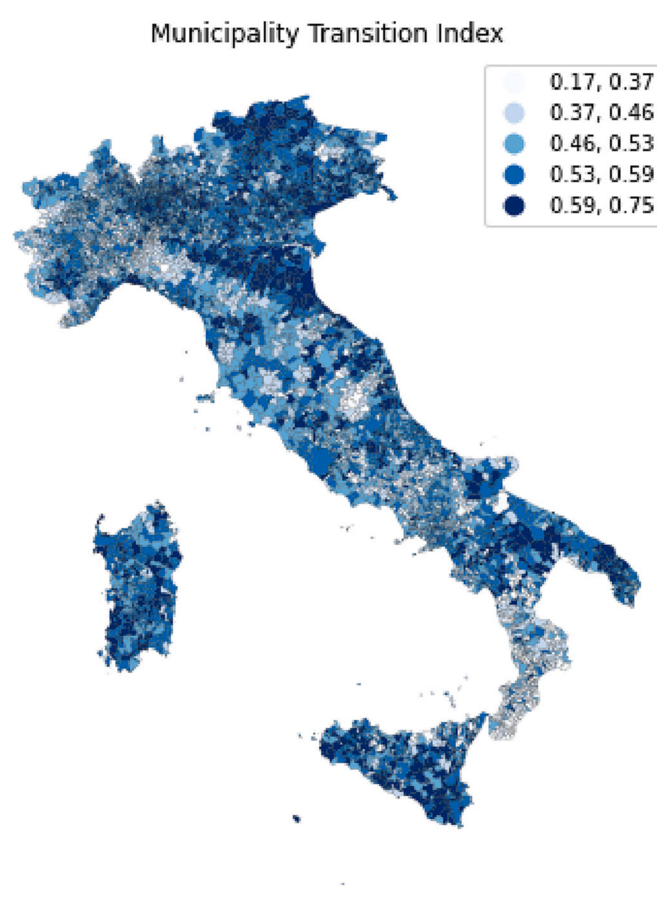


Fig. 4. Geographic distribution of the Municipality Transition Index in Italy.

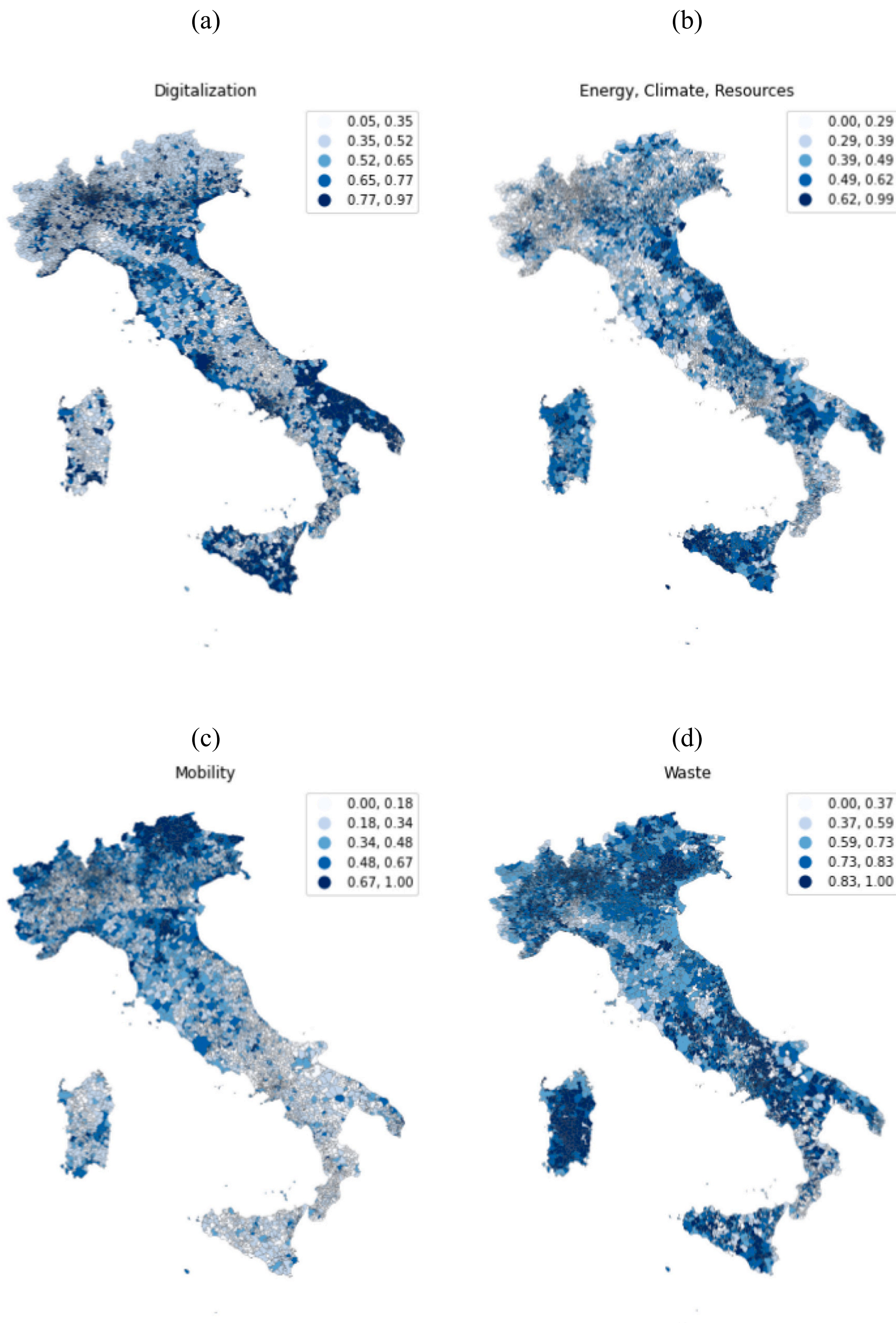


Fig. 5. Distribution of (a) Digitalization, (b) ECR, (c) Mobility and (d) Waste values in Italy.

The largest low-scoring area is in the north-western part of the country. It is worth noting that the island municipalities generally show high values, mainly because renewable energy has been encouraged by regional policies in recent years. Fig. 5(c) maps Mobility which shows the widest disparity between northern and southern Italy, where it is generally in the lower bracket, except in dense urban areas. An additional element that lowers Mobility values is the lack of light mobility infrastructure in southern municipalities (e.g. lack of bike lanes). This difference can be attributed to different factors: the first is the data source,[10] since the main source of open mobility data is OpenStreet Map, sampling of which might not be uniformly distributed; other factors may be related to different socio-economic conditions, which drive different policies on sustainable mobility (e.g. creation of bike lanes or distribution of charging points). Lack of public mobility may also drive the mobility divide. Finally, Fig. 5(d) maps the Waste dimension where values are generally medium to high, except in some mountainous regions. Small municipalities in the south generally show higher values due to low waste per capita and high recycling rates. *E*-waste is not always collected, reducing Waste values in these municipalities.

The maps in Figs. 4 and 5 show some disparities worth investigating at a scale finer than regional. We now consider the distribution of MTI by city size in order to understand whether the disparities that emerge are also found between larger and smaller urban centers.

Fig. 6 shows the distribution of MTI according to the size of the municipality. Average MTI increases with municipality size: those with populations over 100,000 are on average about 0.59, while small municipalities are on average 10 points lower. Medium-sized municipalities (pop. 5000–15,000 and 15,000-100,000) fall in the 0.50–0.60 range.

Fig. 7 shows the distribution of area values by municipality size. The largest gap is found in the Digitalization, with a consistent difference between large and medium-large municipalities (0.8) and small municipalities (0.4), while better uniformity is found in the ECR and Mobility areas, where generally larger municipalities show higher values. An exception to this is found in the Waste area, where small municipalities show higher values with respect to the larger ones.

We now consider the populations of municipalities by MTI quartiles. Table 6 shows that most of the Italian population lives in areas with medium and high MTIs, while about 13 M people live in areas having low or medium-low MTI. The table also shows that the lowest MTIs are more likely to be found in small municipalities (average population up to 4500).

Fig. 8 shows differences in MTI between provincial capitals and the surrounding municipalities. The vertical axis shows the percentage difference between the MTI of the provincial capital ("Capoluogo di Provincia") and the average MTI of all the other municipalities in the same province. Except for a few cases, capitals generally have higher MTIs than the surrounding municipalities, and in many cases the difference exceeds 10% (0.1 on the y axis). This suggests that infrastructure (e.g. for digitalization, mobility, energy) and environmental standards are more developed in the capital municipalities. This pattern is found for all dimensions except Waste, where the capital cities show lower values (see SI section S2). This is presumably because scaling up waste collection and differentiation is more complicated in cities.

4.2. *Relation of MTI to key socio-economic indicators*

When we tested the relation between MTI and socio-economic variables for correlations, we considered population, income (total and per capita) and their variations in recent years. For population we considered a 10-year period (2011−2021), while for income we considered a four-year period (2014–2018) to match the availability of data in the ISTAT database.

Fig. 9(a) shows the correlation matrix of the four dimensions considered in this case study. Dimension scores and MTI generally showed low or near-zero correlations, confirming that the MTI may capture the performance of Italian municipalities by going beyond the main socio-economic drivers and their temporal variation over a period of several years. Specifically, when considering population, the MTI shows a weakly significant correlation (0.396) with the logarithm of population (Fig. 9(b)). This correlation is probably due to the correlation of 0.61 found between Digitalization and population in Fig. 9(a). The correlations become more significant when we consider the change in population over the last ten years, showing values in the range − 0.046 to 0.3 with the dimension scores and MTI.

We found similar results for per capita income, with significantly lower correlations (between −0.21 and 0.43).

These correlations also suggest that high and low MTIs are not strongly correlated with the income and population dynamics of the municipalities. In other words, municipalities that have shown declines in both income and population in recent years do not necessarily have low MTIs.

Taking the higher correlation values, Fig. 9(b) shows a scatter plot of MTI against log10 of municipal population. The Pearson coefficient of ~0.4 confirms that the relationship is weak and probably due to nonlinear effects, investigation of which is beyond the scope of this paper. A similar pattern is seen in the cases with correlations exceeding 0.4 (for plots of the four dimensions, see Supplementary Information section).

4.3. *Measuring MTI on municipal economic performance*

The above correlations suggested we further investigate the relationship between income per capita and MTI. Considering the income per capita of municipality *i* as dependent variable, we tested the following model:

$$IncomePC_i = \alpha^*MTI_i + \beta^*log_{10}(pop_i) + \gamma^*Nuts3_i + \delta^*Geography_i + \lambda^*CityDim_i + \theta^*CityDim_i^*MTI_i + \epsilon_i \quad (3)$$

where the independent variables on the right-hand side are:

- MTI of municipality *i*;
- population (logarithm base 10) of municipality *i*;
- a categorical variable indicating that municipality *i* is in NUTS-3;
- a set of geographic variables at municipality level used as controls, provided by the Italian National Institute of Statistics: altimetric zone (1 to 5), coastal municipality (0–1), degree of urbanization (1–3), average altitude of the municipality (in meters) and area of the municipality (in square kilometers)[11];
- a categorical variable expressing the population of municipality *i* in terms of inhabitants of the city (as used previously: <5000, 5000–15,000, 15,000–100,000 and > 100,000);
- the model also includes interaction terms between MTI and city population.

Table 7 shows the results of the regression computed for the main model of Eq. (3) in column 7. The other columns show different implementations of the model: columns 1 to 4 do not include the categorical variable indicating population, while columns 3 and 6 include the NUTS-3 dummy and columns 4 and 7 also include the geographical control variables. The net effects are shown in Table 8.

Column 7 of Table 7 indicates that in municipalities with populations under 5000, an increment of 0.01 in the MTI corresponds to a yearly increment of ~€27 per capita, statistically significant at 1%. Table 8 tells us that the same MTI increment of 0.01 corresponds to an increment of

[10] See Table S1–1 and Section S2.1.

[11] https://www4.istat.it/it/archivio/156224#:~:text=Le%20Fasce%20altimetriche%20dei%20comuni,base%20all'altitudine%20(es.

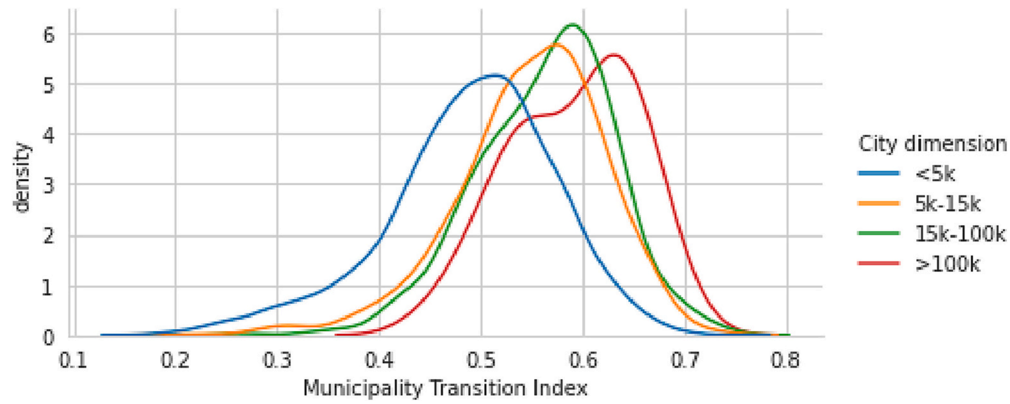


Fig. 6. Distribution of MTI with respect to municipality population.

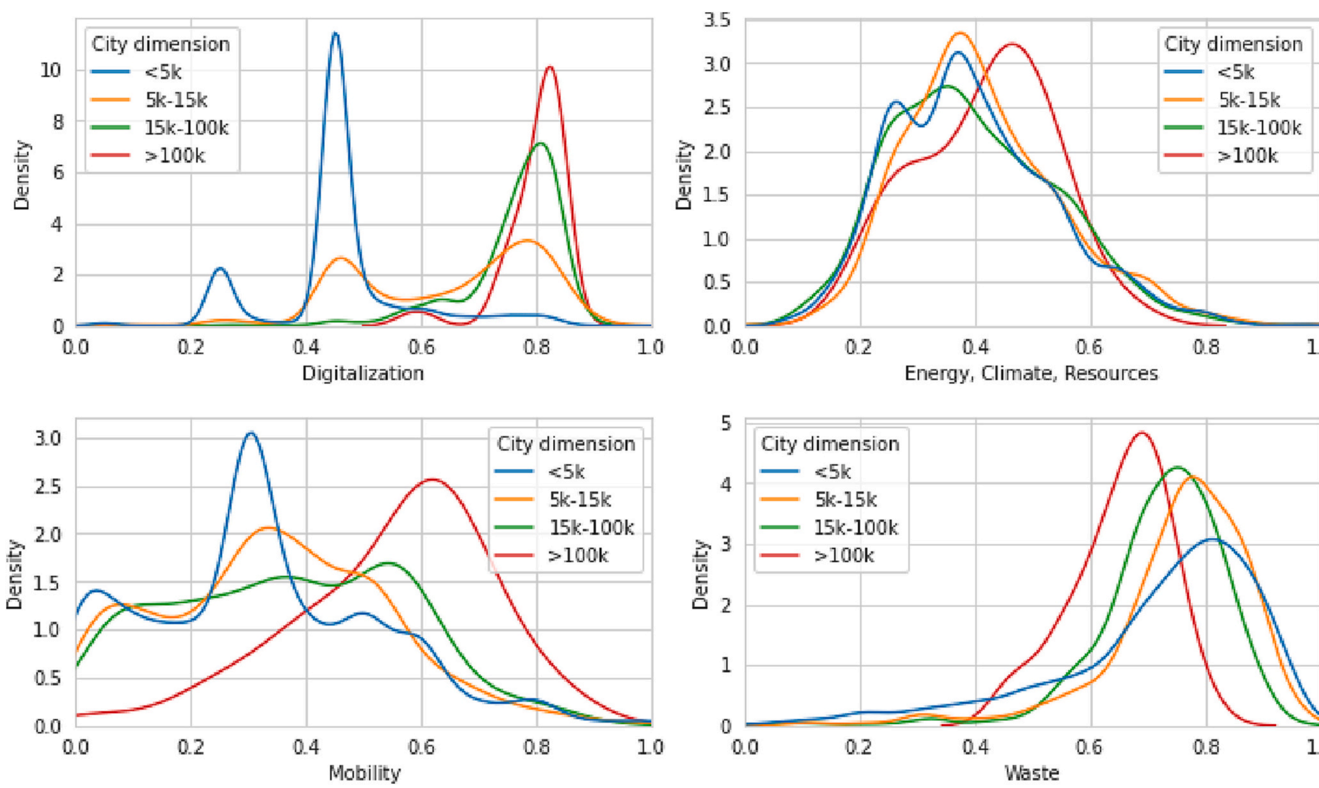


Fig. 7. Distribution of dimension scores for different municipality sizes.

Table 6
Populations of municipalities with low-medium, medium-high and high MTI values.

Quartile	Population	Quartile range	Average population of municipality
1st	5.5 M	0–0.46	2800
2nd	10.8 M	0.46–0.52	5500
3rd	17.8 M	0.52–0.57	9000
4th	25 M	0.57–1	12,700

~€37 per capita in municipalities with populations of 5000 to 15,000 at 1% significance, and to an increment of ~€76 per capita in municipalities with populations of 15,000 to 100,000 at 1% significance, and lastly that for cities with populations >100,000 the effect is not significant.

As expected, a close look at the adjusted R^2 in Table 6 shows that not only does it reach high values (≥0.7), but also that the largest part of the variation in income per capita is explained by the variable indicating the territorial unit, i.e. NUTS-3, to which the municipality belongs (e.g. compare columns 2 and 3). In any case our results show that the MTI is always robust and significant in all specifications of the model, confirming the key role that the four dimensions play in the overall economic performance of Italian municipalities.

5. Discussion

In this paper, we propose a Municipality Transition Index as a tool to evaluate the performance of Italian municipalities in addressing the green transition.

The MTI was computed considering the targets established by existing policies in 4 critical dimensions: Digitalization, Sustainable Transport and Mobility; Energy, Climate and Resources; Waste and Materials. The MTI provides a synthetic description of the scattered situation occurring at local level based on open data.

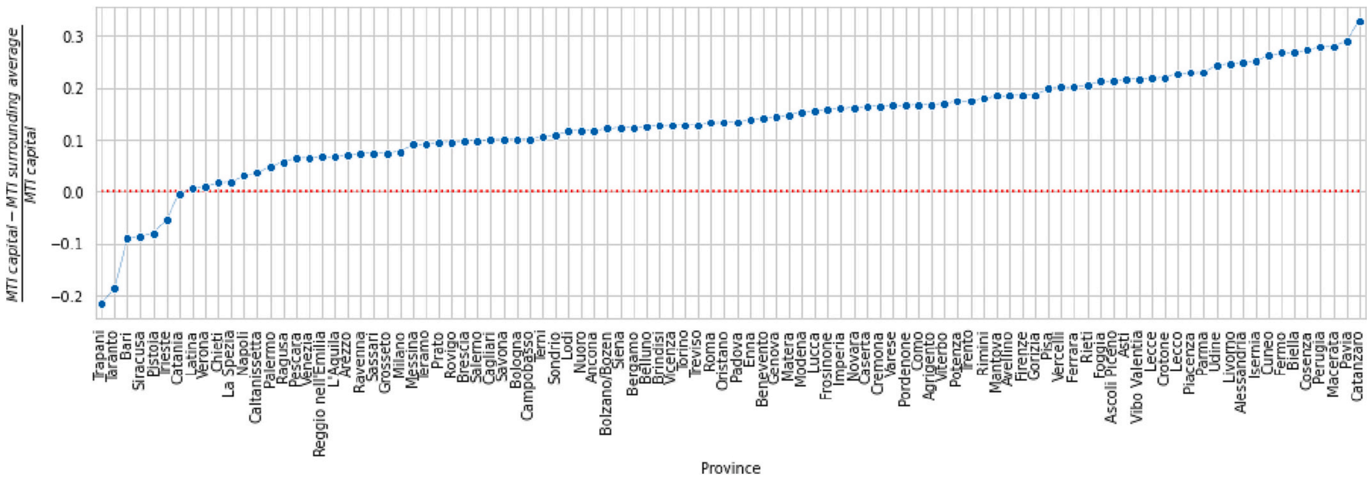


Fig. 8. Difference in MTI between province capital and surrounding municipalities.

When applied to all Italian municipalities, MTI produced a bell-shaped distribution of values. The index also captured disparities in infrastructure and between regions. Geographic analysis highlighted regional disparities in overall MTI values and in all four dimensions.

5.1. Analysis of the four dimensions of MTI

5.1.1. Digitalization

The results highlight a digital divide between large and small municipalities and across regions. Adoption of the ANPR digital platform is widespread among municipalities, with only 300 yet to comply. Accessibility to public digital portals and services is quite widespread, while broadband availability shows a major gap between rural/mountain areas and urban areas. The north-south disparity does not seem to be significant for Digitalization. In general, D is higher in large cities, but we also noted some unexpected exceptions. For example, D is lower in Milan than in some smaller centers (e.g. Livorno); this may appear surprising because Milan is a municipality where digital services are well developed and tested. Even so, the value is lower because of the small percentage of the population with a broadband connection (about 60% versus >90% in Livorno and some other towns). In this case, the D values highlight the ability of the index to identify said gaps, and drive policy decisions towards a better distribution of infrastructure resources among the population.

5.1.2. Energy climate and resources

In the ECR dimension, a significant number of municipalities have signed the Covenant of Mayors,[12] although the commitment shown is generally low (i.e. a small percentage of municipalities have committed to the 2030 targets and submitted an action plan), leaving room for significant improvement. Municipal energy self-sufficiency shows high percentages in many municipalities (20% reach 0.5 self-sufficiency), with well-defined regional patterns linked directly to renewable energy policies implemented in recent decades, especially in the islands and southern-eastern Italy. In the central-north, self-sufficiency seems lower, especially in the mountains and northwest. Here policies encouraging regional self-consumption are most needed to cover the gap. We also note that energy self-sufficiency does not appear to be correlated with population size or income, and some municipalities showed self-sufficiencies above 1, meaning a territorial surplus of energy production. This is not always positive: from an infrastructure and economic perspective, it causes abnormal loads on the power grid that must be managed, leading to distribution and transmission system operator inefficiencies.

From the point of view of resources, we note that average water losses from Italian water distribution networks are generally high (about 40%). The air pollution aspect of ECR clearly reflects areas (especially the northern regions) where air quality is impaired by industrial production and meteorological factors. In the present paper, we assigned low weights to the corresponding KPIs (ECR4, ECR5) due to these weather factors.

Tree cover reflects urbanization patterns and land use for crops. Highly forested areas only remain in the Apennines and near the Alps, while low density forest is found in the north-eastern and north-westerns regions. Because of the high density of small municipalities about 77% of the municipalities reach the threshold value for tree cover.

5.1.3. Mobility

Mobility is the dimension showing the greatest disparity between northern and southern regions, and between large and small municipalities. This disparity can be traced back to the lack of coordination between policies and incentives encouraging light and sustainable mobility in recent years. An exception may be the lack of bike lanes, especially in municipalities located in mountain regions, which can now be remedied by the spread of e-bikes.

Moreover, the Mobility area is correlated with income per capita (as shown in Fig. 9a), confirming that small, peripheral, and rural areas are disadvantaged in terms of sustainable mobility.

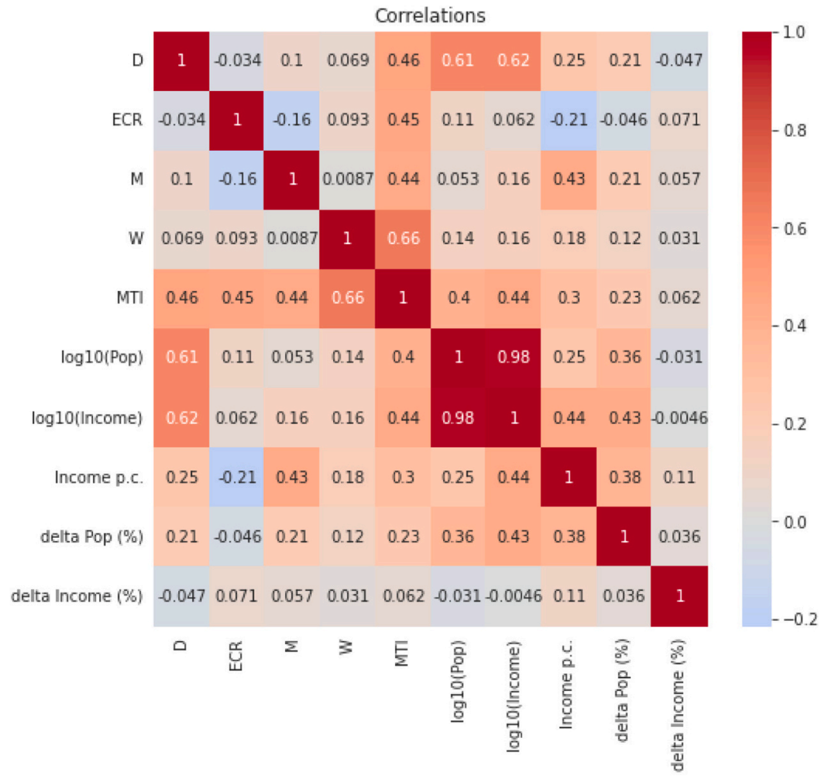
It should be highlighted that the data used for our KPIs are not only open-source but also user-generated, which naturally has limitations (Boeing et al., 2022; Basiri et al., 2019). Data availability on mobility vary both between and within cities, and is plagued by technical and practical barrier that limit the available studies on sustainable mobiliy (da Silva et al., 2015), but nevertheless open data represents a valuable support tool for policy evaluation and analysis (Barrington-Leigh and Millard-Ball, 2017).

5.1.4. Waste

Looking at the distribution of Waste scores, it may seem counterintuitive that southern regions are more virtuous than northern regions. Sardinia, too, shows a substantial number of municipalities with good Waste scores. This can be explained by the fact that the score recognizes high shares of separate collection and low per capita waste production. It was designed in this way because the green transition should involve an increase in recycling and lower waste production. We also observe a decoupling between waste production, population and economic activity, because waste does not appear to be correlated with population size

[12] Signatory cities pledge action to support implementation of the EU 40% greenhouse gas-reduction target by 2030 and adoption of a joint approach to tackling mitigation and adaptation to climate change.

(a)



(b)

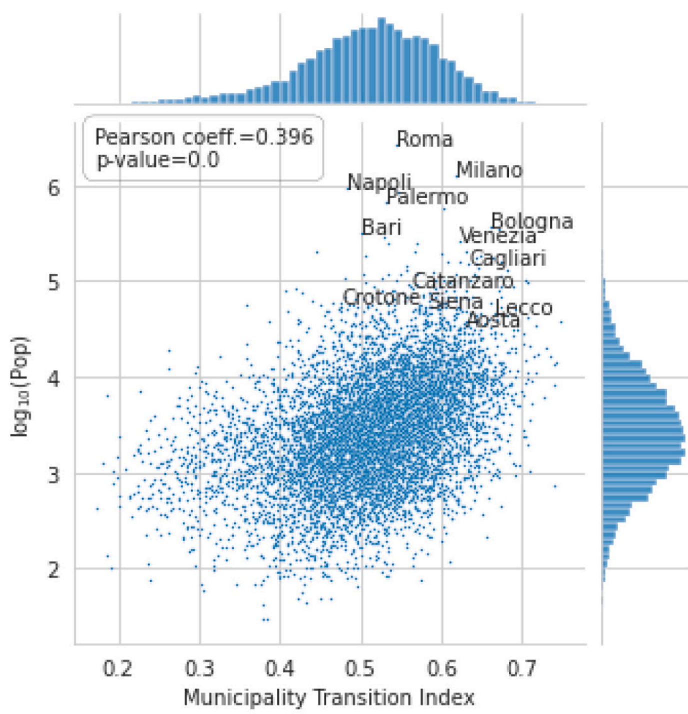


Fig. 9. (a) Correlation matrix of the main variables; (b) Scatter plot of MTI against log10 of municipal population.

Table 7
Results of regression.

Dependent variable: Income per capita	(1)	(2)	(3)	(4)	(5)	(6)	(7)
MTI	12,668.9***	9714.5***	3300.9***	3121.8***	7675.4***	2926.8***	2780.8***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Log_{10}(pop)		1039.9***	1889.8***	1346.7***	949.9***	1936.6***	1507.7***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Dim = 5 k–15 k					−2423.7***	−351.5	−762.8**
					(0.000)	(0.350)	(0.037)
Dim = 15 k–100 k					−7567.6***	−2771.6***	−3120.7***
					(0.000)	(0.000)	(0.000)
Dim>100 k					−8940.0***	1606.8	2588.6
					(0.001)	(0.505)	(0.313)
(Dim = 5 k–15 k)*MTI					5229.5***	710.5	1003.0
					(0.000)	(0.309)	(0.141)
(Dim = 15 k–100 k)*MTI					13,791.5***	4499.7***	4825.8***
					(0.000)	(0.000)	(0.000)
(Dim>100 k)*MTI					18,422.0***	−1262.8	−2666.4
					(0.000)	(0.746)	(0.523)
NUTS-3			Yes	Yes		Yes	Yes
Geography				Yes			Yes
Observations	7869	7865	7865	7865	7865	7865	7865
R^2	0.092	0.120	0.708	0.726	0.129	0.710	0.728
Adj. R^2	0.098	0.119	0.704	0.722	0.128	0.705	0.723

Robust standard errors.
p-values in brackets: * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 8
Net effects.

Dependent variable: Income per capita	Coef.	SE	t	P > |t|	[95% Conf. Interval]	
MTI + MTI * (Dim = 5 k–15 k)	3783.797	625.7677	6.05	0.000	2557.123	5010.471
MTI + MTI * (Dim = 15 k–100 k)	7606.673	1025.021	7.42	0.000	5597.354	9615.993
MTI + MTI * (Dim>100 k)	114.4794	4166.663	0.03	0.978	−8053.308	8282.267

or income (per capita and total) (Fig. 9(a)). An additional feature is the disparity between regional capitals and surrounding municipalities. Figs. S1-S10 show that surrounding municipalities generally show higher values, unlike other areas and excluding some provinces. This may be explained by the fact that capitals produce more waste and find it more difficult to increase the share of separate waste collection beyond the statutory environmental standard (65%). Other factors may be related to how waste collection is organized regionally. For example, a door-to-door collection policy may influence waste collection, or small municipalities pooling their collection and relying on another region for waste management and recycling.

5.2. Critical issues emerging in the search for data

Some critical aspects from the perspective of data collection and analysis, and from the point of view of policy and environmental standards were:

1. *Lack of open sources* covering all Italian municipalities. The data often showed non-uniformity across years, outliers and gaps. Depending on the year of release, there was regional non-uniformity, as Italian municipalities and provinces have been reorganized several times in the last decade. Lack of data concerned certain aspects related to sustainability monitoring, excluding waste collection and air quality (although the latter concerns a small number of municipalities).
2. *Lack of environmental standards* to define adequate benchmarks. Excluding air quality and waste collection, the other KPIs are not subject to rigorous environmental standards. Some benchmarks (see SI, Table 1) have been set according to current policy recommendations, while to the best of our knowledge, there are no recommendations for the others. This may influence the scoring of dimensions (e.g. Mobility) where there are few standards; indeed, observed disparities may also be due to voluntary adoption of policies to support the tools.?

Due attention should be addressed to these issues if we are to improve and implement policy and evaluation tools.

5.3. Critical aspects and limitations of this analysis

The following limitations are intrinsic to our analysis and must be taken into consideration:

1. *Heterogeneity of KPIs.* Coping with different types of values and ranges (e.g. binary, percentage, concentrations, etc.) poses uniformity problems in the calculation of MTI (see Supplementary information, Section S2, for computation function details).
2. *Dimension reduction and linear combination of KPIs.* Combining the values of different dimensions into a single weighted index necessarily leads to a loss of information. Two municipalities with the same index may have different dimensions, making the policies needed to implement the green transition different. For a comprehensive analysis, the dimension scores should always be considered. Furthermore, the linear combination of dimensions into the final MTI cannot account for any nonlinear effects or correlations in the data (e.g. non-negligible correlations between per capita income and waste).

Further research is needed to assess the possibility of using different methods of aggregating such heterogeneous variables.

5.4. Policy implications

The Italian recovery and resilience plan will unleash an unprecedented wave of investments and reforms to foster the green and digital transitions. Resources amounting to €68.9 billion in grants and €122.6 billion in loans will be delivered in the coming years, 37.5% to support climate objectives and 25.1% to support the digital transition. However, the top priorities and most urgent lines of action are still debated. While the purpose of the present analysis is to offer an overview of the infrastructural, institutional and social endowment with respect to the green transition of Italian municipalities, the MTI is a handy tool to identify the areas of action requiring special attention at local level. Regional and local administrations, policymakers and central institutions may therefore benefit from the integrated view proposed here in order to prioritize specific interventions and prevent further regional polarization.

6. Conclusions and future directions

The Municipality Transition Index (MTI) proposed here employs open data and measures to assess the green transition, focusing on circularity, energy, environment and information. The MTI was conceived as a flexible indicator based on four pillars that can easily be extended and adapted to other countries (e.g. in the case of different policies in force or different data collected by the statistical offices). To the best of our knowledge, it is the first attempt to use open data down to municipality level to support green policies at national level. We propose MTI as a policy tool to identify obstacles and structural problems impacting the transition, as well as a useful tool to define optimal transformation paths for individual municipalities, considering the need for tailored policies that take the specific potentials and criticalities of cities and towns, as well as urban, rural and inner areas, into account.

To compose the index, we identified a set of 18 KPIs corresponding to factors that directly and indirectly influence the green transition, with a focus on the Green Deal vision embraced by the European Union. The index was tested on all 7904 Italian municipalities. The results showed that calculation of the index on a large national sample led to a bell-shaped distribution of MTI values, highlighting disparities at regional level and in terms of population size.

We emphasize the strategic value of open data as a fundamental asset to define, plan and monitor the green transition of municipalities on a nation-wide scale. On the basis of the Italian case, we propose our index as a tool to support efficient implementation and monitoring of the Italian government's recovery and resilience plan. This index could be particularly useful since the different factors tend to offset others, and transition-enabling factors may be different from one place to another. It is designed to be a preliminary tool to help policymakers understand what factors could promote the smoothest and fairest possible green transitions for our towns and municipalities. While several institutions provide measures of transition performance at country level or for the largest cities in specific regions, direct information for lower levels of government is scarcer, if available at all. Disparities in the quality of government-performance measures at subnational levels can be even greater than at national level (Barrington-Leigh and Millard-Ball, 2017; Balta-Ozkan et al., 2015; OECD, 2015; Krawchenko and Gordon, 2021). Our research fills this gap, as measures of green transition performance at municipal level are virtually non-existent.

Our future work will be devoted to applying the index with a broad spectrum of socio-economic variables, using spatial econometric methods to define the effect of green transition policies and to glean relevant indications at regional and local level. Finally, we believe that the development of clear and flexible tools will be critical for encouraging dialogue and collaboration between scientists, citizens and policymakers and for building cutting-edge solutions to foster our sustainable future at all levels.

Authors' contributions

AM, SR, SG, GF, EB, AF conceived the idea;
AM, SG, GF, AF designed the research;
AM, SR, AR, AF wrote the article and replied to the peer reviewers;
SR, SG, GF, AF found the data;
SR, AF found policy targets;
AM, SG, GF, AF analyzed the data and performed the computations;
AF, SG supervised the project;
SG and NT provided funding.

Declaration of Competing Interest

The authors declare no conflict of interest

Data availability

Data will be made available on request.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2023.107924.

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